Production and Characterization of Coal-Biomass Briquettes

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Abstract

Roll press briquetting of coal-biomass mixtures presents a significant opportunity to address feedstock challenges associated with co-utilization of coal and biomass in existing coal-fired facilities. However, several technical and economic barriers require further investigation prior to industrial utilization of coal-biomass briquettes. The scientific contributions presented in this dissertation are intended to address the most critical technical challenges pertaining to coal-biomass briquette feedstocks. As with any product of an agglomeration process, the primary technical challenge regarding coal-biomass briquettes is achieving and maintaining a high level of quality from production to utilization. Several laboratory-scale research investigations were conducted to address this challenge. The first study was conducted to identify, develop and refine methods to characterize the most important physical properties indicative of coal-biomass briquette quality. The outcome of this work is a set of recommendations for novel and refined methods to characterize important coal-biomass briquette properties. The second study was conducted to develop a novel method to identify the optimum water content of coal-biomass blends prior to briquette production. As a result of this study, the Briquette Proctor Test was developed to minimize the time and materials required to identify the optimum water content that corresponds to maximum quality of coal-biomass briquettes. The third study was conducted to evaluate the influence of feedstock variables, additive variables, and roll press operating parameters in the production of coal-biomass briquettes from various coal and biomass types. From this study, the influence of each parameter on the quality of briquettes was determined and optimum conditions were identified for a variety of coal-biomass mixtures. The fourth and final study was conducted to develop and evaluate methods to improve the water resistance of coal-biomass briquettes using wood-derived chemicals. Using these chemicals, the novel coating method developed in this study significantly improved the water resistance and weathered durability of coal-biomass briquettes.

Dedication

The time and energy put into this dissertation is dedicated to the memory of Manfred Eric Dohm.

Acknowledgements

This dissertation represents the culmination of my academic pursuits over the past twenty years. I undoubtedly could not have reached this goal without the support and encouragement of so many family members, friends, colleagues and mentors. However, I owe my ultimate gratitude for everything I have learned and accomplished throughout this process to the grace I have received from GOD through his son JESUS CHRIST.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Problem Statement

1.1.1 United States Energy Consumption

In 2011, total energy consumption in the United States was 97.3 quadrillion British thermal units (Btu). As depicted in Figure 1-1, the electric power sector was the largest consumer of energy, followed by the transportation, industrial, and residential and commercial sectors (U.S. Energy Information Administration, 2012). Although a portion of the energy demand is currently met by nuclear power and renewable energy sources, fossil fuels continue to dominate the United States energy portfolio, contributing more than eighty percent to the total energy demand. Fossil fuels offer many benefits over non-fossil energy sources, including high energy density, widespread availability and affordability (DiPeso, 2011). However, there are a number of growing domestic and international concerns regarding current and future consumption of fossil energy.

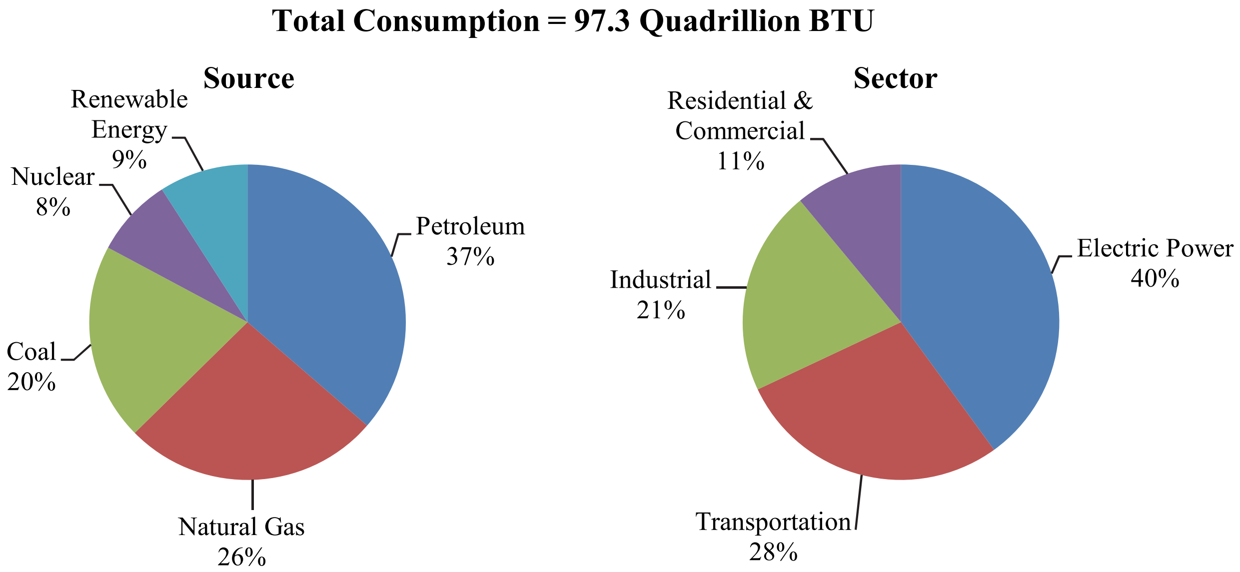


Figure 1-1. United States energy consumption in 2011 (U.S. Energy Information Administration, 2012)

1.1.2 Greenhouse Gas Emissions

The release of greenhouse gases from fossil fuel utilization has received considerable attention in recent years. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons. Carbon dioxide is the second most prevalent greenhouse gas, accounting for approximately 25 percent of the greenhouse effect (Casper, 2010). In 2011, carbon dioxide emissions from energy consumption in the United States totaled 5,481 million metric tons. Of this total, 42 percent was contributed by petroleum, 34 percent by coal and 24 percent by natural gas (U.S. Energy Information Administration, 2012). In an effort to reduce domestic carbon dioxide emissions, the United States Environmental Protection Agency (EPA) is increasing regulatory pressure on stationary emission sources. The most recent rule proposed by the EPA would establish a new source performance standard (NSPS) for carbon dioxide. The proposed standard would establish an emissions limit of 1,000 pounds of carbon dioxide per megawatt-hour of electricity generated for new fossil fuel-fired electric generating units (EGUs) larger than 25 megawatts (U.S. Environmental Protection Agency, 2012). If passed, this new rule could reduce coal-fired power generation, increase energy prices and destroy jobs and investments throughout the United States (Crooks, 2012).

In 2011, the electric power sector accounted for 92 percent of total domestic coal consumption, which was used to produce 46 percent of the total power generated in the United States (U.S. Energy Information Administration, 2012). Due to the current regulatory environment, many electric utilities have investigated options to reduce carbon dioxide emissions from coal-fired power stations. One near-term method that has gained considerable interest is co-firing, which involves substituting a portion of the coal feed with a renewable and carbon-neutral feedstock such as biomass (Sami et al., 2001). Biomass co-firing is an attractive option because it offers an immediate reduction of carbon dioxide emissions and does not require a significant capital investment (Basu et al., 2011). In addition to greenhouse gas mitigation, electric utilities can implement biomass co-firing to contribute to states' renewable portfolio standards in regions that do not possess sufficient wind, solar or other renewable resources (Nussbaumer, 2003).

As of 2009, more than 150 coal-fired power stations across the world reported co-firing coal and biomass on a commercial or trial basis (Fernando, 2009). In 2011, there were 40 power stations co-firing coal and biomass in the United States alone, with the majority located in the eastern and mid-western regions of the country (Basu et al., 2011). However, most industrial co-firing operations have used less than ten percent biomass on a heat input basis, while more than fifty percent would be required to meet the carbon dioxide emission limit proposed by the EPA. Unfortunately, industrial co-firing experiences have revealed a number of technical issues that can be detrimental to achieving this goal. These issues include biomass availability, transportation, storage, handling, and fouling and corrosion of the combustor (Basu et al., 2011; Fernando, 2009; Sami et al., 2001). Therefore, it is anticipated that other capital-intensive modifications to the traditional coal-fired power station, such as efficiency improvements or installation of a carbon capture system, would be necessary to comply with the EPA regulation.

1.1.3 Domestic Energy Independence

Another major concern regarding the current United States energy portfolio is the reliance on foreign sources of energy. Historically, the United States has imported large quantities of petroleum from politically unstable regions of the world, including the Middle East and South America. Petroleum is imported primarily to meet the rising demand of the transportation and industrial sectors for the production of liquid fuels and chemicals. In 2011, petroleum imports to the United States totaled 8.4 million barrels per day, or approximately 45 percent of total petroleum consumption (U.S. Energy Information Administration, 2012). These imports pushed the foreign trade deficit past $500 billion in 2011 and have greatly influenced foreign policy in the Middle East (Snow, 2012). In light of this challenge, there is significant political and industrial interest in technologies to increase domestic energy independence.

An established technology that has gained interest in recent years is gasification, which is a chemical process that converts carbonaceous materials into syngas for the production of chemicals, synthetic fuels and power (Basu, 2010). Specifically, interest in coal gasification has increased significantly due to fluctuations in the price of crude oil and concerns about domestic energy independence. The growing interest in gasification can also be attributed to the development of new applications such as gas-to-liquids processes, the prospect of increased efficiency and environmental performance in power generation, and the ability to process low-value or waste feedstocks (Higman & van der Burgt, 2003).

As of 2010, worldwide gasification capacity was 70,817 megawatts-thermal (MW_{th}) of syngas from 144 operating plants (U.S. Department of Energy, 2010). Additionally, 48 gasification plants with a projected capacity of 51,288 MW_{th} are in the planning or construction phases and should be operational by 2016. The majority of these new gasification plants (40 of 48) are designed to use coal as the primary feedstock. In the United States, gasification capacity was 6,166 MW_{th} from 18 operating plants in 2010 and an additional 18 plants are set to begin operating by 2016. These new gasification plants are projected to increase domestic gasification capacity by more than 500 percent to 33,406 MW_{th}. By 2016, coal will be used as the primary feedstock in the production of 17,783 MW_{th} in the United States, or roughly 53 percent of the total gasification capacity. About 45 percent of domestic coal gasification will be used to produce gaseous or liquid fuels, 42 percent to generate power, and 8 percent for the production of chemicals (U.S. Department of Energy, 2010).

One motivation for the gasification of coal is to replace petroleum as the primary feedstock for the production of chemicals and liquid fuels. Syngas produced from coal gasification is typically composed of 25 to 30 percent hydrogen (H_2) and 30 to 60 percent carbon monoxide (CO) (Ratafia-Brown et al., 2002). Pure hydrogen can be used to produce ammonia and other chemicals, while a mixture of hydrogen and carbon monoxide can be used to produce chemicals such as methanol. Similarly, pure carbon monoxide can be used to produce acetic acid and other chemicals (Higman & van der Burgt, 2003). Additional liquid fuels can be produced by catalytically combining hydrogen and carbon monoxide. For example, diesel fuel can be produced using the Fischer-Tropsch process or gasoline can be produced by methanol synthesis. Finally, syngas produced by coal gasification can also be used to produce synthetic natural gas composed primarily of methane (Fernando, 2008).

Interest in the gasification of coal for power generation began in the 1970s due to economic and environmental considerations. Current motivations for reducing greenhouse gas emissions have enhanced the prospects of power generation from an integrated gasification combined cycle (IGCC) plant (Fernando, 2008). The IGCC plant was developed in the 1980s by integrating gasification technology with a combined cycle power plant, which uses hot gas exiting a gas turbine as a heat source for a steam cycle in a heat recovery steam turbine (Higman & van der Burgt, 2003). Such IGCC coal-fired plants can achieve higher efficiencies than traditional pulverized coal combustion plants. In addition, carbon dioxide capture is considerably easier in the IGCC plant because the concentration and pressure of carbon dioxide is much greater in syngas than in the flue gas produced in a pulverized coal combustion plant (Fernando, 2008). Due to these advantages, the IGCC plant is a promising technology for future power generation using the vast coal reserves in the United States.

1.1.4 Co-Gasification of Coal and Biomass

Coal gasification and biomass co-firing offer significant environmental and economic benefits to the current United States energy portfolio. However, both the efficiency improvement of IGCC and biomass co-firing in coal-fired boilers will not provide adequate reduction in carbon dioxide emissions to meet the proposed EPA standard for power generation. In each case, the power plant would need to install a carbon capture and storage system to comply with the regulation (U.S. Environmental Protection Agency, 2012). Currently, significant government funding and tax incentives are needed to justify the installation of such as system, which would add considerably to the overall cost of electricity generation. Moving forward, the United States must still strive to improve greenhouse gas mitigation and domestic energy independence without sacrificing the nation's abundant, affordable and secure coal resources.

One area of considerable research interest in recent years is the co-gasification of coal and biomass, which incorporates the benefits of traditional biomass co-firing with the versatility of coal gasification. Aside from the environmental benefits, many studies to date have found a number of thermochemical synergies in the co-gasification of coal and biomass, including an improvement in the syngas H_2/CO ratio, faster reaction rates, increased carbon conversion and higher thermal efficiency (Long & Wang, 2011; Pan et al., 2000; Sjostrom et al., 1999). Unfortunately, there are also many technical challenges to co-gasification that can be very costly if not properly addressed. These challenges include upstream issues, such as biomass availability, transportation, storage, and handling, as well as problems encountered within the gasifier, such as fouling, corrosion, inconsistent feeding and segregation (Fernando, 2009). Further research is needed in the field of preprocessing coal and biomass mixtures to alleviate these technical challenges for co-gasification to gain industrial support (Koppejan & Brem, 2008; Reed, 1981).

1.2 Research Objectives

The ultimate objective of the research presented in this dissertation is to support the development of coal and biomass co-gasification by addressing feedstock technical challenges. Research activities were designed to identify and alleviate technical and economic barriers associated with preprocessing coal and biomass mixtures. Specifically, this research investigates the laboratory-scale production and characterization of coal-biomass briquettes composed of various coal and biomass feedstocks. The results of this investigation provide important data on the impacts of feedstock, additive, and operating variables for co-briquetting multiple types of coal and biomass. Additionally, recommendations for the characterization of coal-biomass briquettes in future studies are presented. Specific objectives of this research are to:

1. Identify, develop and refine methods to characterize physical properties of coal-biomass briquettes;
2. Develop a methodology to quickly and easily identify the optimum water content of coal-biomass blends prior to briquette production;
3. Evaluate the influence of the most significant feedstock variables, additive variables and roll press operating variables in the production of coal-biomass briquettes from various coal and biomass feedstocks; and
4. Develop and evaluate methods to improve the water resistance of coal-biomass briquettes using proprietary wood-derived chemicals.

1.3 Dissertation Outline

This dissertation is composed of an introduction (Chapter 1), a literature review (Chapter 2), a series of manuscripts that are prepared for publication (Chapters 3-6), and a concluding summary (Chapter 7). Chapters 3 through 6 are intended to serve as standalone papers that do not require the context provided in any other chapters. As a result, there is some repetition throughout this document with regard to motivations for this research, coal and biomass feedstock properties, and briquette production procedures. References are included separately for each individual chapter.

Chapter 1 provides a description of the motivation for the research described in this dissertation. In addition, the objectives and a brief summary of the studies presented in this dissertation are included.

Chapter 2 presents a comprehensive review of published literature on the topics addressed by the research in this dissertation. The major concepts reviewed include benefits and challenges co-gasification, gasification processes, coal and biomass properties relevant to gasification, and agglomeration of coal-biomass mixtures.

Chapter 3 discusses the identification, development and refinement of methods to characterize the physical properties of coal-biomass briquettes. This chapter begins with a review of established methods that can be used to characterize briquettes and then transitions into an extensive evaluation of these methods. The results of the conducted evaluations were then used to formulate recommendations for standard briquette characterization methods.

Chapter 4 introduces a novel methodology to identify the optimum water content of coal-biomass mixtures prior to briquette production. This chapter begins by describing a theoretical approach to water content optimization used in soil mechanics. Evaluations conducted to determine the applicability of this approach to coal-biomass briquette production is then discussed. Finally, major implications of this approach to experimental determination of optimum briquette quality are presented and discussed.

Chapter 5 describes a comprehensive study of the effects of feedstock variables, additive variables and roll press operating parameters on the quality of coal-biomass briquettes. This chapter begins with an overview of roll press agglomeration and the mechanisms involved in briquette formation. Next, the results of a series of studies are presented and analyzed. This includes inspection of correlations between briquette production variables and briquette qualities, development and analysis of mathematical models that predict briquette properties and numerical optimization of each model to determine ideal briquette production conditions. Finally, this chapter concludes with a detailed investigation of the physical properties, flow properties and gasification behavior of coal-biomass briquettes produced at optimum conditions to evaluate the quality of the co-briquetted feedstocks.

Chapter 6 introduces a novel application of wood-derived chemicals to improve the water resistance of coal-biomass briquettes. The results of two chemical application studies are presented to compare the relative performance of several wood-derived chemicals with commonly used briquetting additives for enhancing the water resistance of briquettes. Lastly, this chapter includes a detailed characterization study on the physical properties of briquettes coated with a selected wood-derived chemical to validate the enhanced quality of briquettes as a result of this chemical application process.

Chapter 7 summarizes the major research activities presented in this dissertation, presents final conclusions drawn from these studies and recommends topics for further research and development.

1.4 References

Basu, P. (2010). *Biomass gasification and pyrolysis: Practical design and theory*. Burlington, MA: Academic Press.

Basu, P., Butler, J., & Leon, M. (2011). Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. *Renewable energy*, *36*(1), 282-288.

Casper, J. (2010). *Fossil fuels and pollution: The future of air quality*. New York, NY: Facts on File.

Crooks, E. (2012). *EPA seeks strict limits on coal plants.* London, England: The Financial Times Limited (FT.com).

Fernando, R. (2008). *Coal gasification*. London, England: IEA Clean Coal Centre.

Fernando, R. (2009). *Co-gasification and indirect cofiring of coal and biomass*. London, England: IEA Clean Coal Centre.

Haslbeck, J., Kuehn, N., Lewis, E., Pinkerton, L., Simpson, J., Turner, M., Varghese, E., & Woods, M. (2010). *Cost and performance baseline for fossil energy plants − Volume 1: Bituminous coal and natural gas to electricity.* Washington, DC: U.S. Department of Energy.

Higman, C., & van der Burgt, M. (2003). *Gasification*. Burlington, MA: Gulf Professional Publishing.

Katzer, J., Ansolabehere, S., Beer, J., Deutch, J., Ellerman, A., Friedmann, S., Herzog, H., Jacoby, H., Joskow, P., Mcrae, G., Lester, R., Moniz, E., & Steinfeld, E. (2007). *The future of coal − Options for a carbon-constrained world*. Cambridge, MA: Massachusetts Institute of Technology.

Koppejan, J., & Brem, G. European Commission, Intelligent Energy − Europe. (2008). *Cofiring and co-processing biomass with coal* (WP2B Deliverable 2B-5).

Long H., III, & Wang, T. (2011). *Case studies for biomass/coal co-gasification in IGCC applications*. Vancouver, Canada: ASME Turbo Expo 2011.

Nussbaumer, T. (2003). Combustion and co-combustion of biomass: Fundamentals, technologies, and primary measures for emission reduction. *Energy & fuels*, *17*(6), 1510-1521.

Pan, Y., Velo, E., Roca, X., Manya, J., & Puigjaner, L. (2000). Fluidized-bed co-gasification of residual biomass/poor coal blends for fuel gas production. *Fuel, 79*(11), 1317-1326.

Ratafia-Brown, J., Manfredo, L., Hoffmann, J., & Ramezan, M. (2002). *Major environmental aspects of gasification-based power generation technologies*. Washington, DC: U.S. Department of Energy.

Reed, T. (1981). Recommendations for future gasification research and development. In T. Reed (Ed.), *Biomass gasification: Principles and technology*. Park Ridge, NJ: Noyes Data Corporation.

Sami, M., Annamalai, K., & Wooldridge, M. (2001). Co-firing of coal and biomass fuel blends. *Progress in energy and combustion science*, *27*(2), 171-214.

Sjostrom, K., Chen, G., Yu, Q., Brage, C., & Rosen, C. (1999). Promoted reactivity of char in co-gasification of biomass and coal: Synergies in the thermochemical process. *Fuel*, *78*(10), 1189-1194.

Snow, N. (2012). Former ambassadors cite foreign policy impacts from oil imports. *Oil and gas journal*, *110*(5), 27-28.

U.S. Department of Energy, National Energy Technology Laboratory. (2010). *2010 Worldwide gasification database*. Pittsburgh, PA.

U.S. Energy Information Administration. (2012). *Annual energy review 2011*. Pittsburgh, PA.

U.S. Environmental Protection Agency. (2012). Standards of performance for greenhouse gas emissions for new stationary sources: Electric utility generating units. *Federal register* *77*(72), 22392-22441.

Chapter 2

Literature Review

2.1 Co-Gasification Benefits

Growing concerns over rising greenhouse gas emissions and foreign petroleum imports have generated significant interest in cleaner and more secure technologies for the production of power, liquid fuels and chemicals. One of the more promising near-term options to address these challenges is co-gasification of coal and biomass. Co-gasification involves substituting a portion of the primary gasifier feed, such as coal, with a renewable and carbon-neutral feedstock, such as biomass (Sami et al., 2001). In addition to a net reduction in carbon dioxide (CO_2) emissions, the incorporation of biomass can also reduce the emission of sulfur oxides (SO_x) and nitrogen oxides (NO_x) due to the low sulfur and nitrogen levels typically present in biomass (Fernando, 2009; Demirbas, 2003).

For example, Long & Wang (2011) reported a reduction in harmful emissions from a 250-MW IGCC plant by incorporating up to fifty percent biomass in the coal feed. The concentration of CO_2 in the syngas was reduced from 14.88% with coal only to 13.97% by adding fifty percent biomass (weight basis) to the feed. Similarly, hydrogen sulfide (H_2S) in the syngas was reduced from 0.27% to 0.15% under the same conditions. Pinto et al. (2010) investigated the abatement of sulfur and nitrogen compounds by catalytic treatment of syngas produced from the co-gasification of coal and biomass. They found that syngas treatment using dolomite and a nickel-based catalyst led to a 97 percent net reduction in H_2S and ammonia (NH_3), which are the primary precursors to SO_x and NO_x emissions.

Aside from the environmental benefits of co-gasification, recent studies have found a number of improvements in process efficiency and syngas composition that are attributed to coal and biomass synergies during thermochemical conversion (Brar et al., 2012). Kumabe et al. (2007) studied the co-gasification of woody biomass and coal with air and steam in a moving bed gasifier at 900 degrees Celsius. Experiments were conducted to determine the effects of biomass content on the molar ratio of H_2, CO and CO_2 in the produced syngas. The results showed an increase in carbon conversion in the syngas as the biomass ratio was increased, whereas the conversion to char and tar decreased. Based on the molar ratios of H_2, CO and CO_2 in the produced syngas, the authors concluded that a low biomass ratio is favorable for the synthesis of methanol and liquid fuels and a high biomass ratio if favorable for dimethyl ether synthesis (Kumabe et al., 2007).

Pan et al. (2000) investigated the co-gasification of low-grade Spanish coals and pine chips at different ratios in a bench scale fluidized bed reactor operating at 840 to 910 degrees Celsius. The results showed an increase in the molar ratio of CO in the syngas as well as an increase in H_2 for blends with less than 25 percent pine chips. Carbon conversion was found to increase from 63.0% with coal alone to 75.3% by adding 25 percent pine chips to the feed. The overall thermal efficiency of the system increased from 40 to 61 percent under the same conditions (Pan et al., 2000). These significant improvements highlight the potential to convert low-grade coals into premium fuels by co-gasification.

Sjostrom et al. (1999) observed a number of synergies in the co-gasification of woody biomass and coal with oxygen in a pressurized fluidized bed reactor operating at 700 to 900 degrees Celsius and 0.4 MPa. Experiments were conducted by varying the content of coal and biomass in the gasifier feed and comparing the results to the gasification of the individual fuels. The study found an unexpectedly high reaction rate and low char yield, which led to an increase in syngas production. Moreover, tar and ammonia yields were lower than the sum of yields from the gasification of the individual fuels (Sjostrom et al., 1999).

2.2 Co-Gasification Challenges

Although there are a number of benefits to co-gasification of coal and biomass, there are also several challenges presented that can be very costly and detrimental to industrial operations if not properly addressed (Basu et al., 2011). As a standalone gasification fuel, biomass faces many economic and technical challenges. When compared to fossil fuels, biomass generally benefits from renewability and decreased harmful emissions (CO_2, NO_x, SO_x); however, the dominant tradeoff is a significant loss in energy density and seasonal availability (Sami et al., 2001). Consequently, more biomass is needed to attain the same energy output as fossil fuels. This problem is compounded when considering the added transportation and handling costs required to distribute the additional material (Smith & Rousaki, 2002; Taulbee et al., 2010). Depending on the distance, the reduction in gasification emissions may be offset by the increase in transportation emissions (Fernando, 2005). Additionally, since many agriculturally-based biomass fuels undergo a yearly cycle of growth, supply may be restricted to only a couple months per year (Fernando, 2009).

Aside from economic and supply issues, many technical issues constrain standalone biomass use. The chemical behavior of biomass is quite different from coal. Typically, biomass has a much higher moisture, ash, and chlorine content than even low rank coals. These differences can cause agglomeration issues during gasification and may add to equipment corrosion (Demirbas, 2003). Furthermore, fuel storage can be problematic since biomass is hygroscopic (i.e. readily absorbs and retains moisture) and can become reactive. For example, when wood chips exceed twenty percent moisture, biologic activity begins to deteriorate the fuel (i.e. rotting), leading to a significant loss in heat value (Fernando, 2005). While biomass generally gasifies at a similar temperature as coal, biomass ash is generally more aggressive and has a lower melting point than coal ash. Consequently, fouling and slagging can be significant if the ash becomes soft and sticky. Biomass particles are typically characterized by high aspect ratios and a fibrous, non-friable nature, which leads to difficulties in size reduction (Couch 2008). In addition, biomass size reduction can be quite expensive and energy intensive and often requires a separate pulverizer in addition to the standard coal pulverizer (Fernando, 2009).

To alleviate many of the technical and economic constraints of standalone biomass use, many industrial facilities have experimented with co-gasification of biomass with coal (Fernando, 2009; Smith, 2001). By combining specific mixtures of coal and biomass, a plant can achieve increased sustainability and reduced harmful emissions while avoiding the drawbacks of inconsistent supply and diminished thermodynamic efficiency. Furthermore, if the feed fuels are properly engineered, little if any retrofitting is required for existing plants. Direct co-firing, where biomass and coal are gasified together in the same reactor, is the simplest and most widely accepted practice, since the process can easily be accommodated using existing equipment (Fernando, 2005; Demirbas, 2003).

While more advantageous than standalone biomass gasification, direct co-gasification is still limited by inherent technical constraints. When independent feeds of biomass and coal are introduced into a moving bed or fluidized bed gasifier, a natural segregation occurs due to the density difference between coal and biomass. This segregation of fuel types can lead to thermal inconsistencies throughout the vessel and reduce gasification efficiency. If the biomass is excessively moist, further disturbance to the reactor heat balance can proliferate, leading to reduced biomass consumption and net accumulation in the reactor (Fernando, 2005). Additionally, the low melting point, increased alkalinity, and aggressive quality nature of the biomass ash can cause fouling and slagging problems along with extensive corrosion at relatively low temperatures (Sami et al., 2001).

2.3 Gasification Processes

To adequately appreciate the benefits and challenges of coal and biomass co-gasification, a basic understanding of gasification processes is required. Collot (2002) defines gasification as "the reaction of solid fuels with air, oxygen, steam, carbon dioxide or a mixture of these gases at a temperature exceeding 700 degrees Celsius to yield a gaseous product suitable for use either as a source of energy or as a raw material for the synthesis of chemicals, liquid fuels or other gaseous fuels." In other words, gasification is a thermochemical process that converts carbonaceous materials into synthetic gas (syngas) with recoverable heating value (Mulvaney & Robbins, 2011).

The principal mechanism of syngas production is partial oxidation of carbon, which occurs when fuel particles are heated in the presence of an oxidant typically composed of oxygen, air and/or steam (Fernando, 2008). The resultant syngas is comprised primarily of hydrogen, carbon monoxide and other light hydrocarbons that can be used directly for power generation or as a feedstock to produce chemicals, liquid fuels or other gaseous fuels (Higman & van der Burgt, 2003). Gasification differs from combustion in a number of fundamental aspects; most notably is the lack of useful heating value in the gaseous product from combustion. In addition, combustion occurs in an oxidizing environment which converts the potential energy within a feedstock into thermal energy. In contrast, gasification occurs in a reducing environment which converts the energy stored within a material into chemical energy (Basu, 2010).

As shown in Figure 2-1, gasification processes can be divided into three major unit operations: upstream processing, thermochemical gasification, and downstream processing (Kumar et al., 2009). Upstream processing includes acquisition and on-site storage of the fuel source and can also include particle size reduction and drying to ensure reliable, consistent feeding and optimal syngas composition. For dry feed entrained flow gasifiers, coal is pulverized in a ring-roller mill to reduce the particle size to an acceptable level. In contrast, rod mills are generally used for size reduction upstream of coal-water slurry gasifiers (Higman & van der Burgt, 2003). Drying is usually required to ensure consistent coal moisture content for dry feed gasifiers. Similar to the systems used in conventional pulverized coal boilers, the dryer is integrated in a recycle loop with the mill and heated with a gas burner.

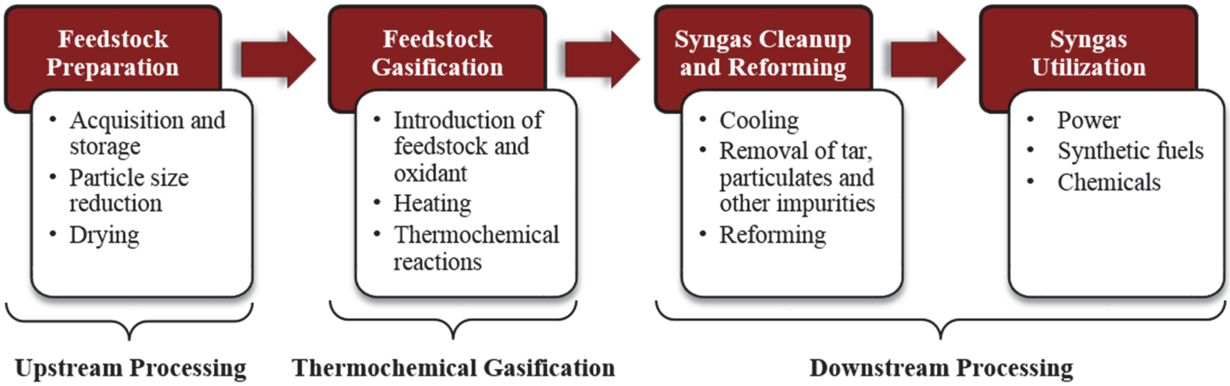


Figure 2-1. Gasification unit operations and processes (modified from Kumar et al., 2009)

Size reduction of agricultural and wood biomass is often accomplished with tub grinders, hammer mills and knife mills (Kumar et al., 2009). Due to the high moisture content inherent to many types of biomass, a drying process is often required. This process is energy intensive so waste heat must be recovered and utilized to maintain the plant efficiency at an acceptable level. Commercially available biomass dryers include perforated floor bin dryers, band conveyor dryers, rotary cascade dryers, fluidized bed steam dryers and pneumatic conveying steam dryers (Cummer & Brown, 2002).

Downstream processing operations include syngas cleanup, reforming and utilization (Kumar et al., 2009). Depending on the intended end product, these operations require a number of different complex processes and pieces of equipment. To illustrate the complexity of downstream gasification operations, a process flow sheet of a typical coal and biomass co-gasification polygeneration system is presented in Figure 2-2. In this example, the products are diesel, naptha, methanol and electric power.

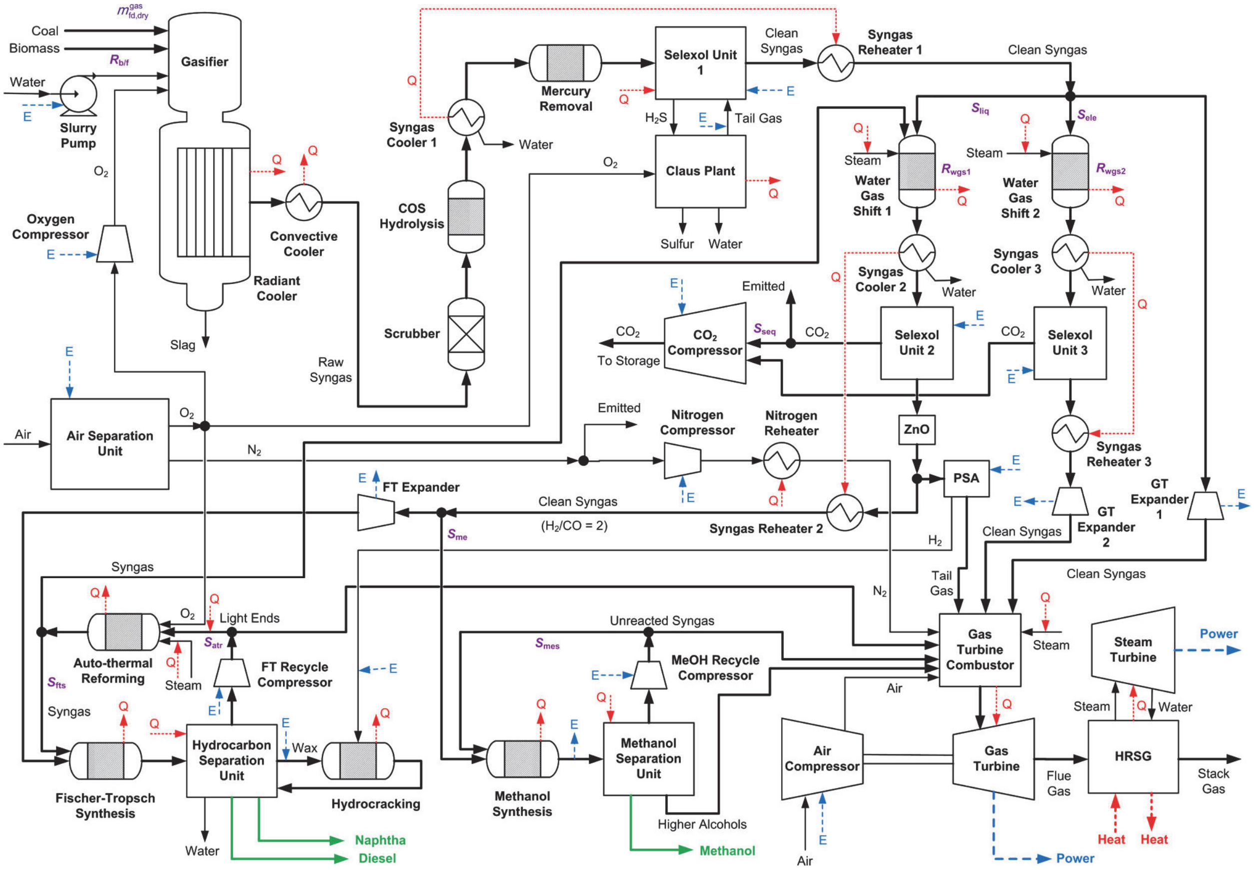


Figure 2-2. Process flow sheet of a coal and biomass co-gasification polygeneration system (reprinted with permission from Chen, Y. Adams, T., II, & Barton, P. (2011). Optimal design and operation of flexible energy polygeneration systems. Industrial & engineering chemistry research, 50(8), 4553-4566. Copyright 2011 American Chemical Society.)

Syngas cleanup operations generally involve raw gas cooling, particulate, tar and acid gas removal and sulfur recovery (Mondal et al., 2011). Syngas reforming operations include the water gas shift reaction and separation of the constituents (H_2, CO, CO_2) for purification or separate uses in a polygeneration plant. Detailed descriptions of syngas cleanup and reforming operations are available in a number of publications (Bell et al., 2011; Mondal et al., 2011; Speight, 2008; Higman & van der Burgt, 2003; Ozum et al., 1993; Bennett, 1981).

There are many useful applications for syngas derived from the gasification of carbonaceous fuels. As displayed in Figure 2-3, a wide range of products are directly obtainable by reforming hydrogen and carbon monoxide, the two main components of syngas. These products are generally classified as power, synthetic fuels and chemicals (Higman & van der Burgt, 2003). Power from syngas is obtained by direct firing in gas turbines to generate electric power. Synthetic fuels from syngas include Fischer-Tropsch fuels, synthetic natural gas (SNG), town gas and reduction gas. Chemicals directly obtainable from syngas include ammonia, methanol, hydrogen, carbon monoxide and oxo-alcohols. Many of these direct products are further processed and refined to produce more useful consumer products like polyurethanes and acetates (Higman & van der Burgt, 2003).

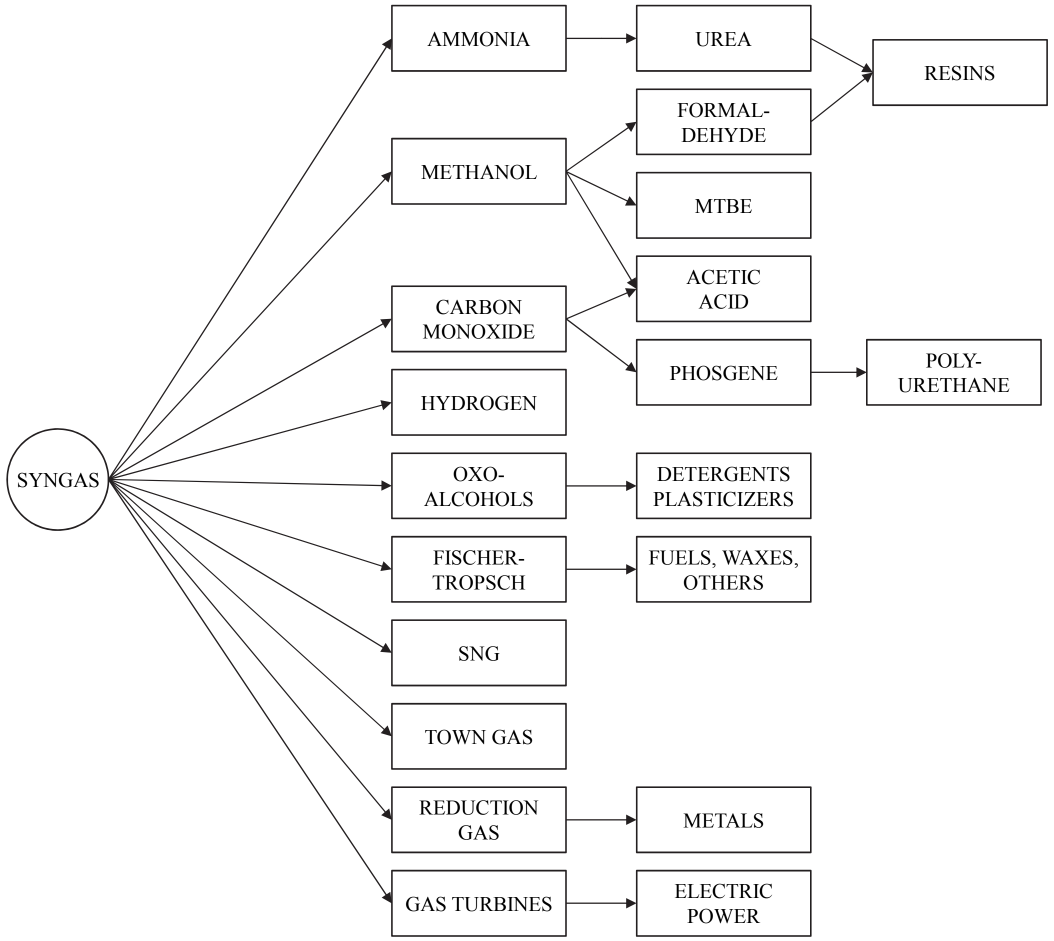


Figure 2-3. Products obtainable from syngas (modified from Higman & van der Burgt, 2003)

2.3.1 Types of Gasifiers

At the heart of the gasification process is the gasifier, which brings the fuel and oxidant into contact at elevated temperatures. Each reactor must be uniquely designed and operated to accommodate specific feedstock conditions and the desired composition of the resultant syngas. The primary design and operating parameters of the gasifier include the reactor type and geometry, temperature profile, feed rate of the fuel and oxidant, and the type and amount of catalysts added to the system (Kumar et al., 2009).

Many different reactor types have been developed for coal gasification, which generally follow one of three generic processes: moving bed (also known as fixed bed), fluidized bed and entrained flow (Fernando, 2009). The physical configuration of each type of reactor varies, which affects how the fuel and oxidant are brought into contact within the system. Each reactor type is also distinct with respect to feed condition sensitivity, operating conditions and the characteristics of the resultant syngas. For example, a major distinction between gasifiers is whether the ash is removed from the system in a dry form or as slag. Additionally, each process is designed for specific types of feedstocks which must be fed to the system in either slurry form, as a dry powder, as granules or in lump form. The operating temperature and pressure within the gasifier and the resultant syngas temperature can also vary for each type of process (Couch, 2008). A summary of these and other important characteristics of moving bed, fluidized bed and entrained flow reactors are summarized in Table 2-1.

Table 2-1. General characteristics of gasification reactors (modified from Ratafia-Brown et al., 2002 as cited in Fernando, 2009 and from Simbeck et al., 1993 as cited in Higman & van der Burgt, 2003)

Category	**Moving Bed**		**Fluidized Bed**		**Entrained Flow**
Ash condition	Dry	Slagging	Dry	Agglomerating	Slagging
Commercial versions	Lurgi	BGL	HTW, KRB	KRW, U-Gas	GE, E-Gas, Shell, Siemens, MHI, EAGLE, PRENFLO
Feed Characteristics					
Size limits	5-80 mm	5-80 mm	< 6 mm	< 6 mm	< 0.1 mm
Acceptability of caking coals	Possibly	Yes	Possibly	Yes	Yes
Ash content limits	No limits	< 25% preferred	No limits	No limits	< 25% preferred
Ash melting temperature	> 1200 °C	< 1300 °C	> 1100 °C	> 1100 °C	< 1300 °C
Preferred feedstock	Lignite, reactive bituminous, anthracite, biomass, wastes	Bituminous, anthracite, petcoke, biomass, wastes	Lignite, reactive bituminous, wastes	Lignite, bituminous, cokes, biomass, wastes	Lignite, sub-bituminous, bituminous, anthracite, petcoke
Operating Characteristics					
Syngas temperature	425-650 °C	425-650 °C	900-1050 °C	900-1050 °C	1200-1600 °C
Gasification pressure	3 MPa	> 3 MPa	0.1 MPa	0.1-3 MPa	2-8 MPa
Oxidant requirement	Low	Low	Moderate	Moderate	High
Steam requirement	High	Low	Moderate	Moderate	Low
Unit capacities	10-350 MWh	10-350 MWh	100-700 MWh	20-150 MWh	up to 700 MWh
Key technical issue	Use of fines and hydrocarbons		Carbon conversion		Raw gas cooling
Distinguishing characteristic	Hydrocarbons in raw gas		Large char recycle		High heat in raw gas

2.3.1.1 Moving Bed Gasifiers

As the first commercially available gasifiers, moving bed reactors played an important role in the early production of syngas from coal and coke (Higman & van der Burgt, 2003). In moving bed gasifiers, relatively large fuel particles are fed into the top of the vessel and the oxidant is introduced at the bottom, producing a countercurrent flow. As shown in Figure 2-4, the fuel particles move downward under gravity, forming a bed, and the ash is removed from the bottom of the reactor. As the oxidant enters the bottom of the vessel, it absorbs heat and reacts with the fuel as it moves upward through the bed of particles. Before exiting the gasifier, the hot syngas preheats and pyrolyses the downward flowing fuel, which results in high carbon conversion and hence high thermal efficiency (Fernando, 2008; Waitzman et al., 1975).

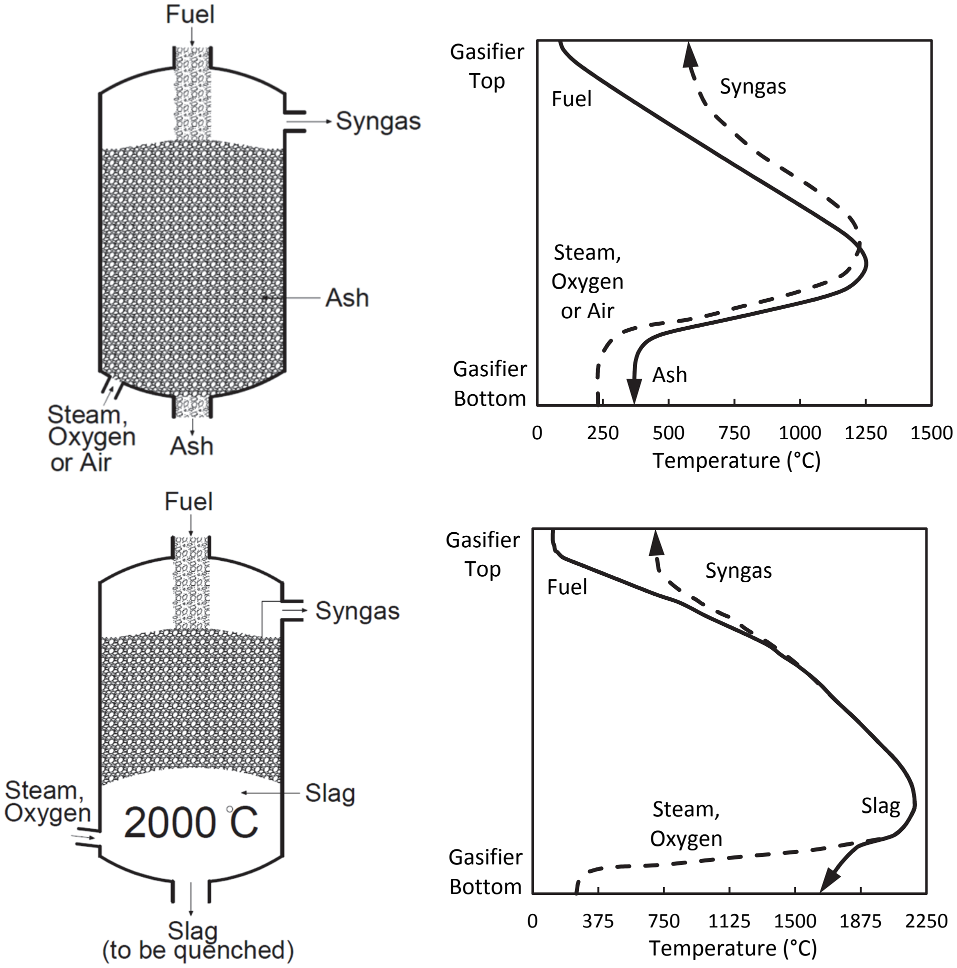


Figure 2-4. Dry ash and slagging moving bed gasifier schematics and temperature profiles (modified from Kristiansen, 1996 and Simbeck et al., 1993 as cited in Carpenter, 2008)

The gasification process can be divided into four distinct zones within the reactor: drying, pyrolysis, reduction, and oxidation (Brar et al., 2012; Mondal et al., 2011). The drying zone is located at the top of the reactor where the feed is introduced and the syngas is cooled before exiting the system. As the particles descend downward they are further heated and enter the pyrolysis zone. Next, the particles enter the reduction zone where they are gasified by reacting with steam and carbon dioxide. In the combustion zone, located toward the bottom of the reactor, the highest temperatures are reached as oxygen reacts with the residual char. Finally, ash is formed at the bottom of the vessel either in the form of dry ash or slag and is removed from the system (Carpenter, 2008). Excess steam is introduced to keep the temperature below the ash fusion temperature in the dry ash process, while much less steam is used and higher temperatures are achieved in the slagging process (Fernando, 2009; Brar et al., 2012).

Moving bed reactors are generally used to gasify solid fuels in the range of 5-80 mm, including coals, biomass and waste materials. Fuel particles less than 5 mm tend to pack into the reactor bed, thus reducing the total surface area of the fuel and decreasing the overall efficiency of the reactor. It is also possible for fine particles to follow the countercurrent gas flow and blow back into the feed mechanism or cake onto the syngas exit opening. This problem is intensified when dealing with caking or moist feedstocks (Fernando, 2009). The residence time of the fuel within the gasifier is dictated by the operating pressure and the type of oxidant used. For example, residence time in atmospheric steam/air gasifiers is typically several hours yet high pressure steam/oxygen gasifiers only require 15 to 60 minutes.

Moving bed gasifiers are most commonly used for the production of synthetic fuels and chemicals, although there are instances where they have been used for power generation in the integrated gasification combined cycle (IGCC) plant. There are two main commercial versions of the moving bed gasifier, the Lurgi dry ash gasifier and the British Gas/Lurgi (BGL) slagging gasifier. These systems differ in a number of fundamental aspects including ash conditions, feed sensitivity, maximum throughput and syngas composition (Fernando, 2008). For example, the Lurgi dry ash gasifier is characterized by low oxygen consumption and high steam demand, which is in direct contrast to the BGL slagging gasifier. Detailed descriptions of these systems, including process flowsheets, performance data and typical applications, are discussed by Bell et al. (2011), Basu (2010), Fernando (2008) and Higman & van der Burgt (2003).

2.3.1.2 Fluidized Bed Gasifiers

In fluidized bed gasifiers, fine fuel particles are gasified as a suspended bed that is created by an upward flow of fluidizing gases. As displayed in Figure 2-5, this is achieved by feeding the fuel into the side of the vessel and injecting the oxidant at the bottom with enough velocity to fully suspend the bed of particles as they move downward under gravity. This configuration creates intense back mixing, where feed particles are mixed with the particles already undergoing gasification. As a result, fluidized bed gasifiers offer a consistent temperature profile throughout the vessel, which promotes both heat and mass transfer (Higman & van der Burgt, 2003). Depending on the degree of fluidization and bed height, fluidized bed gasifiers are classified as circulating fluidized bed, bubbling fluidized bed and transport reactors. Another distinguishing feature of fluidized bed systems is the nature of the ash, which can be dry or agglomerated (Fernando, 2008).

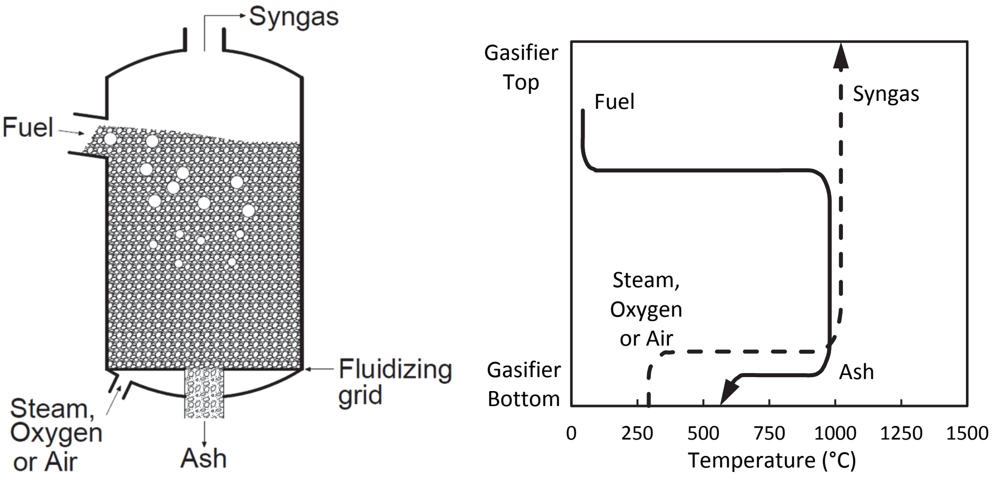


Figure 2-5. Fluidized bed gasifier schematic and temperature profile (modified from Kristiansen, 1996 and Simbeck et al., 1993 as cited in Carpenter, 2008)

Fuel residence time in fluidized bed gasifiers is typically on the order of 10-100 seconds, which enables much higher throughputs than achievable in moving bed reactors (Fernando, 2008). To reach maximum thermal efficiency, particle size of the feed must be constantly monitored and controlled. One common issue arises when superfine particles (<0.5 mm) become entrained in the rising syngas and flow out of the top of the vessel. To alleviate this problem, a cyclone is typically installed downstream to capture and return these particles to the bed. In contrast, particles that are too large (>6 mm) fail to fluidize and disrupt the bed formation (Minchener, 2005). These issues can limit the carbon conversion and thermal efficiency of the system (Fernando, 2008).

The temperature within fluidized bed reactors must be maintained below the ash fusion temperature as ash melting will cause clinker formation and destabilize the suspended bed (Gomz-Barea, 2010). This specification makes fluidized bed gasifiers best suited to handle relatively reactive fuels such as low grade coals and biomass (Fernando, 2008). Other technical challenges encompass the process of ash removal. In a fluidized bed, overly dense ash eventually moves to the bottom of the vessel where it drops through a grate. Ash that has a low fusion temperature, high free swelling index or a high alkali concentration will agglomerate at high temperatures. These agglomerations can destabilize the bed, stick to discharge openings, and hinder process efficiency in dry ash systems (Couch, 2008).

The most widely used commercial versions of the dry ash fluidized bed process include the High Temperature Winkler (HTW) bubbling fluidized bed gasifier and the Kellogg Brown and Root (KBR) transport gasifier. More recently, there has been commercial interest in the development of agglomerated ash fluidized bed reactors that can increase carbon conversion by preferentially separating low-carbon ash from the bed. Commercial reactors that use the agglomerated ash technique include the Kellogg Rust Westinghouse (KRW) fluidized bed gasifier and the U-Gas bubbling fluidized bed gasifier. Detailed descriptions of these systems, including process flowsheets, performance data and typical applications, are presented by Bell et al. (2011), Basu (2010), Fernando (2008) and Higman & van der Burgt (2003).

2.3.1.3 Entrained Flow Gasifiers

In entrained flow gasifiers, fuel particles and oxidant are introduced at the top of the vessel and flow downward together under gravity as depicted in Figure 2-6. This co-current flow regime results in the oxidant surrounding or entraining the fuel particles as they flow down through the reactor. Entrained flow gasifiers are operated at high temperatures (1250-1600 °C) and pressures (2-8 MPa) to melt the ash into inert slag (Higman & van der Burgt, 2003). The temperature must be kept relatively high to ensure that the ash behaves as a liquid throughout the vessel (Gomez-Barea, 2010). Ultrafine fuel particles (<0.1 mm) are fed to the vessel in dry form or as a slurry to promote mass transfer and entrainment within the gas. The fine feed and high operating temperature produce very high carbon conversion rates and thus residence time is low (a few seconds) (Fernando, 2008).

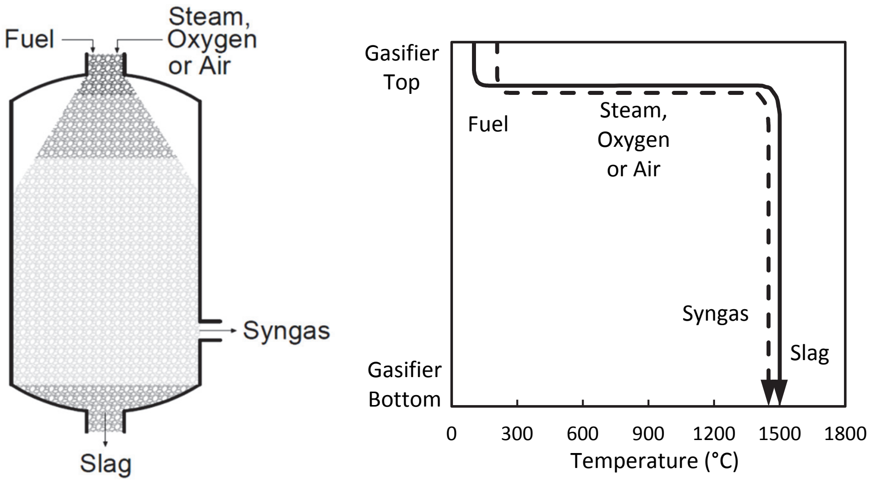


Figure 2-6. Entrained flow gasifier schematic and temperature profile (modified from Kristiansen, 1996 and Simbeck et al., 1993 as cited in Carpenter, 2008)

After the short residence time, both the syngas and the ash are removed from the bottom of the vessel. Typically, consistent ash content is desired, as the ash provides added insulation which prevents heat loss. Ash fusion temperature of the fuel must be low enough for slag formation to enable the inert material to flow down the reactor walls and exit the vessel under standard operating temperatures (Bell et al., 2011). If insufficient ash melting is experienced, fluxes such as limestone can be introduced with the feed to improve slag formation. Additionally, excessive impurities in the ash (e.g. sulfur, chlorine) may cause downstream blockage and added corrosion (Fernando, 2009). Although entrained flow gasifiers produce relatively clean syngas free of tar and phenols, there are large amounts of sensible heat in the raw gas that must be recovered downstream to maximize the thermal efficiency of the system (Basu, 2010).

Entrained flow gasifiers are often characterized as the most versatile type of reactor because they can efficiently gasify essentially all coal types (Fernando, 2008; Higman & van der Burgt, 2003). As a result of this and other advantages, entrained flow gasifiers are the most widely used industrial gasification technology throughout the world. The most popular commercial systems that employ dry feed entrained flow technology include the Shell Coal Gasification Process (SCGP), Siemens Fuel Gasification (SFG), Mitsubishi Heavy Industries (MHI), Energy Application for Gas, Liquid and Electricity (EAGLE), and Pressurized Entrained Flow (PRENFLO). In contrast, the most significant commercial slurry feed entrained flow gasifiers are the GE reactor and ConocoPhillips E-Gas reactor. Detailed descriptions of these systems, including process flowsheets, performance data and typical applications, are presented by Bell et al. (2011), Fernando (2008) and Higman & van der Burgt (2003).

2.3.2 Thermochemical Reactions

The thermochemistry of coal gasification has been widely studied and is well established. Although biomass gasification has not been studied as extensively, it is generally described by the same basic thermochemical reactions as coal gasification. However, the chemistry of coal and biomass co-gasification is not well understood. Several different thermochemical reactions take place within a gasifier during the conversion of coal or biomass to syngas. This section provides a general overview of gasification thermochemistry for carbonaceous materials but does not examine the thermodynamic or kinetic characteristics of gasification, which together dictate the rate and efficiency of the process and regulate the composition of the resultant syngas. However, detailed descriptions of gasification thermodynamics and kinetics are available in a number of publications (Bell et al., 2011; Basu, 2010; Higman & van der Burgt, 2003; Desrosiers, 1981; Graboski, 1981).

The first process that takes place when a carbonaceous material enters a gasifier is vaporization of surface and inherent moisture. This reaction can be formally written as:

$$H_2O_{(l)} \rightarrow H_2O_{(g)} \;\; \Delta H = +44\ MJ/kmol \qquad \text{(R. 2-1)}$$

where ΔH is the associated heat of reaction. A positive sign (+) indicates that heat is absorbed and a negative sign (−) indicates that heat is released. The water phase transition can have a significant effect on gasification thermodynamics due to the resulting steam mixing with the gases introduced to the system. This effect is particularly apparent with high-moisture feedstocks and in slurry-fed gasifiers (Bell et al., 2011).

As the carbonaceous material increases beyond the vaporization temperature in a restricted oxygen environment, it is pyrolyzed, or decomposed into char and hydrogen-rich volatile matter such as hydrocarbon gases, tars and phenols (Fernando, 2008). This reaction can be written as:

$$Feedstock_{(s)} \rightarrow Char_{(s)} + Volatiles_{(s,g)} \;\; \Delta H = positive, variable \qquad \text{(R. 2-2)}$$

The gasification of char begins with the following combustion reactions which occur as oxygen is fed to the gasifier (Higman & van der Burgt, 2003).

$$2C_{(s)} + O_{2_{(g)}} \rightarrow 2CO_{(g)} \;\; \Delta H = -222\ MJ/kmol \qquad \text{(R. 2-3)}$$

$$C_{(s)} + O_{2_{(g)}} \rightarrow CO_{2_{(g)}} \;\; \Delta H = -394\ MJ/kmol \qquad \text{(R. 2-4)}$$

Oxygen may also react with hydrogen to produce water vapor. This reaction can be formally written as:

$$2H_{2(g)} + O_{2(g)} \rightarrow 2H_2O_{(g)} \ \ \Delta H = -484\ MJ/kmol \qquad \text{(R. 2-5)}$$

Reactions 2-3, 2-4 and 2-5 provide the heat necessary for subsequent gasification reactions, which include the steam gasification reaction, the Boudouard reaction and the methanation reaction (Bell et al., 2011). The steam gasification reaction, also known as the water gas reaction, can be formally written as:

$$C_{(s)} + H_2O_{(g)} \rightarrow CO_{(g)} + H_{2(g)} \ \ \Delta H = +131\ MJ/kmol \qquad \text{(R. 2-6)}$$

The reaction of carbon and steam is endothermic and is generally characterized by high temperatures and low pressures (Fernando, 2008). The Boudouard reaction involves gasification with carbon dioxide and can be formally written as:

$$C_{(s)} + CO_{2(g)} \rightarrow 2CO_{(g)} \ \ \Delta H = +173\ MJ/kmol \qquad \text{(R. 2-7)}$$

The Boudouard reaction is also endothermic although it typically takes place slower than the steam gasification reaction. The methanation reaction involves gasification with hydrogen and can formally be written as:

$$C_{(s)} + 2H_{2(g)} \rightarrow CH_{4(g)} \ \ \Delta H = -75\ MJ/kmol \qquad \text{(R. 2-8)}$$

This reaction is very slow except at high pressures (Fernando, 2008). Reactions 2-6, 2-7 and 2-8 can be reduced to two homogeneous gas reactions which occur spontaneously as a result of high reaction temperature. The first reaction is the water gas shift reaction, which affects the H_2/CO ratio and can be formally written as:

$$CO_{(g)} + H_2O_{(g)} \rightarrow CO_{2(g)} + H_{2(g)} \ \ \Delta H = -41\ MJ/kmol \qquad \text{(R. 2-9)}$$

The second reaction is the steam methane reforming reaction which can be formally written as:

$$CH_{4(g)} + H_2O_{(g)} \rightarrow CO_{(g)} + 3H_{2(g)} \ \ \Delta H = +206\ MJ/kmol \qquad \text{(R. 2-10)}$$

Reactions 2-3 through 2-8 describe the possible pathways to gasification for all carbonaceous materials. However, most gasification processes depend on a balance between Reactions 2-3 (partial oxidation) and 2-6 (water gas reaction). The overall gasification reaction for fossil fuels, which also contain hydrogen, can be formally written as:

$$C_xH_{y(s)} + x/2\, O_{2(g)} = xCO_{(g)} + y/2\, H_{2(g)} \qquad \text{(R. 2-11)}$$

In this reaction, x and y are a function of the type of feedstock and specific material properties (Higman & van der Burgt, 2003). For coal, the ratio x/y is approximately equal to 1; therefore x and y are equal to one.

The gasification of biomass is similar to that of coal; however, coal is primarily composed of carbon, while biomass contains a mixture of more complex compounds including cellulose, hemicellulose and lignin (Brar et al., 2012). These large polymeric molecules are broken down into gases (H_2, CO, CH_4 and lighter hydrocarbons), char, ash, tar and minor contaminants in the presence of heat and oxidant during gasification (Kumar et al., 2009). Char and tar production are undesirable in the process and occur as a result of incomplete conversion of the biomass material. Kumar et al. present the overall gasification reaction for biomass as:

$$CH_xO_{y_{(s)}} + O_{2_{(g)}} + H_2O_{(g)} = CO_{(g)} + H_{2_{(g)}} + C_{(s)} + tar_{(s)} \qquad \text{(R. 2-12)}$$

where x and y are a function of the type of biomass and specific material properties.

2.4 Coal and Biomass Properties Relevant to Gasification

There are many different coal and biomass properties relevant to gasification processes. These properties can be divided into four categories: chemical composition, thermal properties, physical properties, and mechanical properties (Berkowitz, 1994; Speight, 2005). The chemical composition, thermal characteristics and physical properties are generally of greatest relevance to the thermochemical gasification process and downstream operations. In contrast, the mechanical properties discussed are of greater significance to upstream processing operations. Standard test methods have been developed to directly measure many of these coal and biomass properties; however, further research is needed to determine the suitability of applying other methods that are not specifically intended for coal and biomass (Basu, 2010; Higman & van der Burgt, 2003). Table 2-2 lists some of the published standard test methods that can be used to determine coal and biomass properties relevant to gasification.

Table 2-2. Standard test methods for determining coal and biomass properties relevant to gasification

Category	Coal	Biomass		
	ASTM	ASTM	CEN	ASABE
Proximate Analysis	D3172-07a	E870-82[4]	--	--
Moisture	D3173-11, D3302/D3302M-12	E871-82[5]	EN 14774[7]	ASAE S358.3[8]
Volatile Matter	D3175-11	E872-82[5]	EN 15148[7]	--
Ash	D3174-12	E1755-01, E1534-93[5]	EN 14775[7]	--
Fixed Carbon	D3172-07a	--	--	--
Ultimate Analysis	D3176-09	E870-82[4]	--	--
Carbon	D5373-08	E777-08[6]	EN 15104[7]	--
Hydrogen	D5373-08	E777-08[6]	EN 15104[7]	--
Sulfur	D3177-02	E775-87[6]	EN 15289[7]	--
Nitrogen	D5373-08	E778-08[6]	EN 15104[7]	--
Oxygen	D3176-09	--	--	--
Physical Properties				
Particle Size	D4749-87	--	EN 15149-2[7]	ASAE S424.1[8]
True Density	D167-93[1]	--	--	--
Apparent Density	D167-93[1]	--	EN 15150[7]	--
Bulk Density	D291-07, D7481-09[2]	E870-82[4]	EN 15103[7]	--
Porosity	D167-93[1]	--	--	--
Thermal Properties				
Calorific Value	D5865-12	E870-82[4]	EN 14918[7]	--
Specific Heat	D2766-95[3]	D2766-95[3]	--	--
Thermal Conductivity	C518-10[10]	C518-10[10]	--	--
Thermal Diffusivity	E1461-11[11]	E1461-11[11]	--	--
Thermoplasticity	D2639-08, D720-91, D5515-97	--	--	--
Ash Fusibility	D1857/D1857M-04	--	CEN/TS 15370-1[7]	--
Mechanical Properties				
Grindability	D409/409M-12	--	--	--
Flow Behavior	D6128-06[2], D6773-08[2], D6683[2]	D6128-06[2], D6773-08[2], D6683[2]	--	ASAE D274.1[9]

[1]lump coke [2]powder [3]liquid and solid [4]wood fuel [5]particulate wood fuel [6]refuse-derived fuel [7]solid biofuels [8]forage material [9]grain and seed [10]flat slab [11]isotropic solid material

Precise knowledge of feedstock properties is essential to the proper design and efficient operation of gasification systems, as evidenced by numerous journal publications on this topic (Tremel et al., 2012; Voitkevich et al., 2012; Montagnaro et al., 2011; Song et al., 2011; Song et al., 2010b; Collot, 2006; Geyer et al., 2000; Mills & Rhine, 1989a; Mills & Rhine, 1989b; van Heek & Muhlen, 1987; van Heek & Muhlen, 1985). The following sections describe the most important gasification-related properties of coal and biomass and highlight some published results on the gasification of different coal and biomass types.

2.4.1 Chemical Composition

2.4.1.1 Proximate Analysis

Proximate analysis of coal or biomass is an assay of the moisture, volatile matter, ash and fixed carbon content of the material determined by a series of standard tests (Basu, 2010; Speight, 2005). This series of tests provides an initial indication of fuel quality for the design of gasification systems and is relatively simple and inexpensive to perform. Methods for performing the proximate analysis of coal have been established by each of the major standards institutions (e.g. ASTM, ISO, CEN) with slight procedural differences, so it is important to specify the method used when reporting results (Petrakis & Grandy, 1980). Proximate analysis of coals is specified by ASTM D3172-07a (2007); however, there is not an ASTM standard for proximate analysis that encompasses all types of biomass, although ASTM E870-82 (2006) describes the procedure for particulate wood fuels.

Coal and biomass moisture content is an important gasification property because the evaporation of moisture consumes a significant amount of the deliverable energy from a gasification plant. Therefore, moisture content must be known to properly design the system for minimal energy loss (Basu, 2010). Moisture content also affects bulk handling and conveying operations upstream of the gasifier. For example, Liang et al. (2011) found that the mass flow rate of a pneumatic conveyor feeding a pressurized entrained flow gasifier decreased with an increase in lignite moisture content (3.24 to 8.18%). However, the mass flow rate was found to increase at first, then decrease with a rise in subbituminous coal moisture content (0.40 to 6.18%) under the same operating conditions (Liang et al., 2011).

Determination of coal and biomass moisture content is complicated by its presence in two separate forms: surface (free) moisture and inherent (equilibrium) moisture (Allardice & Evans, 1978). As the name implies, surface moisture is the moisture present on the surface of the coal or biomass particle, which is ordinarily deposited during processing, transportation and storage. In contrast, inherent moisture is the moisture absorbed within the coal matrix or biomass cell walls (Speight, 2005). Total moisture is defined as the sum of the surface and inherent moisture and can be expressed on a wet basis or a dry basis. The wet basis moisture content of coal and biomass is calculated as:

$$M_{wet} = 100\left(\left(m_{wet} - m_{dry}\right)/m_{wet}\right) \tag{Eq. 2-1}$$

where M_{wet} is the wet basis moisture content expressed as a percentage, m_{wet} is the wet weight and m_{dry} is the dry weight (Basu, 2010). The dry basis moisture content is calculated as:

$$M_{dry} = 100\left(\left(m_{wet} - m_{dry}\right)/m_{dry}\right) \qquad \text{(Eq. 2-2)}$$

where M_{dry} is the dry basis moisture content expressed as a percentage. Finally, the wet basis and dry basis moisture contents are related as:

$$M_{dry} = M_{wet}/(100 - M_{wet}) \qquad \text{(Eq. 2-3)}$$

ASTM D3173-11 (2011) and ASTM D3302/D3302M-12 (2012) specify standard procedures for determining and reporting coal moisture content. Similarly, ASTM E871-82 (2006) specifies a method for determining and reporting the moisture content of wood fuels, while ASAE S358.3 (2008) specifies a method for forage materials and EN 14774 (2009) specifies a method for solid biofuels. Typically, these methods involve drying materials in an oven at a temperature of 105 degrees Celsius until constant mass is achieved and moisture content is calculated from the loss in mass of the sample.

Volatile matter content is a measure of the condensable and noncondensable vapor (excluding water vapor) produced while heating coal or biomass under specified conditions (Speight, 2005). The determination of this value depends on a number of factors including the maximum temperature reached (typically 950 °C), the heating rate, the type of heating equipment, and the size, shape and composition of the crucible in which the material is heated (Basu, 2010). The applicable ASTM standards for determination of volatile matter are D3175-11 (2011) for coal and E872-82 (2006) for particulate wood fuels. Volatile matter content is important to consider when designing a gasification system because it will be released within in the gasifier and transported downstream with the syngas.

Ash content is a measure of the inorganic solid residue remaining after the combustion of coal or biomass under designated conditions. The applicable ASTM standards for determination of ash content are D3174-12 (2012) for coal, E1755-01 (2007) for biomass, and E1534-93 (2006) for particulate wood fuels. It is also important to determine the major and minor elements that comprise the ash, which can be determined for coal by ASTM D3682-01 (2006). The elemental composition of ash is complex and varies with the mineral composition of a material and the incineration conditions employed. Some typical ash constituents include silica, aluminum, iron, calcium, magnesium, titanium, sodium and potassium (Basu, 2010; Higman & van der Burgt, 2003). Ash composition has a major impact on the occurrence of fouling and slagging within a gasifier. For example, ash with high alkali-oxide content often creates fouling and slagging problems due to the reduction of ash melting temperature (Speight, 2005). Ash composition also affects gasification reactivity and the rate of carbon conversion. Specifically, calcium, magnesium, sodium and potassium have been found to catalytically enhance carbon conversion during gasification of various rank coals (Hattingh et al., 2011; Nattermann & Hutinger, 1994). Finally, ash composition influences the ash fusion temperature, which is an important thermal property discussed in *Section 2.4.3* (Song et al., 2010a).

Fixed carbon content is a measure of the material remaining after the determination of moisture, volatile matter and ash present in coal or biomass as outlined above (Speight, 2005). It is calculated by subtracting the mass percentage of each component from 100 and can be formally written as:

$$FC = 100 - (M + VM + ASH) \tag{Eq. 2-4}$$

where FC is the mass percentage of fixed carbon, M is the mass percentage of moisture, VM is the mass percentage of volatile matter and ASH is the mass percentage of ash in a given material (Basu, 2010). Fixed carbon content is an important parameter for gasification analysis because the conversion of fixed carbon to syngas is the last reaction to occur within the gasifier. As a result, it dictates the gasification rate and syngas yield and is used to determine the required size of the gasifier. The procedure to determine fixed carbon content of coal is specified by ASTM D3172-07a (2007), while fixed carbon content of biomass is simply determined by Equation 2-4.

2.4.1.2 Ultimate Analysis

Ultimate analysis of coal or biomass is an assay of the elemental composition, ash content and moisture content of the material as determined by a series of standard tests (Higman & van der Burgt, 2003). Elemental composition is the weight percentage of carbon, hydrogen, sulfur, nitrogen, and oxygen in the fuel. Moisture and ash contents are determined using the same methods specified for the proximate analysis to convert the elemental composition to a dry ash-free basis. In addition to the components covered by ultimate analysis, the determination of chlorine content is important for biomass materials because it can be present at rather high levels and can cause fouling and corrosion within the gasifier (Graboski & Bain, 1981). Standard methods to determine chlorine content of biomass is covered by EN 15289 (2011). Chlorine content in coal is typically less than one percent by weight, although some coals can contains as much as 2.5 percent. Coal chlorine content is determined by ASTM D4208-02 (2007).

Methods for performing the ultimate analysis of coal have been established by each of the major standards institutions (e.g. ASTM, ISO, CEN) with slight procedural differences, so it is important to specify the method used when reporting results (Petrakis & Grandy, 1980). Ultimate analysis of coals is specified by ASTM D3176-09 (2009); however, there is not an ASTM standard for ultimate analysis that encompasses all types of biomass, although ASTM E870-82 (2006) describes the procedure for particulate wood fuels. These tests provide more detailed and useful information than proximate analysis for the design of gasification systems (Speight, 2005). For example, elemental composition can be used to predict syngas composition and estimate the true density of coal and biomass. However, ultimate analysis is more difficult and expensive to perform than proximate analysis (Basu, 2010).

Carbon is the largest component of coal, accounting for 70 to 95 percent by weight on a dry ash-free basis, while hydrogen typically accounts for 2 to 6 percent (Speight, 2005). Most of the carbon and hydrogen in coal is contained in complex organic compounds, although some carbon is trapped in mineral carbonates and hydrogen is also present in surface and inherent moisture. The determination of carbon and hydrogen in coal is specified by ASTM D5373-08 (2008). Biomass materials typically have a lower carbon content and similar hydrogen content compared to coal on a dry ash-free basis (Graboski & Bain, 1981). Carbon and hydrogen content determination is specified by EN 15104 (2011) for biomass and by ASTM E777-08 (2008) for refuse-derived fuels.

Sulfur content is an important consideration in coal and biomass gasification because of the production of sulfur oxides during the combustion phase. The release of these compounds to the environment is problematic because of their contribution to acid rain, and therefore sulfur oxide emissions are strictly regulated (Speight, 2008). Additionally, sulfur oxides can cause equipment corrosion and unwanted slagging within the gasifier that can lead to downtime and production losses (Speight, 2005). As a result, there are a number of publications detailing efforts to improve the precision and accuracy of sulfur determination (Gorbaty et al., 1992; Ahmed & Whalley, 1978).

The sulfur content of coal is typically 0.5 to 6.0 percent by weight, depending on rank and formation (Higman & van der Burgt, 2003). Sulfur can be present in three different forms within coal: pyritic sulfur, organically bound sulfur, and inorganic sulfates (Speight, 2005). In coals with high sulfur content, the majority of the sulfur is present in the form of pyrite. The determination of sulfur in coal is specified by ASTM D3177-02 (2007). The sulfur content of biomass is generally much lower than coal, with typical values less than one percent by weight (Basu, 2010). As a result, biomass energy conversion does not significantly contribute to the emission of sulfur oxides, which is one of the major motivations for biomass co-firing. Sulfur content determination is specified by EN 15289 (2011) for biomass and by ASTM E775-87 (2008) for refuse-derived fuels.

Nitrogen content is another important consideration in coal and biomass gasification because it directly influences ammonia production and due to environmental concerns over nitrogen oxides emissions that result from syngas combustion. Coal generally contains 0.5 to 2.5 percent nitrogen by weight, of which a portion is converted to ammonia (NH_3) and the remainder is converted to elemental nitrogen (N_2) (Higman & van der Burgt, 2003). The determination of nitrogen in coal is specified by ASTM D5373-08 (2008). The nitrogen content of most biomass fuels varies from 0.2 to 1.0 percent by weight (Jenkins et al., 1998). Zhou et al. (2000) reported that more than ninety percent of the fuel-bound nitrogen in agricultural and woody biomass is converted to ammonia and elemental nitrogen. Nitrogen content determination is specified by EN 15104 (2011) for biomass and by ASTM E778-08 (2008) for refuse-derived fuels.

No reasonable test methods exist to measure the oxygen content of a fuel. As a result, it is calculated by subtracting the mass percentage of each of the other calculated components from 100 and can be formally written as:

$$O = 100 - (C + H + N + S + M + ASH) \qquad \text{(Eq. 2-5)}$$

where O is the mass percentage of oxygen, C is the mass percentage of carbon, H is the mass percentage of hydrogen, N is the mass percentage of nitrogen, M is the mass percentage of moisture and ASH is the mass percentage of ash in a given material (Basu, 2010). The procedure to determine oxygen content of coal is specified by ASTM D3176-09 (2009), while oxygen content of biomass is simply determined using Equation 2-5.

2.4.2 Physical Properties

2.4.2.1 Particle Size

Certain physical properties of coal and biomass influence the design and performance of the gasification process. Often, the first physical property that must be considered is the size of individual particles in the gasifier feed. Standard methods for measuring particle size by sieve analysis are available for both coal (ASTM D4749-87, 2002) and biomass (EN 15149-2, 2010; ANSI/ASAE S424.1, 1992). Particle size is important because it directly relates to the surface area of the fuel particles and therefore has a large impact on the rate at which chemical reactions take place within the gasifier (Collot, 2002).

The selection of the proper type of gasifier is largely influenced by particle size because each type of gasifier is uniquely suited for a particular particle size range. For example, commercial moving bed reactors are generally used to gasify fuel particles in the range of 5-80 mm, fluidized bed reactors are generally used to gasify particles less than 6 mm and entrained flow reactors are generally used to gasify particles less than 0.1 mm (Fernando, 2008; Collot, 2006; Higman & van der Burgt, 2003, Simbeck et al., 1993). Once the proper gasifier has been identified for a particular feed particle size, further research is often conducted to determine the effects of particle size on the performance of a particular system. Most of the research to date on coal and biomass co-gasification has been focused on optimizing gasifier operating conditions and determining the influence of different ratios of coal and biomass. However, there has been considerable research on the effect of particle size for independent coal gasification and biomass gasification.

Kim et al. (2011) studied the effects of coal type and particle size on the performance of char-CO_2 gasification in a laboratory-scale moving bed reactor. The tests were conducted over a range of operating temperatures (1050-1400 °C) with four mean coal particle sizes (0.045, 0.09, 0.18, and 0.274 mm). The results showed that the effect of particle size on the reactivity of the char was larger at the highest operating temperatures and that char reactivity decreased as the particle size increased. Additionally, the authors found that the shrinking core model (SCM) was more accurate for modeling the kinetic behavior of larger particles while the volume reaction model (VRM) was better suited for smaller particle sizes (Kim et al., 2011).

Hanson et al. (2002) investigated the relation between initial coal particle size and char particle size evolution during pyrolysis and steam gasification in an air-blown system. The study focused on coal particle sizes in the range of 0.5-2.8 mm and determined that the larger size fractions of coal were more likely to fragment during gasification while the smaller size fractions had a greater tendency to produce char particles larger than the initial coal particles. Testing the reactivity of the produced char indicated that particle size does not play a large role in the pyrolysis and gasification performance within the range of particles sizes investigated (Hanson et al., 2002).

Gaston et al. (2011) investigated the effects of white oak sawdust particle size on the yield of light gas and tar compounds in a laboratory-scale fluidized bed gasifier. The sawdust was milled into four size classes with mean diameters of 6, 13, 18 and 25 mm for the study. The authors found that light gas yield increased and char content decreased as the mean particle size of the sawdust increased. Additionally, mass spectrometry measurements indicated that tar and polycyclic aromatic hydrocarbon formation increased with particle size. The results of this study highlight the potential restrictions on heat and mass transport for the gasification of sawdust with larger particle sizes (Gaston et al., 2011).

Luo et al. (2009) examined the effects of particle size and bed temperature on the gasification performance of a laboratory-scale moving bed reactor using ultrafine pine sawdust. The sawdust was separated into five size classes (<0.075, 0.075-0.15, 0.15-0.3, 0.3-0.6, and 0.6-1.2 mm), individually gasified and the composition of the produced syngas was determined. The study found that the dry gas formation, hydrogen yield and carbon conversion efficiency increased with a corresponding decrease in particle size, while tar and char content decreased. However, at the highest temperatures the change in gasification performance due to varying particle size was not significant. The hydrogen and carbon monoxide content of the syngas reached maximum values of 51.2% and 22.4% respectively at 900 degrees Celsius with the smallest size fraction and the values decreased with each incremental increase in particle size (Luo et al., 2009).

Yin et al. (2003) studied the effect of particle size on the gasification performance of a pilot-scale moving bed reactor using peach tree prunings as the feedstock. The prunings were separated into five size classes (<10, 10-20, 20-40, 40-60 and 60-80 mm) and the resulting gas and hydrocarbon compositions were analyzed by gas chromatography and gas chromatography-mass spectrometry. The results indicated that gas yield and lower heating value increase with a corresponding increase in particle size while tar and dust content decrease. The hydrogen and carbon dioxide content of the syngas reached maximum values of 16.1% and 14.4% respectively with the smallest size fraction and the values decreased with each incremental increase in particle size (Yin et al., 2003).

2.4.2.2 Density and Specific Gravity

Coal and biomass densities are important to consider when examining energy content on a volumetric basis. This property is particularly important when sizing a gasifier and feed conveyor to meet desired production. Density must also be considered for operations upstream of the gasifier such as fuel transportation, bulk handling and storage (Graboski & Bain, 1981). Coal and biomass density can be reported in three principal ways: true density, apparent density and bulk density. These density values differ due to the method in which the volume of the material is calculated and reported. In addition, density can be reported relative to the density of water as specific gravity (SG), which is calculated as:

$$SG = \rho/\rho_{water} \tag{Eq. 2-6}$$

where ρ is the density of the material and ρ_{water} is the density of water.

The true density of coal and biomass is a measure of the mass per unit volume occupied by the solid constituent of an individual particle (Basu, 2010). To calculate true density, the total mass is divided by the actual volume of the solid content. This can be formally written as:

$$\rho_{true} = n_{total}/v_{true} \tag{Eq. 2-7}$$

where m_{total} is the total mass and v_{true} is the true solid volume. For porous solids such as coal and biomass, the precise determination of true density is often challenging because it is difficult to measure the true solid volume without including pore volume. To determine true solid volume of a material, the entire pore structure must be filled with a fluid that has no interaction with the solid component. For coal, true density is commonly determined by helium displacement because helium can penetrate the pores within the coal structure without any chemical interaction (Speight, 2005). This density measurement, often referred to as helium density, is performed by placing a weighed sample of coal into a gas pycnometer of known volume, introducing a known quantity of helium and measuring the pressure of the helium at a given temperature, which gives the volume of the solid component of the coal. However, there is evidence that a portion of the coal pore structure may be inaccessible to the helium (Berkowitz, 1994). Another possible way to calculate the true density of coal is to use the standard test method for true specific gravity of lump coke (ASTM D167-93, 2004). This method specifies the use of a Hogarth's specific gravity bottle to calculate the true density of coke particles less than 0.075 mm.

True density can also be estimated for a given material by determining the ultimate analysis and multiplying the weight percent of each constitutive element by the element's true density (Basu, 2010). The true density of coal can be estimated from its elemental composition by the following equation:

$$\rho_{He} = 1.534 - 0.05196H + 0.007375O - 0.02472N + 0.003853S \tag{Eq. 2-8}$$

where ρ_{He} is the helium density and H, O, N and S are the calculated weight percent of hydrogen, oxygen, nitrogen and sulfur on a dry mineral-matter-free basis (Speight, 2005). Due to significant variations in the elemental composition of different biomass types, a generic correlation between true density and elemental composition has not been established for biomass. However, the values provided in Table 2-3 can be used to approximate the true density of biomass given the elemental composition of a particular material.

Table 2-3. True density of selected elements (modified from Weast, 1960 as cited in Jenkins, 1989)

Element	**C**	**Ca**	**Fe**	**K**	**Mg**	**Na**	**P**	**S**	**Si**	**Zn**
True Density (g/cm^3)	1.80-2.10	1.54	7.86	0.86	1.74	0.97	1.82-2.70	2.07	2.32	7.14

Apparent density, or particle density, of porous solids is a measure of the mass per unit volume occupied by the solid, including pores and cracks (Mahajan & Walker, 1978). To calculate apparent density, the total mass is divided by the external volume of the solid (Basu, 2010). This can be formally written as:

$$\rho_{apparent} = m_{total}/v_{external} \qquad \text{(Eq. 2-9)}$$

where m_{total} is the total mass and $v_{external}$ is the external solid volume. For regularly shaped particles, stereometric methods can be used to approximate external solid volume. Stereometric methods are based on the measurement of particle dimensions (e.g. length, width, height, diameter) by means of a mechanical instrument (e.g. micrometer, caliper, ruler). The volume of the solid is then estimated by calculating the volume of the closest geometric shape using the recorded dimensions (Rabier et al., 2006). Due to the irregular shape of coal and biomass particles, this method is rarely used. Apparent density of coal and biomass is more commonly determined by calculating external particle volume using one of three methods: mercury displacement (Gan et al., 1972); salinization (Ettinger & Zhupakhina, 1960) or gas flow (Ergun, 1951). Apparent density is used more often than true density in engineering design because it provides the actual volume occupied by a particle in a system and its measurement is relatively straight forward.

Bulk density of coal and biomass is a measure of the mass per unit volume occupied by a group of particles, including interstitial volume between the particles (Berkowitz, 1994). Many factors influence bulk density, including apparent density, particle size and shape, surface and inherent moisture, and degree of compaction (Speight, 2005). To calculate bulk density (ρ_{bulk}), the total mass of particles is divided by the volume of the container in which they are placed (Basu, 2010). This can be formally written as:

$$\rho_{bulk} = m_{total}/v_{container} \quad \text{(Eq. 2-10)}$$

where m_{total} is the total mass and $v_{container}$ is the total volume of the container. The precise measurement of this property is important because it is often used to design bulk handling, transportation and storage systems upstream of the gasifier. As a result, standard methods have been developed for bulk density determination of both coal (ASTM D291-07, 2012) and biomass (ASTM E870-82, 2006). There is also a method to determine the loose and tapped bulk densities of powders that can potentially be applied to particulate coal and biomass particles (ASTM D7481-09, 2009).

2.4.2.3 Porosity

Porosity is the fraction of a volume of coal or biomass that is occupied by pore space. Similarly to particle size, the surface area of fuel particles is a function of porosity and therefore this property has a large impact on the rate at which chemical reactions take place within the gasifier (Speight, 2005). There are two types of porosity to define: particle porosity and bulk (or bed) porosity (Basu, 2010). Particle porosity is calculated by dividing the volume of pore space within an individual particle by the total solid volume. Particle porosity is mathematically related to true and apparent density by:

$$\varepsilon_{particle} = 100 - 100\left(\rho_{apparent}/\rho_{true}\right) \quad \text{(Eq. 2-11)}$$

where $\varepsilon_{particle}$ is the particle porosity expressed as a percentage. The standard method for determining true specific gravity of lump coke (ASTM D167-93, 2004) also outlines the procedure for determining particle porosity using Equation 2-6. Bulk porosity is calculated by dividing the volume of interstitial space within a bed of particles by the bulk volume of the bed. Bulk porosity is mathematically related to bulk and apparent density by:

$$\varepsilon_{bulk} = 100 - 100\left(\rho_{bulk}/\rho_{apparent}\right) \quad \text{(Eq. 2-12)}$$

where ε_{bulk} is the bulk porosity expressed as a percentage.

2.4.3 Thermal Properties

2.4.3.1 Calorific Value

The calorific value of a fuel is the heat produced when a unit quantity undergoes complete combustion in the presence of oxygen under a specified set of conditions (Speight, 2005). The value is calculated in units of calories per gram and can be easily converted to other units appropriate for specific applications (i.e. 1.0 cal/g = 4.187 kJ/kg = 1.8 Btu/lb). Calorific value can be reported as either the gross calorific value (GCV) or the net calorific value (NCV), which differ with respect to the latent heat of vaporization of water (Basu, 2010). Gross calorific value is particularly important for gasification systems in the North America because thermal efficiency is reported with respect to the gross calorific value of the fuel. However, many European countries define the efficiency of thermal systems in terms of the net calorific value (Basu, 2010).

Gross calorific value, also known as higher heating value (HHV), accounts for the latent heat of vaporization of steam in the combustion product as determined by returning all of the combustion products to the pre-combustion temperature (typically 25 °C). The gross calorific value is determined using either an isoperibol or adiabatic bomb calorimeter as specified by ASTM D5865-12 (2012) for coal and by ASTM E870-82 (2006) for wood fuels. If these experimental methods cannot be performed, gross calorific value can be estimated from empirical correlations. For example, the Dulong equation relates the elemental composition of coal to gross calorific value by:

$$GCV = 338.6C + 1444(H - O/80) + 94.28S \tag{Eq. 2-13}$$

where *GCV* is expressed in kJ/kg, and *C*, *H*, *O* and *S* are the mass percentage (dry ash-free basis) of the elements determined by ultimate analysis (Perry & Chilton, 1973). Similarly, Channiwala and Parikh (2002) developed an empirical correlation that relates elemental composition and ash content to gross calorific value, which can be used to approximate both coal and biomass calorific values. This correlation is presented as:

$$GCV = 349.1C + 1178.3H + 100.5S - 15.1N - 103.4O - 21.1ASH \tag{Eq. 2-14}$$

where *GCV* is expressed in kJ/kg, *C*, *H*, *S*, *N*, *O* and *ASH* are the mass percentage (dry basis) of the constituents determined by ultimate and proximate analyses (Channiwala & Parikh, 2002).

Net calorific value, also known as lower heating value (LHV), is the difference between the gross heat released and the latent heat of vaporization of steam produced during combustion (Speight, 2005). The latent heat of vaporization of steam is usually not recovered because the combustion products are rarely cooled to the pre-combustion temperature (Basu, 2010). Thus, net calorific value is a measure of the effective heat stored in a fuel that can actually be converted to energy, which is less than the chemical energy stored in the fuel. Basu (2010) relates net calorific value to gross calorific value by:

$$NCV = HHV - h_g(9H/100 + M/100) \qquad \text{(Eq. 2-15)}$$

where h_g is the latent heat of vaporization of steam in kJ/kg and H and M are the mass percentage of hydrogen and moisture, respectively, in the sample.

2.4.3.2 Specific Heat

Specific heat is the ratio of the heat capacity of a substance to the heat capacity of water at 15 degrees Celsius, and thus it is a dimensionless quantity. Heat capacity is the heat required to produce a given temperature change within a unit quantity of a substance, with units of Btu per pound per degree Fahrenheit (Btu/lb-°F) or joules per kilogram per Kelvin (J/kg-K) (Speight, 2005). Knowledge of this thermal property is essential for the effective design and operation of both coal and biomass gasification systems (Collazo et al., 2012). However, methods for the measurement of specific heat of coal and biomass are not standardized so it can be challenging to obtain accurate and precise values.

Specific heat and heat capacity are numerically equal because the heat capacity of water is 1.0 Btu/lb-°F (4187 J/kg-K). As a result, these two terms are often used interchangeably. The specific heat of coal and biomass can be measured by ASTM D2766-95 (2009), which specifies the standard test method for specific heat measurement of liquids and solids. Specific heat of coal is generally between 0.25-0.37 and typically increases with moisture and volatile content yet decreases with carbon content (Baughman, 1978). Specific heat can also be estimated as the sum of the specific heats of the major elements in coal by:

$$C_p = 0.189C + 0.847H + 0.215S + 0.491N + 0.360O \qquad \text{(Eq. 2-16)}$$

where C_p is the specific heat and C, H, S, N and O are the mass percentage (dry ash-free basis) of the elements determined by ultimate analysis (Speight, 2005). Jenkins (1989) correlates the specific heat of dry wood species and temperature over the range of 0 to 106 degrees Celsius. This equation is formally presented as:

$$C_p = 0.266 + 0.00116T \qquad \text{(Eq. 2-17)}$$

where C_p is the specific heat and T is the temperature in degrees Celsius.

2.4.3.3 Thermal Conductivity

The thermal conductivity of a material is the time rate of heat transfer by conduction across a unit area of unit thickness for a unit temperature gradient, as calculated by:

$$Q = (kA\Delta t)/d \qquad \text{(Eq. 2-18)}$$

where Q is the heat transfer rate, k is the thermal conductivity, A is the area, and Δt is the temperature gradient for the distance d (Carslaw & Jaeger, 1959). The rate of heat transfer through a material is typically expressed in units of Btu/hr-ft-°F or W/m-K (Speight, 2005). Heat transfer rate, and thus thermal conductivity, is very important to the rate and efficiency of syngas production in modern gasification systems. Thermal conductivity of a material can be measured by ASTM C518-10 (2010), which specifies the standard method for determination of steady-state thermal transmission properties by means of the heat flow meter apparatus.

Although thermal conductivity is a well-understood concept, the determination of a single value for anisotropic materials such as coal and biomass is very difficult, if not impossible to obtain. The difficulty arises due to banding and bedding planes in coals and the fibrous nature of biomass, which significantly affect the conduction of heat through the materials (Speight, 2005; Jenkins, 1989). For example, the longitudinal thermal conductivity of wood is roughly 2.25-2.75 times the conductivity across the grain, with the conductivity in the tangential direction slightly less than that in the radial direction (Jenkins, 1989). The thermal conductivity of different wood types ranges from 0.039-0.172 W/m-K depending on the species and composition, while the thermal conductivity of U.S. coal ranges from 0.22-0.55 W/m-K depending on rank and composition (Herrin & Deming, 1996). The thermal conductivity of coal typically increases with apparent density, volatile matter, ash content and temperature and is lower perpendicular to the bedding than parallel to the bedding (Cercone et al., 1996; Speight, 1994).

2.4.3.4 Thermal Diffusivity

The thermal diffusivity is the rate at which temperature change can occur through a material. It is related to steady-state thermal conductivity by:

$$\alpha = k/(\rho C_p) \qquad \text{(Eq. 2-19)}$$

where α is the thermal diffusivity, k is the thermal conductivity, C_p is the specific heat and ρ is the density of the material (Speight, 2005). From Equation 2-19 it is apparent that thermal diffusivity increases with thermal conductivity and decreases with specific heat. As with thermal conductivity, thermal diffusivity of coal is typically higher parallel to the bedding than perpendicular to the bedding. Jenkins (1989) reports that the average value of thermal diffusivity of wood is $1.74 \cdot 10^{-7}$ m^2/s, but cautions that the value depends on the direction tested relative to the grain. The thermal diffusivity of coal and biomass can be measured by ASTM E1461-11 (2011), which specifies the standard test method for thermal diffusivity by the flash method. However, this test is recommended for primarily homogeneous isotropic materials, which indicates that it could be difficult to obtain accurate and precise measurements.

2.4.3.5 Thermoplasticity

The term thermoplasticity is used to describe the caking, agglomerating and swelling behavior of coals under the influence of heat, which is of great importance to the gasification process (Speight, 2005). These thermoplastic properties influence particle size in fluidized bed and entrained flow gasifiers, which in turn affects heat and mass transfer and the overall carbon conversion within the reactor. In moving bed gasifiers, thermoplastic behavior can cause undesired agglomeration of coal particles that can lead to adherence to surfaces and plugging of the reactor (van Heek & Muhlen, 1987). For example, to efficiently gasify caking coals in moving bed reactors, a stirrer must be installed at the top to prevent agglomeration of coal particles once the temperature exceeds the softening point. However, the stirrer is only effective for mildly caking coals, whereas heavily caking coals require prior oxidative treatment for use in moving bed systems (Higman & van der Burgt, 2003).

In addition to chemical changes that all coals undergo in the presence of heat, caking coals soften, melt, fuse, swell and resolidify within a specific temperature range, known as the plastic range (Berkowitz, 1994). It is in this temperature range that agglomeration occurs. The caking behavior of coal is directly related to chemical composition, including volatile matter, mineral matter, carbon, hydrogen and oxygen content. Specifically, caking tendency increases with volatile matter content up to 35 percent and decreases beyond that range. Similarly, caking behavior increases with carbon content up to around 89 percent and decreases beyond that point. As a result, anthracite and semianthracite coals generally do not exhibit any caking behavior. The caking tendency of coal also has been shown to increase with hydrogen content and decrease with mineral matter and oxygen content (Speight, 2005).

The thermoplastic properties of coal can be measured with a constant-torque Gieseler plastometer, as specified by ASTM D2639-08 (2008). The coal properties normally determined by this test are the initial softening temperature, maximum fluid temperature, solidification temperature and maximum fluidity (Speight, 2005). Another useful indication of the thermoplastic properties of coal is the agglomerating index, which is a qualitative designation of the appearance of coal residue produced from the determination of volatile matter content by ASTM D3175-11 (2011).

The swelling behavior of coal when heated under specified conditions can be used as a rather definitive measurement of thermoplastic properties. The empirical method for determining swelling behavior, referred to as the free-swelling index, is specified by ASTM D720-91 (2010). This procedure requires heating approximately one gram of coal in a crucible to 820 degrees Celsius to produce a coke button, which is then compared to a series of standard coke button profiles with corresponding free-swelling indices (Berkowitz, 1994). The swelling properties of bituminous coal can also be determined by ASTM D5515-97 (2010) using a dilatometer. However, this test method is limited in applicability to coals with a free-swelling index greater than or equal to one.

2.4.3.6 Ash Fusibility

Ash fusibility refers to the softening and melting behavior of the noncombustible mineral residue that is produced during the combustion of coal and biomass (Berkowitz, 1994). This is one of the most important variables to consider for gasification processes because each reactor is specifically designed for particular ash removal conditions. For example, dry ash moving bed gasifiers and fluidized bed gasifiers require feedstocks with high ash softening and melting temperatures to ensure that the ash does not form a slag and plug the reactor. In contrast, a low ash softening and melting point is preferred for slagging moving bed gasifiers and entrained flow gasifiers to ensure maximum process efficiency (Higman & van der Burgt, 2003).

The determination of ash fusibility of coals is specified by ASTM D1857/D1857M-04 (2010). By this method, several temperature points are measured by observing the behavior of triangular ash cones formed in a standard mold and subjected to heat in a controlled atmosphere. The temperatures that are determined include the initial deformation temperature (T_i), softening temperature (T_s), hemispherical temperature (T_h) and fluid temperature (T_f). The softening temperature is often used to distinguish between slagging coals (T_s < 1200 °C) and nonslagging coals (T_s > 1425 °C). Coals with ash softening temperatures between these limits are generally suitable for use in both slagging and nonslagging gasifiers (Berkowitz, 1994). For gasification applications, it is important that these properties are determined under reducing conditions due to considerable differences typically experienced under oxidizing conditions (Higman & van der Burgt, 2003). The determination of biomass ash melting behavior is specified by CEN/TS 15370-1 (2006). Additionally, ash fusibility determination has been reported for woody and agricultural biomass materials by the ASTM method specified for coal (Jenkins, 1989).

An additional property that is important for slagging gasifiers is the slag viscosity-temperature relationship, which affects the flow and removal of slag from the gasifier (Higman & van der Burgt, 2003). This relationship must be determined empirically for each coal type and gasifier type to optimize the gasifier operating conditions. As a result, there have been numerous publications detailing the viscosity and flow properties of coal ash slags (e.g. Montagnaro et al., 2011; Song et al., 2011; Song et al., 2010b; Hurst et al., 1999; Seggiani, 1998; Nowok, 1994). It is generally accepted that slag viscosity less than 25 Pa·s is required for continuous reliable removal from gasifiers, although this value can vary depending on system specific variables such as geometry. The relationship between slag viscosity and temperature varies for different slags. For example, some slags are characterized by exponential slag-temperature relationships while others behave more linearly (Higman & van der Burgt, 2003).

2.4.4 Mechanical Properties

2.4.4.1 Grindability

Grindability is a measure of the energy required to reduce the particle size and increase the surface area of a particular substance. The most commonly used method to measure the grindability of coals is ASTM D409/D409M-12 (2012), which specifies the use of the Hardgrove machine to calculate the Hardgrove Grindability Index (HGI). This test method covers the determination of the relative grindability or ease of pulverization of coals relative to coals chosen as standards. The theoretical basis for the method is the proposition that the work required to pulverize a material is proportional to the new surface area produced (Berkowitz, 1994). In this test, a representative 50 g sample of 16-30 mesh coal is ground by 8 steel balls in the Hardgrove machine for 60 revolutions. The material is then removed from the machine and the mass of minus

200 mesh material is used to determine the Hardgrove Grindability Index from a calibration chart, which must be created by grinding standard reference samples of coal for 40, 60, 80 and 110 rotations (Speight, 2005; Berkowitz, 1994).

The grindability of coal is dependent on a number of factors including rank, friability and thermoplasticity (Speight, 2005). A general relationship between coal rank and grindability is presented in Speight (2005) and Berkowitz (1994) where anthracites and lignites have the lowest Hardgrove Grindability Index and bituminous coals exhibit the highest value. However, grindability varies from seam to seam and within seams, so each coal must be tested independently to ensure accurate values. A strong correlation exists between coal friability and grindability to the extent that highly friable coal generally is found to have a high Hardgrove Grindability Index. The relation between grindability and thermoplasticity is due to plastic deformation from the heat produced by grinding, which leads to agglomeration of small particles and effectively reduces the fraction of minus 200 mesh material (Berkowitz, 1994).

Grindability is particularly important for feed preparation prior to gasification in entrained flow reactors, which require a feed size less than 0.1 mm for faster and more complete carbon conversion (Higman & van der Burgt, 2003). Unfortunately, grinding is energy intensive and can reduce the overall efficiency of a gasification plant if the process is not optimized or if significant changes in feed composition are experienced (Sami et al., 2001). Another difficulty concerning co-gasification of coal and biomass is the lack of knowledge on the grinding characteristics of coal-biomass blends and the underlying mechanisms that affect size reduction. Doroodchi et al. (2013) investigated the milling characteristics of blends of bituminous coal and hardwood chips and determined that the output particle-size distribution is the arithmetic average of the input particle-size distributions for blends containing up to fifty percent (by mass) woodchips. This information could be used to predict the grindability of coal-biomass blends prior to co-gasification.

2.4.4.2 Flow Behavior

The flow behavior of coal and biomass (also referred to as flowability or handleability) is important to consider for handling, storage and processing operations upstream of the gasifier to ensure consistent feed availability. For example, several industrial co-firing operations have experienced flow issues with equipment such as hoppers, silos and gravity stockpile reclaim when attempting to incorporate biomass with coal feed (Hunt et al., 1997; Boylan, 1996). Common flow problems include arching, ratholing, erratic flow, limited live storage capacity, flooding and segregation. These issues can lead to decreased production, increased maintenance costs and even equipment failure (Khambekar et al., 2010).

Arching is the formation of a cavity in the shape of an arch over a discharge outlet that prevents material flow and forms due to cohesion or mechanical interlocking of particles. In contrast, ratholing is the formation of a vertical cavity surrounded by stagnant material that forms down through an outlet and also prevents material flow. When a combination of arching and ratholing occurs and obstructs flow the condition is known as erratic flow (Prescott & Barnum, 2000). Limited live storage capacity is the reduction in storage capacity in a stockpile, silo or hopper as a result of the buildup of stagnant material. Flooding can arise when fine material becomes aerated and pours out of a discharge chute uncontrollably, similar to fluid flow. Finally, segregation can occur in mixtures of particles with a wide size distribution or variations in density. The primary mechanism of segregation is particle sifting, which produces localized regions of particles with similar physical properties (Schulze, 2008).

Flow behavior is a multidimensional characteristic that is influenced by both material parameters and processing equipment. The fundamental theory on flow behavior of particulate solids was originally developed by Jenike (1964) and has since been applied to nearly every industry that involves powder or bulk solids handling, including powder coating, food, cement, coal, ore, clay, and biomass (Schulze, 2008). For reliable handling and storage of coal and biomass particles, the geometry and materials of construction of equipment must be designed to suit the flow behavior of the particular material, which is influenced by common properties such as particle-size distribution, particle shape, chemical composition, moisture, and temperature. Thus, critical flow properties must be determined to design a reliable and effective handling system (Khambekar et al., 2010).

Flow of bulk solids is defined as plastic deformation due to an applied load. The magnitude of the load necessary to induce flow, measured by a uniaxial compression test, can give a preliminary indication of the flow behavior of a material (Schulze, 2008). For the uniaxial compression test, a hollow cylinder is filled with material and a consolidating load (σ_1) is applied, then the consolidated material is removed from the cylinder and an increasing vertical compressive load is applied until the material yields. The compressive stress that causes the material to yield is known as the unconfined yield strength (σ_c). This procedure is repeated for different consolidating loads to generate pairs of values (σ_1, σ_c). The values are then plotted to determine the flow function (ff_c) of the material, where:

$$ff_c = \sigma_1/\sigma_c \quad \text{(Eq. 2-20)}$$

Classification of flow function values with lines of constant flow behavior are displayed in Figure 2-7, where larger flow function values correspond to better flow behavior. An example of the flow function of a material (A) is also plotted in Figure 2-7, which shows that flow behavior is clearly dependent on consolidation stress. The flow function can be analyzed to determine the minimum outlet diameter for bins and hoppers to prevent arching and ratholing (Prescott & Barnum, 2000). Unfortunately, the uniaxial compression test is problematic for extremely fine-grained bulk solids because unconfined yield strength values are lower than expected and preparation of the hollow cylinder to obtain frictionless walls is difficult and time consuming (Schwedes & Schulze, 1990).

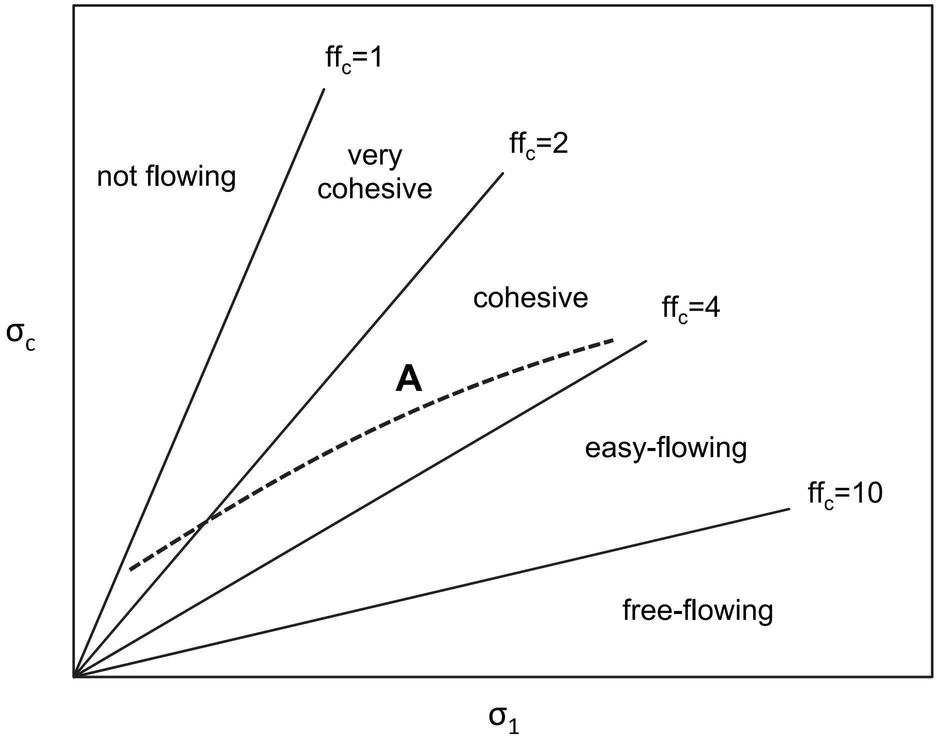


Figure 2-7. Flow function classification and lines of constant flow behavior (modified from Schulze, 2008)

The most commonly used method to accurately determine the flow behavior of fine-grained materials in advanced bulk solids technology is shear testing, which is specified by ASTM

D6128-06 (2006) using the Jenike shear cell and ASTM D6773-08 (2008) by the Schulze ring shear tester. These tests calculate the shear force required for a material to yield as a function of consolidating pressure to develop the flow function for a material (Schulze, 2008). The information obtained from shear testing can be analyzed to determine material properties indicative of flow behavior, such as cohesive strength and internal angle of friction (Prescott & Barnum, 2000). Shear testing can also be used to determine the friction between particles and the walls of a bin or hopper, referred to as the wall friction angle or the coefficient of sliding friction. This property is determined by sliding a material sample across a stationary wall surface in a shear tester. Wall friction angles can be used to determine required hopper angles to ensure reliable and consistent flow (Khambekar et al., 2010).

Another material property that is commonly determined to analyze the flow behavior of bulk solids is the variation of bulk density as a function of consolidating pressure. The apparatus and procedure for determining the range of bulk density values is specified by ASTM D6683-08 (2008). The range of values is often expressed as a straight line on a log-log plot of consolidating pressure versus bulk density where the slope of the line is the compressibility of the material. The results obtained from this test can be used to properly design processing, storage and transfer equipment to accommodate desired capacities (Khambekar et al., 2010).

Flow behavior is also influenced by the permeability of bulk solids during discharge from bins and hoppers, which is measured as a function of bulk density. The permeability of a material controls the maximum achievable discharge rate and thus must be considered when designing the size of bin outlets and transfer chutes to sustain desired flow rates. Permeability values are typically determined by measuring the rate of air flow at a constant pressure drop through numerous samples of varying bulk density. The range of values is often expressed as a straight line on a log-log plot. This relationship can then be used to calculate the required orifice size to achieve desired discharge rates (Prescott & Barnum, 2000).

Although shear testing to assess flow behavior is well-established and fundamentally sound, there are a number of drawbacks to its application to real-time analysis of coal and biomass at industrial facilities. The drawbacks include the complexity of shear testing equipment and procedures, the time and cost associated with analyses and the need for an experienced operator to interpret the results (Brown et al., 1997). In addition, shear testing can only be performed on samples less than 1.0 mm, so preparation of the material (e.g. screening, crushing) is typically required to enable testing. Hence, shear testing has not been widely adopted in the coal industry (Brown & Miles, 2004). As a result, a number of simpler techniques and devices have been developed specifically for the rapid assessment of coal and biomass flow behavior. The techniques and devices developed for coal assessment include the Durham Cone, the Nottingham Handleability Monitor, the Edinburgh Cohesion Tester and the avalanching technique. The only method that was identified for the assessment of biomass flow behavior is ASAE D274.1 (1992), which gives equations and graphs to estimate the flow rate of specific grains and oilseeds through horizontal and vertical orifices.

The Durham Cone was originally developed in the United Kingdom by the National Coal Board to assess the ease of discharge of fine coal blends (up to 50 mm) from 32 ton HAA rail wagons (Hall and Cutress, 1960). Mikka and Smitham (1985) evaluated the influence of moisture, fines and clay content on the results obtained from the Durham Cone. Their results showed that moisture content largely influenced coal handleability when a significant portion of fines were present but the effect was not apparent at a very low fines content. In addition, they showed that the coal size distribution influenced the extent to which handleability was affected by moisture and fines content. Finally, by comparing the results obtained from Durham Cone to those from the Jenike shear cell for two different coals, the authors concluded that the Durham Cone gave a better prediction of coal handleability (Mikka & Smitham, 1985). The advantages of the Durham Cone for coal handleability assessment are that it is relatively quick to perform (approximately 15 min), it can handle coal up to 50 mm in size and it does not require a skilled operator to interpret results. However, the main disadvantage of this method is that the results have been shown to exhibit poor repeatability and reproducibility (Brown & Miles, 2004).

The Nottingham Handleability Monitor was developed at the University of Nottingham for reliable on-line measurement of coal handleability using an extrusion trough (Brown et al., 1997). The device was designed to measure the maximum hydraulic pressure required to move coal through a circular tube with a venturi arrangement. The pressure reading is considered to be a measure of coal handleability and is known as the Extrusion Trough Handleability Index (Brown & Miles, 2004). The repeatability and reproducibility of the Nottingham Handleability Monitor was found to be a significant improvement over the Durham Cone in a comparative study (Brown & Atkin, 2000). Another advantage of this technique is the ability to handle large coal particles (up to 50 mm) and perform tests quickly and continuously.

The Edinburgh Cohesion Tester was developed at Edinburgh University to enable real time measurements of coal cohesion to prevent flow problems commonly encountered in coal bunkers at power stations (U.K. Department of Trade and Industry, 2002). This device was designed to measure the unconfined yield strength (cohesive strength) of coal particles after the application of a known consolidating pressure, similar to the uniaxial compression test. The Edinburgh Cohesion Tester incorporates several critical features that address the major drawbacks of uniaxial compression testing. For example, a three piece mold is used to minimize disturbance when removing the sample from the mold. This mold is supported by a soft elastic base which minimizes wall friction effects during vertical consolidation. Brown and Miles (2004) concluded that the Edinburgh Cohesion Tester is useful for predicting the occurrence of coal flow problems in bunkers and repeatable results can be obtained with very little operator training and experience.

Brown and Miles (2004) also present a novel technique for assessing the handleability of coals, known as the avalanching technique. This method was developed based on the work presented by Rastogi and Klinzing (1994), which recognized that the avalanching of powders could be a useful method to characterize and monitor flow behavior. To assess coal handleability, the avalanching behavior is monitored as the mass flow rate of material using an apparatus comprised of a variable speed feed conveyor, an avalanche ramp and an electronic balance connected to a computer to continuously retrieve data. Further testing and development of this technique will be undertaken to investigate the potential for use as an on-stream assessment of handleability at industrial facilities (Brown & Miles, 2004).

2.5 Agglomeration of Coal-Biomass Mixtures

Many of the challenges associated with co-gasification of coal and biomass can be mitigated by agglomeration of coal-biomass mixtures. Size enlargement by agglomeration is defined as any process in which small particles are combined to form larger particles (Capes, 1980). Agglomeration processes are used across many different industries in a wide variety of applications to improve the bulk properties of particulate solids. The objectives and benefits of agglomeration for the co-utilization of coal and biomass include increased bulk density, improved storage and handling properties, improved flow properties, improved homogeneity of blends, reduced dust losses and improved particle bed heat transfer (Browning, 1967). Pietsch (2002) and Capes (1980) have written extensive reviews on all aspects of agglomeration processes, to which the interested reader is directed for additional details. The following section is intended to simply provide an overview of significant aspects of agglomeration theory, tumble/growth agglomeration processes and pressure agglomeration processes.

2.5.1 Agglomeration Theory

2.5.1.1 Particle Binding Mechanisms

Size enlargement by agglomeration is differentiated from other grain growth technologies by the types of mechanisms that bind small particles together to form larger particles. The binding mechanisms in agglomeration process are generally classified into five major groups by the nature of particle-particle interactions: (1) solid bridges, (2) adhesion and cohesion forces, (3) surface tension and capillary pressure, (4) attraction forces between solids and (5) interlocking bonds (Rumpf, 1962). These groups of forces can be further divided into several subgroups, and in practice, a combination of forces act simultaneously within agglomerates to bond individual particles to one another. Figure 2-8 depicts the particle binding mechanisms in agglomeration processes.

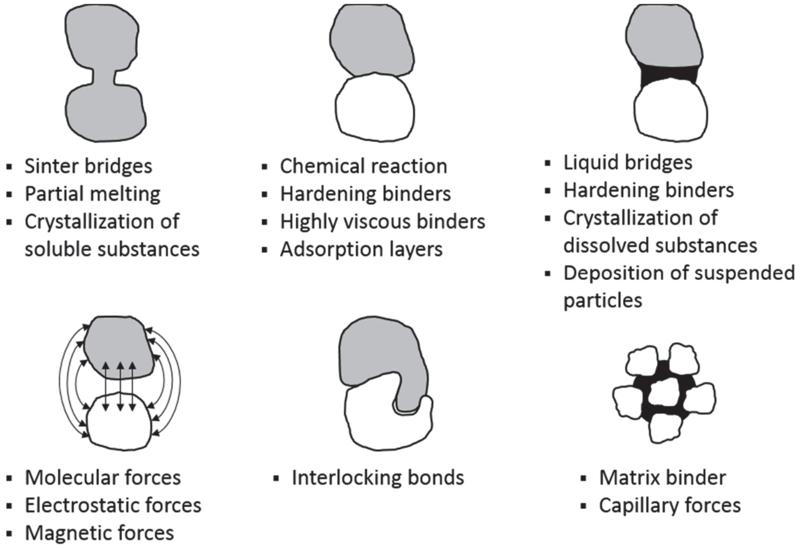


Figure 2-8. Particle binding mechanisms in agglomeration processes (modified from Pietsch, 2002)

Solid bridges can form between particles by the diffusion of atoms or molecules at points of contact as a result of elevated temperatures and pressures that occur in some agglomeration processes. The rate of diffusion of these bridges, known as sinter bridges, increase with a corresponding increase in pressure, temperature and contact area. Another type of solid bridge mechanism is partial melting, in which edges of particles melt from friction or pressure and quickly resolidify. Solid bridges may also form as a result of chemical reactions, hardening of binders and recrystallization of dissolved substances (Pietsch, 2002). Kaliyan and Morey (2008) determined that solid bridges are formed in corn stover and switchgrass briquettes and pellets from hardening of natural binders. This occurs when water soluble carbohydrates, lignin, protein starch and fat are activated in the presence of water under high pressures and temperatures. The solid bridges are formed when pressure is removed and the binder materials cool.

Adhesion and cohesion forces act to bind individual particles when a highly viscous binder (e.g. bitumen, pitch or molasses) is utilized. In this process, adhesion forces are present at the interfaces between the solid particles and binding material, while the cohesion forces act within the binder to strengthen the agglomerate. Another example of adhesion and cohesion forces are immobile adsorption layers (< 3 nm) that form around particles from the attraction of free atoms or molecules within a system. These layers strengthen the bond between particles by enabling molecular attractive forces due to the decreased distance between particles. In addition, adsorption layers can improve agglomerate strength through the deformation of solid particles at contact points, wherein surface roughness is decreased and the contact area between particles is increased (Pietsch, 2002).

Surface tension and capillary forces often improve interparticle bonding in wet agglomeration processes. For example, liquid bridges can form between particles as a result of free moisture within the system or from capillary condensation. Liquid bridge formation is often a precursor to the formation of solid bridges, thus this interaction plays an important role in the development of agglomerate strength. Another significant interparticle bonding mechanism is the negative capillary pressure that forms as a result of total saturation of the agglomerate pore structure. In general, both of these mechanisms act in wet agglomeration process to bond individual particle to one another (Pietsch, 2002).

Several different types of attraction forces between solid particles can occur within the structure of an agglomerate. The strength of these mechanisms, which include molecular, electric and magnetic forces, are highly dependent on the distance between particles. Molecular forces consist of van der Waals forces, free chemical bonds (valence forces) and hydrogen bonds. Van der Waals forces, which occur naturally at the surface of all solid particles due to electric polarization induced by the presence of other particles, generally provide the greatest attractive energy of the molecular forces. Van der Waals forces exert a magnitude on the order of 0.1 eV, have a maximum range of 100 nm and decrease significantly with the distance between particles. When the surfaces of two particles contact one another, electrostatic attractive forces form electric double layers due to the difference in electron work functions, which in turn induce permanent bonding. Magnetic forces can also contribute to agglomerate strength if ferromagnetic particles are present in a particulate system (Pietsch, 2002).

Interlocking bonds can form between elongated, fibrous materials (e.g. fibers, threads, lamellae) when particles bend, twist or weave together during agglomeration processes. These bonds can also be formed when a plastic material wraps around the exterior of a more rigid material due to the application of high pressure. This phenomena generally produces a very durable bond similar to that of a matrix binder (Pietsch, 2002). Due to the fibrous nature of many biomass materials, interlocking bonds are thought to contribute to the strength of biomass agglomerates. For example, Pickard et al. (1961) concluded that interlocking bonds may contribute to the formation of durable hay briquettes due to the interlacing of stem and leaf materials.

2.5.1.2 Binders, Lubricants and Other Additives

Particle size enlargement operations often require the addition of binders, lubricants or other additives to improve the quality of agglomerates when sufficient bonding cannot be achieved through natural binding mechanisms (Capes, 1980). The use of additives is also required in applications where a specific product characteristic must be obtained (e.g. water resistance) and with agglomeration of relatively large particles. Binders are components added to a particulate system prior to or during agglomeration processes to improve the strength of interparticle bonds, and thus improve the overall strength of agglomerates. Similarly, lubricants are components added prior to or during agglomeration to increase the density of agglomerates, which is achieved by a reduction in porosity as a result of a decrease in the coefficient of friction between particles. Many other types of additives can be combined with particulate solids prior to or during agglomeration to produce a desired functional property that is otherwise unattainable (Pietsch, 2002).

The selection of a binder for a specific agglomeration process depends on a number of considerations, most notably the desired agglomerate strength, cost and availability of additives and compatibility with the intended end use of the agglomerate. As a result, the development of binder formulations is usually very specific to a particular industrial application. However, all binders can be classified according to chemical type and function regardless of the intended application (Capes, 1980). The functions of binders are generally classified as matrix, film or chemical type according to the bonding mechanism utilized. For example, matrix type binders embed solid particles in a continuous matrix whereas film type binders are usually solutions or dispersions such as starch gels. In contrast, chemical type binders produce a chemical reaction between the binder and the solid particles or between binder components (e.g. Portland cement). Binders can be further classified as organic or inorganic based on their chemical composition. Examples of inorganic binders employed in agglomeration processes include lime, sodium silicates, bentonite, gypsum, salts, cement and magnesia. In contrast, examples of organic binders used in agglomeration processes include alcohols, asphalt, coal tar, dextrin, gelatin, lignosulfonates, molasses, petroleum residues, starches and sucrose (Pietsch, 2002; Messman, 1977). In compaction processes, binders often serve a dual purpose by improving agglomerate strength and also providing adequate lubrication to achieve a desired level of compaction.

The selection of a lubricant for agglomeration processes is dependent upon the same considerations as binder selection: desired strength, cost, availability and compatibility. Lubricants can be classified by the physical state and intended function of the additive. For example, liquid lubricants that have been used in agglomeration processes include water, glycerin, oils, silicones and ethylene glycol. In contrast, solid lubricants include paraffin, graphite, stearic acid and other waxes (Pietsch, 2002). The function employed by lubricants can be characterized as internal or external types. Internal lubricants are added to solid particles to increase the density of agglomerates by reducing the coefficient of friction between particles and to assist in removal of the agglomerate from a confined space, as is common in compaction processes. Conversely, external lubricants are additives applied directly to a mold or die in compaction processes to prevent friction and wear of surfaces (Capes, 1980).

2.5.1.3 Agglomerate Quality

The most important and widely used indicator of agglomerate quality is the strength of bonds between particles (Pietsch, 2002). The only scientifically defined method to characterize the strength of agglomerates that provides information on the fundamental nature of interparticle bonds is tensile strength measurement. Tensile strength is defined as the tensile force at failure divided by the cross-sectional area of the agglomerate. In cases where the agglomerate does not have a uniform shape, the area of the failure plane that results from this test can be used in place of cross-sectional area. Universal equations and theoretical models for approximation of the tensile strength of agglomerates is discussed in detail by Pietsch (2002).

In practice, the tensile strength of agglomerates can be accurately and reproducibly measured with a variety of specially designed and general purpose devices. Typically these devices are comprised of three main components for (1) gripping the sample, (2) applying a deforming load and (3) measuring the applied deforming load (Capes, 1980). Tensile strength measurement devices can include other features to measure deformation and peak load during testing, which can provide additional information about the strength and durability of particle bonds within an agglomerate. However, there is no standard device or procedure for measuring the tensile strength of agglomerates due to the many different shapes and sizes of agglomerated products. In any case, the major issue surrounding tensile strength measurement is the difficulty involved in mounting and gripping individual agglomerates without impacting the strength or integrity of the sample.

Many different devices and procedures have been used over the past fifty years to measure agglomerate tensile strength. For example, Rumpf (1962) reported a method for determining the tensile strength of spherical pellets that requires several different sample preparation steps prior to evaluation. In this procedure, two parallel plane surfaces are first cut on opposite ends of each pellet. Next, the surfaces are coated with a lacquer and an adhesive to facilitate attachment of metal adaptors to each end of the pellet. The pellet is then turned down to a cylindrical shape (0.18-mm diameter) in a lathe and the finished sample is mounted to a tensile strength measurement device through the metal adaptors. Unfortunately, this procedure is labor intensive and requires great care when cutting and machining the pellets to ensure that the strength is not impacted by the preparation process. Also, since the outer portion of the pellets is removed prior to tensile strength measurement, this method would not provide an accurate result for agglomerates with an unequal strength distribution (Capes, 1980).

A number of indirect tensile strength measurement techniques have been developed to address the difficulties of traditional methods. For example, Berenbaum and Brodie (1959) investigated three alternative methods for measuring tensile strengths of brittle materials, including a bending test, an indentation test and a test in which disks are compressed diametrically. It was determined that the results from the indentation test and the diametrical compression test are in reasonable agreement with traditional tensile strength results. The diametrical compression test was used to evaluate the tensile strength of agglomerates by Fell and Newton (1968) in a study on the strength of lactose tablets.

Although tensile strength measurement is the only scientifically defined and fundamentally understood method to measure agglomerate strength, these methods are rarely used in practical and industrial applications due to the complexity of the procedures and the required interpretation of results. As a result, a wide variety of industry-specific methods have been developed to simulate the forces that agglomerates are subjected to during handling, transportation and storage. Unfortunately, the results obtained from these types of tests are empirical and not theoretically predictable because the fundamental failure mechanisms are not understood. Nonetheless, these types of strength and durability measurements are important to consider because of their simplicity and industrial acceptance.

A comprehensive review of reported strength and durability evaluation methods for all types of agglomerates is beyond the scope of this discussion. Therefore, this review is limited to method used to evaluate coal and biomass solid fuels. Over the past several decades, researchers involved in the development of fuel briquette formulations and processes have reached a consensus regarding the most important physical properties that should be measured to indicate the quality of briquettes. The identified physical properties are impact-shatter resistance, compressive strength, and attrition resistance (Taulbee et al., 2010; Honaker et al., 2005; Richards, 1990; Eckerd, 1967; Moore, 1957; Prostel, 1953; Boley & Rice, 1949). The measurement of these three parameters can be used to indicate the extent to which briquettes will remain intact during handling, transportation and storage.

Briquettes continually experience impact-shatter forces, compressive forces and attrition forces from formation to utilization. Impact-shatter is defined as breaking violently into pieces from a sudden impact. Impact-shatter forces are encountered when briquettes drop in stockpiling, at conveyor transfer points and from bins and chutes. Compression is defined as the act, process or result of pressing or squeezing together. Briquettes experience compressive forces in bins, stockpiles and railcars from the load applied by other briquettes. Attrition is defined as wearing or grinding down by friction. Briquettes are subjected to attrition forces during transportation and at loading and unloading points.

Although researchers generally agree on the most important physical properties concerning briquette durability, specific test methods to quantify these parameters are highly variable.

Generally, researchers independently develop assessment procedures appropriate to the nature of the particular investigations performed at their laboratories. For example, many researchers have designed assessment procedures for attrition and impact-shatter resistance to mirror existing ASTM procedures for coal and coke, yet there is still very little consistency between the procedures employed at separate laboratories.

The only documented procedures that have been used to quantify the durability of coal-biomass briquettes are those that have been in use at the University of Kentucky's Center for Applied Energy Research (CAER) over the last decade. Taulbee et al. (2010) and Patil et al. (2009) describe methods to quantify the 'compressive' strength and attrition index of briquettes prepared from blends of biomass and fine coal. Patil et al. (2009) and Honaker et al. (2005) describe a drop test method that is used to determine the impact-shatter resistance of briquettes made from blends of coal fines and sawdust. This method consists of averaging the number of drops to failure for four briquettes dropped from a height of 18 inches onto a steel plate. However, this method was eventually abandoned due to an inherently high level of data scatter and the time consuming nature of these evaluations. In addition, this method requires the technician to visibly determine when the briquette has split into two or more significant pieces, which is a subjective decision that could vary from one person to another.

The importance of impact-shatter evaluation has also been realized by the coal industry. ASTM D440-07 (2012) describes a drop shatter test for coal that was established to indicate the extent to which lump coal will break in conventional transit and handling operations. This standard specifies dropping fifty kilograms of coal from a box equipped with a false bottom that is positioned six feet above a steel plate. The coal is dropped from the box by releasing the false bottom, recovered from the steel plate and dropped a second time to further break the coal. The broken coal is then hand screened through nested sieves (8, 6, 4, 3, 2, 1½, 1, ¾, ½, ¼, and ⅛ inch apertures). The results reported are the mass percentage in each class to the nearest 0.1% and the percentage size stability of each class to the nearest 0.5%.

Taulbee et al. (2010) and Patil et al. (2009) describe a method to measure briquette 'compressive' strength using either a Mark-10 EG-200 force gauge (200 lb_f capacity) or a Lloyd Instruments LRX Plus load cell (1,000 lb_f capacity). Each gauge is mounted to an automated test stand and equipped with a ¾-inch diameter plunger which travels downward at a rate of one inch per minute. This ability to control the rate of loading is very important to ensure the accuracy and reproducibility of test results (Capes, 1980). The force gauges are configured with a break detect feature which stops the movement of the plunger once the applied force drops to 95 percent of the maximum force attained during the test. The plunger then reverses direction and the maximum force attained during the test is designated as the compressive strength of the briquette. Measurements are recorded along the axis used to apply force during briquette formation and reported values represent the average of a minimum of 15 measurements. Values less than 50 lb$_f$ are classified as poor, between 50 and 100 lb$_f$ as marginal, between 100 and 150 lb$_f$ as good, and greater than 150 lb$_f$ as excellent. Although the measurement recorded following this procedure provides important information regarding the strength of briquettes, the use of the term ‘compressive’ strength is not scientifically valid (Pietsch, 2002).

Taulbee et al. (2010) and Patil et al. (2009) also describe a method to measure attrition indices for briquettes that have cured for seven days in a controlled-environment chamber. Approximately 200-gram samples (20 to 25 briquettes) are placed into a 12-inch diameter Plexiglas cylinder equipped with three, 2-inch lifters; tumbled for five minutes at 40 rotations per minute; and screened through a 4.75-millimeter (U.S. Standard 4 mesh) sieve in a Ro-Tap sieve shaker for two minutes. The attrition index is reported as the fraction of the starting briquette weight retained on the 4.75-millimeter sieve. Attrition Indices less than 0.80 are considered poor, 0.80 to 0.90 marginally acceptable, 0.90 to 0.95 good, and greater than 0.95 excellent. This and the other methods described provide a solid foundation for coal-biomass briquette evaluations. However, optimization and standardization of coal-biomass briquette evaluation procedures is an important area that requires further investigation.

2.5.2 Tumble/Growth Agglomeration

The most basic particle size enlargement technique is tumble/growth agglomeration (Pietsch, 2002). This process is characterized by the collision and coalescence of fine particles as a result of some form of agitation in the presence of natural or supplemental binding mechanisms. The most widely used method of bulk particle agitation in the mineral processing industry to induce agglomeration is tumbling in rotating discs, drums and cones (Capes, 1980). In this context, tumbling refers to irregular, turbulent motion of all particulate solids in a defined environment. Typically, agglomerates produced by these methods are spherical in shape with diameters ranging from 4-6 millimeters. Other technologies for tumble/growth agglomeration include mixer agglomeration, drying of solutions and suspensions, low density particle clouds and agglomeration in liquid suspensions. This section provides a general overview of tumble/growth agglomeration mechanisms, disc and drum agglomeration technology and some practical applications of these concepts in solid fuel production.

2.5.2.1 Process Overview

The process of tumble/growth agglomeration begins when individual particles within a particulate system collide and stick together as a result of agitation. A nuclei (or seed) is formed when the strength of the activated binding mechanisms is greater than the sum of the ambient separation forces (e.g. gravity, inertia, drag) within the system acting on the nuclei. This process, referred to as nucleation, is the most delicate stage of tumble/growth agglomeration because the adhesive forces that develop from the collision of particles are relatively weak (Pietsch, 2002). As a result, nucleation is an inherently time consuming process as many nuclei disintegrate and only a small proportion survive at any given time. After nucleation, size change within a system of particulates can take place by a number of different mechanisms, including coalescence, layering, abrasion transfer, shatter, breakage and attrition (Capes, 1980). These mechanisms are visually depicted in Figure 2-9.

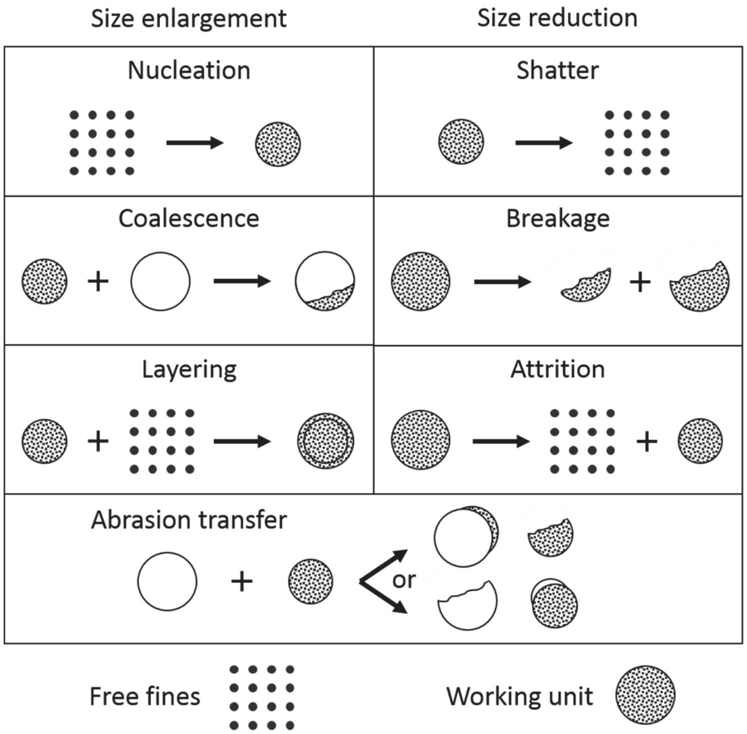


Figure 2-9. Mechanisms of size change in tumble/growth agglomeration (modified from Pietsch, 2002)

Pietsch (2002) proposes that the tendency for adhesion of particles in tumble/growth agglomeration processes can be expressed as:

$$T_a = \sum B_i(x) \,/\, \sum F_{jy}(x) \qquad \text{(Eq. 2-21)}$$

where T_a is the adhesion tendency of two particles, $B_i(x)$ is the sum of all active binding forces and $F_{jy}(x)$ is the active sum of all separation forces within the system. For successful adhesion between two or more particles, the adhesion tendency (T_a) must be greater than or equal to one. The particle size (x) has a very large influence on the magnitude of adhesive forces and ambient system forces, and thus on the adhesion tendency of two or more particles.

Addition of supplemental binders is typically required for tumble/growth agglomeration processes unless the average particle diameter is less than ten microns (Pietsch, 2002). The strength of naturally occurring binding mechanisms (e.g. van der Waals forces, electrostatic forces) in a system of nano-sized particles can equal or exceed other system forces, even with little or no presence of moisture. As a result, the adhesion tendency of fine particles increases with a corresponding decrease in particle size. In more common tumble/growth agglomeration processes, green agglomerates (moist or wet) are formed through coalescence and layering as a result of binder addition. If the solid particles contain a significant amount of moisture, a solid binder can be used, but in most industrial applications a liquid binder is required (Pietsch, 2005). The strength of green agglomerates is primarily attributed to bridges formed by freely movable liquids, capillary pressure at the surface of particles or adhesive forces produced by viscous binders (Pietsch, 2002). Green agglomerates generally require a post-treatment (curing) process after formation to remove excess moisture, which often reduces market appeal, and to improve the strength of bonds. The curing process results in the formation of solid bridges though sintering, chemical reactions, partial melting or recrystallization.

2.5.2.2 Disc and Drum Agglomerators

The most widely used tumble/growth agglomeration devices in mineral processing applications are inclined disc and rotary drum pelletizers. The operating principle of these devices is the formation of spherical pellets by rotating a cylindrical vessel containing a mixture of particulate solids and binders (Pietsch, 2005). As a result of the rotation of the vessel, the mixture is continuously subjected to irregular, turbulent motion until particles of a desired size are formed and removed from the system. These systems can be configured as batch or continuous processes to facilitate a wide variety of applications across many different industries (Capes, 1980).

Disc pelletizers (also referred to as pan or dish pelletizers) are characterized by a round, flat-bottomed, inclined shallow pan that rotates about the center point (Figure 2-10). Solid feed particles are gravity fed to the center of the rotating disc from above and the formed agglomerates discharge over the bottom rim of the disc. The ratio of rim height to the rim diameter is typically in the range of 0.1-0.2 for shallow disc pelletizers, although many modified pan designs have been developed (Pietsch, 2002). An expanded metal liner or an abrasive coating is fixed to the interior of the disc to reduce wear and prolong the operational life of the disc. Adjustable spray nozzles are mounted to a frame that is attached to the base of the pelletizer for the addition of water or other liquid binders. Scrapers or plows are also mounted to the frame to agitate stagnant material and to control the flow pattern of solids within the disc. The inclination of the disc can be adjusted between 40 and 70 degrees to the horizontal to optimize the process for a particular feed and desired agglomerate characteristics. Disc rotation is driven by a fixed-speed or variable-speed motor mounted to the base of the pelletizer. Variable-speed motors provide greater control over agglomerate formation and quality (Capes, 1980). The diameter of disc pelletizers can range from 0.5 meters for laboratory or small-scale applications to more than 10 meters for high-tonnage industrial operations (Pietsch, 2002).

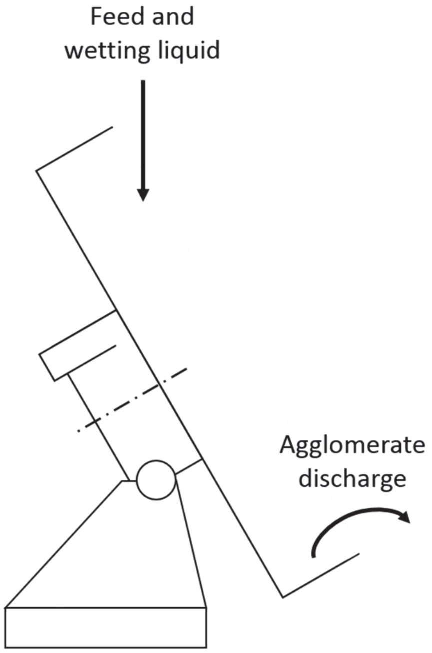


Figure 2-10. Disc pelletizer schematic diagram (modified from Capes, 1980)

The most distinguishing characteristic of disc pelletizers is the size classification of agglomerates that occurs as a result of the unique flow pattern within the pan. As displayed in Figure 2-11, larger agglomerates move to the top of the bed by natural segregation and discharge over the rim as additional feed is added to the system. The seed agglomerates and individual particles are concentrated in the bottom of the bed for additional agglomerate formation. Due to this classification effect, the size particle size of agglomerates discharged from the disc is rather uniform and there is often no need for an additional screening operation (Capes, 1980). Under clockwise rotation, the distribution of solids is restricted primarily to the left side of the pan. Due to the coefficient of friction of the solids, particles are carried clockwise from the bottom to the top of the pan. Once the particles reach the top portion of the pan, gravity causes the particles to cascade down to the bottom of the pan, where the cycle is continued (Pietsch, 2002).

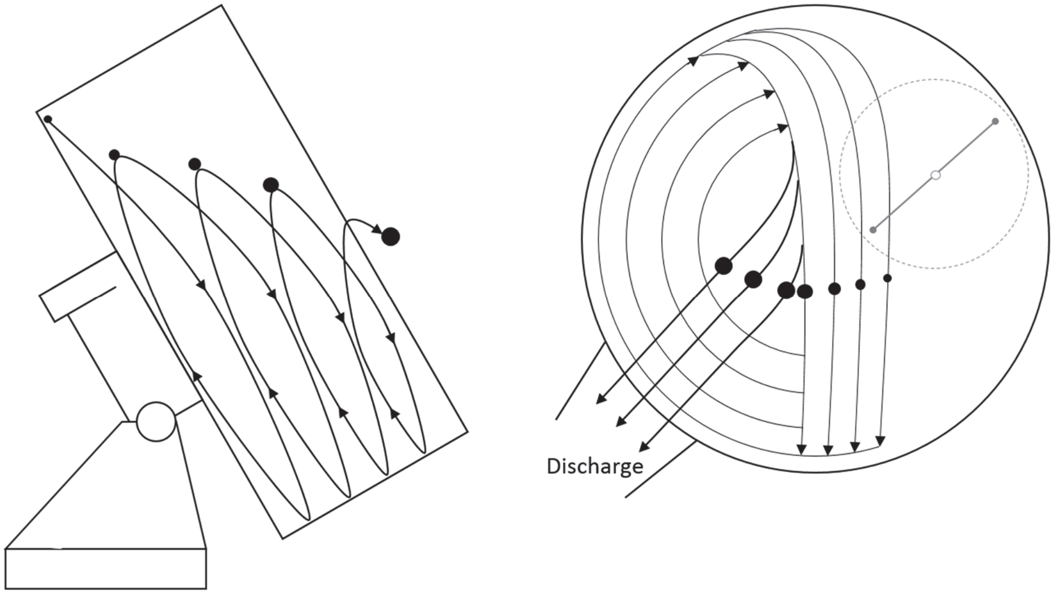


Figure 2-11. Particle flow pattern in disc pelletizers (modified from Pietsch, 2002)

Aside from feed and binder properties, a number of system operating variables influence the size, shape and density of tumbled agglomerates (Capes, 1980). The flow rate of added liquid and the position of the spray nozzles influences the shape of agglomerates. The proper configuration for liquid addition to a disc pelletization system promotes growth by layering, in which dry fines are collected on the surface of established agglomerates that have been wetted by the sprays. In contrast, addition of too much liquid will result in the undesirable production of abnormally shaped particles. Agglomerate size is controlled by liquid addition rate and retention time in the disc. Retention time can be increased by reducing the particle feed rate, decreasing the angle of inclination of the disc or by increasing the height of the rim. Each of these options can be employed to increase agglomerate particle size. The density of agglomerates is primarily influenced by disc diameter, angle of inclination and the liquid addition rate. Sufficient liquid must be added to the system to for agglomerate growth and densification by the formation of liquid bridges and other interparticle bonds. Disc diameter and angle of inclination have a similar effect on agglomerate density in that an increase in both parameters results in the increase of the kinetic energy of cascading particles. This in turn produces greater compaction stresses upon impact with other particles and the rim, and thus higher density agglomerates are formed. However, it must be considered that as the angle of inclination increases, agglomerate residence time is reduced, which will result in a reduction in agglomerate particle size (Capes, 1980).

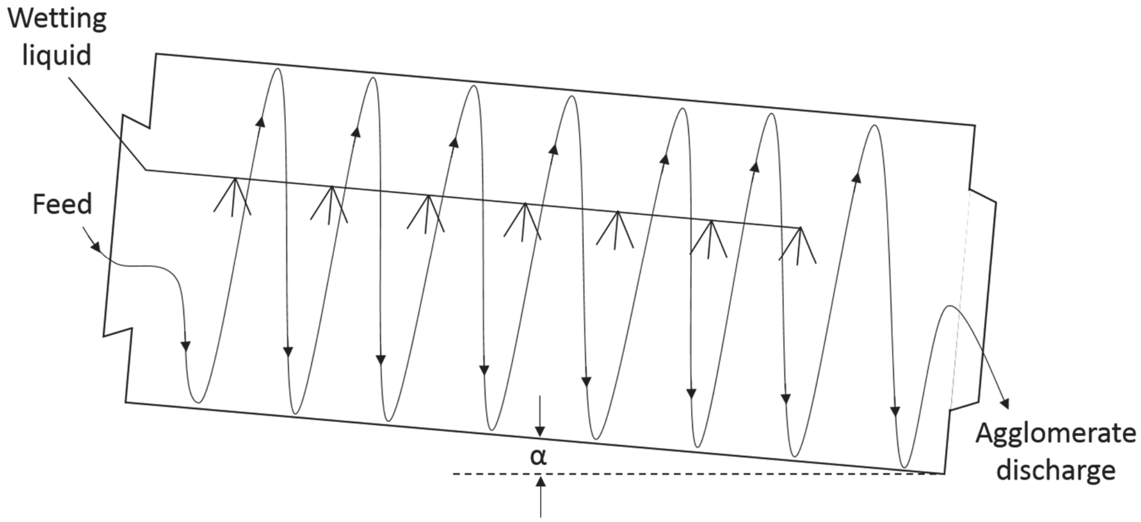


Figure 2-12. Drum pelletizer schematic diagram and particle flow pattern (modified from Pietsch, 2002)

Drum pelletizers are more commonly used than disc pelletizers for high-tonnage applications such as iron ore pelletization and fertilizer granulation. These devices are characterized by a large rotating steel cylinder with a slight inclination (α, up to ten degrees) to the discharge end that is driven by a fixed-speed or variable-speed drive (Figure 2-12). Feed material is introduced to the inclined end of the drum and is tumbled down the length of the drum. This irregular, turbulent motion leads to the formation of spherical pellets in the presence of liquid, which can be added prior to, or with the feed (Pietsch, 2002). To prevent spill-back of feed material, a retaining ring is commonly installed to the feed end of the drum. Additionally, a dam ring can be installed to the discharge end of the drum to increase bed depth and residence time, which is beneficial in many applications. Similar to disc pelletizers, the interior of drum pelletizers is often lined with an expanded metal liner or an abrasive coating to reduce wear and facilitate proper tumbling motion. Scrapers or plows are also mounted to the interior of the drum to limit material build-up and control the uniformity of the drum surface (Capes, 1980).

Although the configuration of drum pelletizers is quite different from disc pelletizers, the material flow pattern in drums is very similar to that of discs. However, the main difference is that particle discharge from drum pelletizers is largely due to gravity, whereas natural segregation discharges larger particles from disc pelletizers. The result is a much wider distribution of agglomerate particle size in the discharged product from drum pelletizers. Consequently, most drum pelletization operations require a recycle loop where fine material is screened from the produce and returned to the feed end of the drum (Capes, 1980). The size, shape and density of agglomerates produced in drum pelletizers are influenced by the same parameters as products of disc pelletization: liquid addition rate, retention time, drum diameter and drum inclination. These effect of these parameters is very similar in both types of tumbling agglomeration, and thus optimization of operating variables must be conducted for every unique application.

2.5.2.3 Solid Fuel Applications

The most significant solid fuel application of tumble/growth agglomeration is the pelletization of wet coal fines. Modern coal mining and preparation operations produce large tonnages of wet coal fines due to the methods used for coal extraction and cleaning. Due to the unfavorable economics of cleaning and drying wet coal fines, vast quantities of fine coal have been deposited in slurry impoundments in coal mining regions. For example, it is estimated that more than 2 billion tons of recoverable fine coal is contained in slurry impoundments in the eastern United States alone (Pietsch, 2005). An additional 30-50 million tons are added to slurry impoundments in this region every year. This has led to significant interest in methods to reconstitute and dry fine coal to improve the marketability of this valuable waste product.

Tumbling/growth agglomeration is the only economical method to reconstitute ultra-fine filter cake coal, which is formed when water is removed from the flotation product of a modern coal preparation plant (Holley & Antonetti, 1977). The advantage of this method over other agglomeration process (e.g. pressure agglomeration) is that the moisture content of filter cake upon discharge from the vacuum filter is in the ideal range for coal pelletization. Thus, there is no need for a preliminary drying stage prior to agglomeration. However, high-moisture coal pellets formed by tumble/growth agglomeration methods require drying after formation to improve the strength and durability. This process can be accomplished with many commercially available dryers (e.g. fixed bed) without production of harmful pollutants. In comparison, pressure agglomeration processes require a feed material that is much drier, and commercially available technologies for drying fine coal can no longer be permitted due to air quality regulations. However, there are many innovative fine coal drying technologies currently being developed which may increase the feasibility of pressure agglomeration of coal fines in the future.

Holley & Antonetti (1977) described a coal pelletization pilot-plant that was built to agglomerate coal obtained from a tailings impoundment. The purpose of the pilot-plant was to determine if construction and operation of a production plant was economically feasible. For the pilot-plant evaluations, coal was recovered from the impoundment, cleaned by two-stage froth flotation and dewatered with a vacuum filter. Several batches of pellets were produced with different binders (lignosulfonate and coal tar) at a rate of 500 pounds per hour of product. The coal and binder was mixed in 100 pound batches and fed to a 36-inch diameter disc pelletizer, in which 0.5-inch diameter pellets were formed. The pellets were discharged directly onto a fluidized-bed vibratory dryer operated at 300 degrees Fahrenheit to reduce the pellet moisture below 6 percent. The quality of the pellets was measured by a modified drop shatter test. The lignosulfonate binder was found to be far superior to the coal tar in this application.

Mehrotra (1980) investigated the kinetics and strength aspects of coal pelletization for 14 different coal samples. In batch pelletization experiments, it was observed that the moisture content of the feed coal had the most significant impact on pellet growth kinetics. Specifically, the pellet growth rate increased with increasing water content. The fineness of the coal samples was also found to have a large impact on the growth rate of pellets. For example, pellet growth rate was found to decrease with increasing fineness for anthracite and bituminous coals. Mehrotra also observed that the strength of pellets tends to decrease with a corresponding decrease in the ash and sulfur content of the feed coal, whereas pellet strength increases with an increase in the fineness of the feed. Moreover, it was found that pellet strength was independent of the feed moisture content. Finally, this study found that corn starch is more effective than asphalt and bentonite for improving the strength of the coal pellets and that binder addition led to a small reduction in the growth rate of pellets.

A more recent application of coal pelletization is described in a patent claim by Taulbee (2012). This document claims that briquette production can be enhanced by the sequential pelletization and briquetting of coal fines. The first step of this process is the formation of spherical pellets in a disc or drum pelletizer from mixtures of wet coal fines, biomass and/or binders. Next, the pellets are conveyed to a fixed-bed dryer to reduce the moisture content below ten percent. This allows quick and efficient drying of the coal fines due to the high porosity of the green pellets. After drying, the pellets are conveyed to a briquetting machine where an additional 2 to 30 percent biomass and 1 to 15 percent binder are mixed with the pellets prior to briquette production. The briquettes produced following this procedure are shown to exhibit good initial strength and durability. However, the strongest and most durable briquettes are produced when the pellets are still hot during the briquetting process. Briquetting processes are covered extensively in the following section on pressure agglomeration.

2.5.3 Pressure Agglomeration

The most versatile and widely used technique for size enlargement of particulate solids is pressure agglomeration. This process is characterized by the compaction and densification of particulate solids by application of external forces in a confined space (Capes, 1980). Pressure agglomeration technologies can be classified by the level of forces exerted during densification and shaping, which affect the strength and other properties of the compacted products. In low-pressure agglomeration processes, feed materials with high moisture and plasticity are formed by pressing through a structurally weak die, and thus generally require a post-treatment process to improve strength and durability. In medium-pressure agglomeration (also known as pelleting), inherent plasticity of drier feed materials is activated by a conditioning process prior to extrusion through perforated dies. This technology has seen significant application in the biomass fuel industry, particularly in the production of wood pellets for home heating and industrial power generation. High-pressure agglomeration techniques are characterized by deformation and destruction of dry feed materials in the presence of high forces, which results in the production of durable densified products with high green strength (Pietsch, 2002). The most commonly used high-pressure agglomeration technology for fine coal reconstitution is roll press briquetting. This section provides a general overview of pressure agglomeration processes, roll pressing technology and some practical applications of these concepts in solid fuel production.

2.5.3.1 Process Overview

The mechanisms of solid particle compaction in pressure agglomeration processes can be divided into two stages. In the initial stage, low pressures cause bulk particles to settle and rearrange, which results in a reduction of porosity and an increase in bulk density. The total surface area of contact between particles also increases during this stage and bonds are formed through liquid bridges and capillary pressure (Drzymala, 1993). At this point, agglomerates are relatively weak and require additional compaction pressure to improve strength and durability. In the second stage, much higher pressures are exerted on the densified mass, which results in the fracture of brittle particles and/or plastic deformation of malleable materials (Pietsch, 2002). Additional bonds are formed during this stage by activation of interparticle adhesive forces, which occurs when the surface area of contact between particles is further increased and the distance between particles becomes extremely small. A schematic representation of these processes is provided in Figure 2-13.

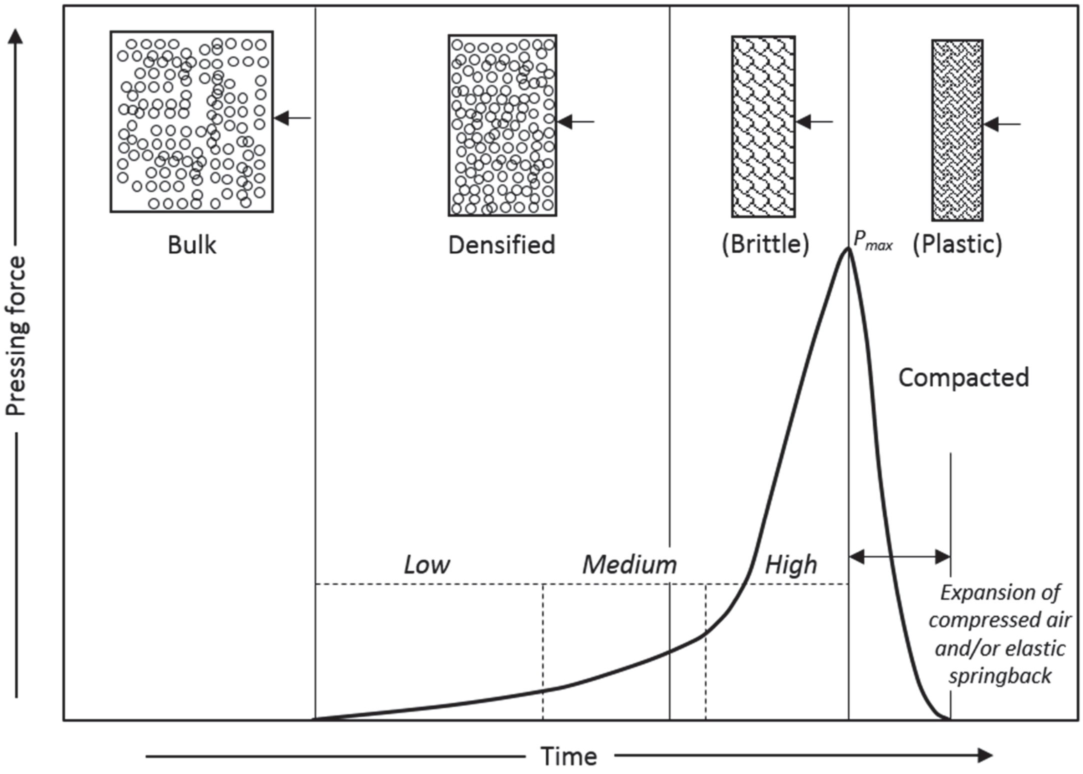


Figure 2-13. Mechanisms of compaction in pressure agglomeration (modified from Pietsch, 2002)

The top half of this figure shows the structural change of particulate solids with the progression of compaction, densification, fragmentation and plastic deformation that occurs with increasing pressure in a confined space or die. The bottom half of the figure depicts the increase in pressing force at a constant compression rate over a period of time until the maximum pressure (P_{max}) is reached. The reason for a sharp reduction in pressing force beyond this point depends on the agglomeration technique. For example, in a roll press system, the maximum force is applied to a material as it passes through the center of the rolls. A sharp decrease in pressing force is immediately observed as the material is ejected from the rolls. Similarly, in a punch and die agglomeration system, the maximum force applied to a material is defined by the predefined displacement of the punch, after which the punch is retracted and the force applied to the material sharply declines. Another important phenomena in pressure agglomeration processes is listed in the bottom right corner of Figure 2-13: expansion of compressed air and elastic spring-back. These mechanisms cause cracking and weakening of agglomerates, the magnitude of which is determined by material properties and operating conditions. If not adequately addressed, these mechanisms can cause partial or complete destruction of agglomerates. One method to reduce the effects of elastic spring-back and expansion of compressed air is to reduce the speed of compaction, which in turn increases the amount of time material remains confined under the influence of the load. This parameter is referred to as dwell time (Pietsch, 2002).

The primary goal of pressure agglomeration is to improve the density of particulate solids by applying external pressure to a system of particles in a confined space. Thus, a common method to evaluate a pressure agglomeration process is to measure the apparent density of the formed products. Comparison of this value with the true density of the solid particles gives a clear indication of the level of densification achieved. Specifically, the ratio of the apparent density of an agglomerate to the true density of the constituent solids is often measured. This agglomerate characteristic, referred to as packing density, is influence by particle size, shape, surface roughness and internal structure for any given densification system (Standish et al., 1991). In high pressure agglomeration systems, the internal structure (or strength) of materials greatly influences particle fragmentation, which in turn influences the size and shape of particles within a system. For example, the fragmentation of brittle solids during compaction reduces packing density due to the development of hydrostatic pressure and the high strength exhibited by smaller particles (Pietsch, 2002).

Without fragmentation or plastic deformation of particles, the maximum theoretical packing density of perfect spheres is 74 percent (i.e. $\sqrt{2}\,\pi/6 = 0.7405$). This value increases to 86 percent if a smaller size fraction of spheres is added to the material that occupy the void spaces between the larger particles (Scott & Kilgour, 1969). Similarly, if third and fourth size fraction is added that fills the new void spaces between the larger particles then the theoretical packing density approaches 90 to 92 percent and 95 to 97 percent, respectively (Drzymala, 1993). For real-world applications, these theoretical packing densities are generally not achievable due to the irregular shape and inconsistent size of common materials. However, fine-grained materials with regular shape, low surface roughness and compact structure can realistically achieve packing densities up to 90 percent. When additional densification beyond that achievable by particle size manipulation is desired, lubricants are commonly added to reduce interparticle friction and saturate the pore volume. However, the addition of lubricants often degrades the quality of agglomerates, so this parameter must be optimized to balance agglomerate density with desired quality.

2.5.3.2 Roll Press Compactors

The most widely used pressure agglomeration technology for size enlargement of particulate solids in the mineral processing industry is roll pressing. Roll presses were originally developed in the mid-19th century as an economic method to produce strong agglomerates from large quantities of coal fines (Pietsch, 2002). Roll presses are characterized by two identical counter-rotating rolls held together by an applied force that compact particulate material as it is drawn between the rolls. Figure 2-14 provides a schematic diagram of two different roll press configurations.

In the most simple roll press configuration, particulate solids are fed by gravity through smooth rollers to produce dense sheets of material (Figure 2-14a). Fluted, corrugated and waffled rollers can also be used to form dense sheets, which are typically crushed and screened after production to create a granular product (Capes, 1980). In a different roll press configuration, particulate solids are force fed by a rotating screw through pocket rollers to produce briquettes of uniform size and shape (Figure 2-14b). This process produces a ‘web’ or ‘flash’ material on the edges of the briquettes due to the flat area around each pocket. The majority of the web material is typically removed by screening the briquettes after formation and recycled back into the feed to minimize the production of fines during handling. Roll presses can be built with any combinations of feeding mechanism and roll type. Vertical feed systems can also be substituted by horizontal force feed systems, which are desirable for some applications.

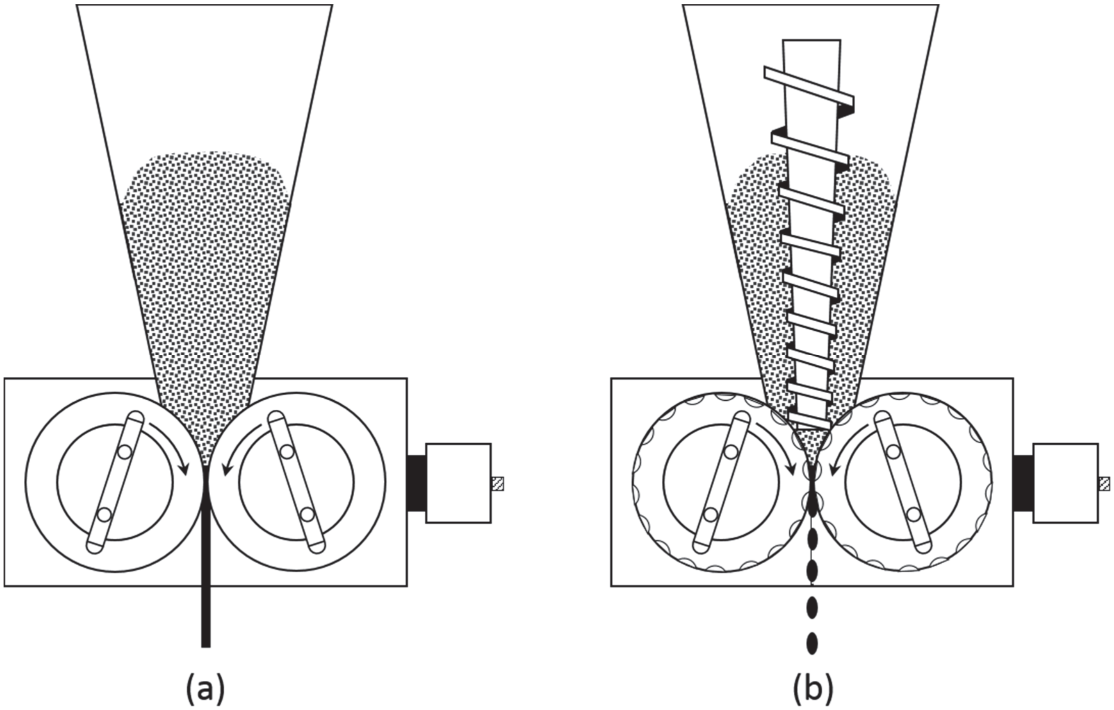


Figure 2-14. Schematic diagram of (a) gravity fed roll press with smooth rollers and (b) force fed roll press with pocket rollers (modified from Pietsch, 2002)

As particulate solids enter the nip region between the rollers and compaction begins, three distinct zones can be defined: the feed zone, the compaction zone and the release zone (Pietsch, 2002). Figure 2-15 depicts the movement of material through these zones for a gravity fed system with two smooth counter-rotating rollers. In the feed zone, material is drawn into the nip region by the combination of gravity and friction between the rollers and the particulate solids. This zone is defined by the width of the rectangular feed opening (h_O), the angle of delivery (α_F) and the angle of nip (α_C). As shown in the pressure-displacement diagram on the right side of Figure 2-15, low pressure forces are developed in the feed zone, which leads to preliminary densification by particle rearrangement. From here material continues into the compaction zone, defined by the area between the angle of nip (α_C) and the neutral angle (α_N), where a sharp increase in pressure leads to the fragmentation and plastic deformation of particles. Beyond the neutral angle (α_N), the densified product enters the release zone, in which particles are subjected to the maximum pressure (P_{Max}) within the system and the maximum sheet density is attained with a thickness (h_A) equal to the width between the rollers. Finally, the frictional force is reversed and the agglomerate is ejected from the rollers. Immediately following ejection, the final sheet thickness (h_S) slightly increases due to the expansion of compressed air and elastic spring-back. The complexity of material flow through the nip region is greatly enhanced in the case of roll press briquetting with pocket rollers (Pietsch, 2002).

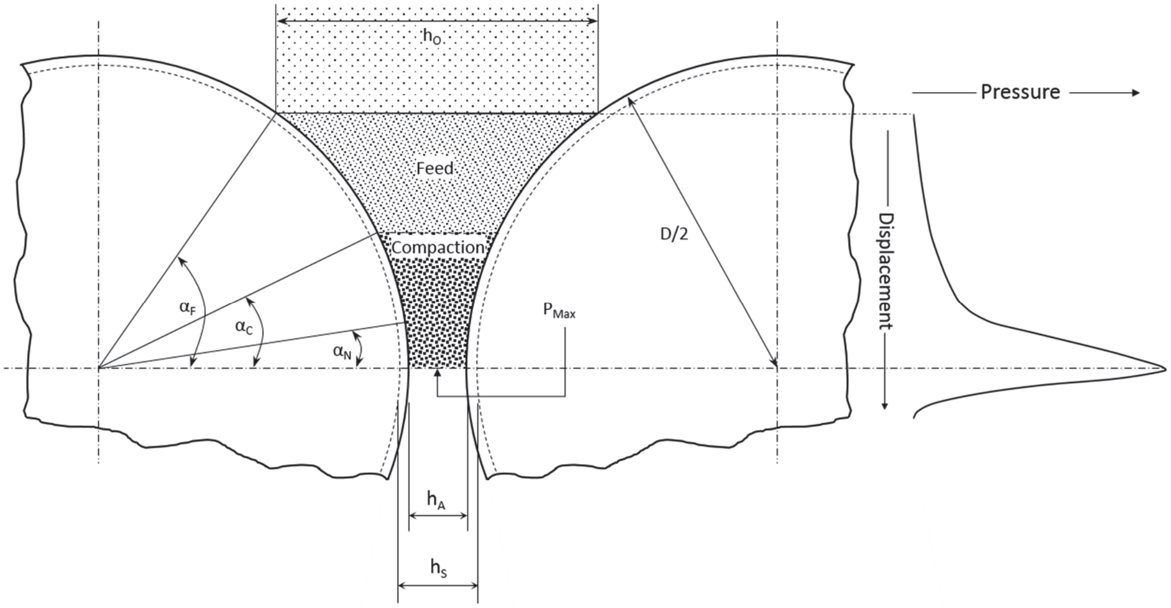


Figure 2-15. Schematic diagram of the nip region between two smooth counter-rotating rollers (modified from Pietsch, 2002 and Capes, 1980)

As previously stated, roll presses can be configured vertically, horizontally or at an incline. In any case, roll presses consist of three major components: a frame, a roller-pressurization system, and a feeding system. Two frame designs are commonly employed in roll press systems, which are distinguished by the position of the rollers with respect to the frame. A common frame design for smaller machines is a cantilevered shaft assembly, where rollers are mounted in a bearing block on the end of a shaft that provides easy access for maintenance. This design is contrasted by a multi-shaft assembly, in which rollers are mounted in the middle of a shaft between two bearing blocks (Guigon & Simon, 2003). The roller and pressurization system is comprised of two countercurrent rotating rolls that are mounted to individual bearing blocks and driven by a fixed-speed or variable-speed motor with a reduction gear. Spacers are placed between the bearing blocks to prevent wear that would result if the rollers were touching. The rollers are brought into close contact by a hydraulic piston system, which in turn dictates the width of the gap between rollers.

A variety of feeding systems can be used to provide a continuous and uniform flow of material to the nip region of the rollers. For free-flowing solids in a vertical roll press configuration, gravity feed systems are often utilized. A device can also be installed upstream of the rollers in a gravity feed system to control the feed rate of material to the nip region (e.g. adjustable gate). In fine powder pressing applications, a force feeding system (e.g. tapered screw) is often required to deaerate, pre-compact and pressurize the feed as it enters the nip. In these systems, the feed rate to the nip can be precisely controlled by a variable-speed drive (Capes, 1980). An additional device can be installed to provide an even distribution of material to the screw (e.g. paddle feeder), which also assists in deaeration of the feed. Force feed systems are typically required in all horizontal and inclined press configurations.

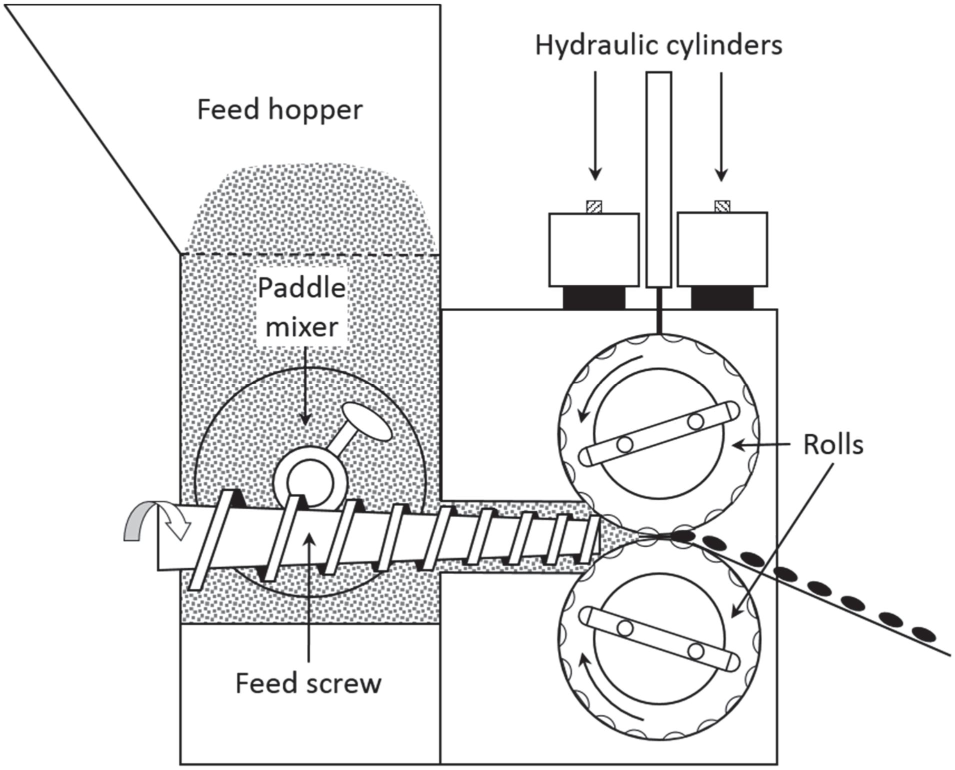


Figure 2-16. Komarek B-100R roll press schematic diagram (modified from Guigon & Simon, 2003)

Figure 2-16 shows the configuration of the Komarek B-100R laboratory roll press, which is commonly used for optimization and scale-up of briquette production processes. This machine is configured horizontally with two counter rotating rolls on cantilevered shafts, two hydraulic cylinders, a horizontal tapered screw and a paddle feeder. The hydraulic cylinders control the position of the upper roll and thus control the gap between the rolls. The paddle feeder is driven by a fixed speed motor and distributes the material to the horizontal screw that in turn feeds material to the rolls. The counter rotating rolls and the horizontal screw are driven by variable speed motors, which enable adjustment of the torque applied to the material from the rolls and screw.

Roll press compaction presents several advantages over other pressure agglomeration methods. For example, the configuration of roll press systems facilitates continuous production at very high capacities. When multiple units are operated in a parallel circuit, several hundred ton per hour production rates can be achieved. Additionally, energy consumption is low since the only power consumed is for driving the rollers and, in feed force systems, for driving the screw. This results in low compaction costs, which is necessary in high tonnage industries such as fertilizer and mining/minerals, and in the compaction of waste materials. Finally, roll pressing can be used to process hot materials up to 1000 degrees Celsius, which is often challenging with other pressure agglomeration technologies (Guigon & Simon, 2003). However, there are also some challenges to roll press agglomeration. For instance, particulate solids can be lost by leakage in the nip region, which is typically addressed by installing a vacuum deaeration system to recover and recycle fines back to the feed. Deaeration systems serve a dual purpose by also improving agglomerate quality and production throughput. Further, geometry and stress distribution of briquettes produced in pocket rollers is more irregular than extruded products, which can lead to downstream handling issues.

2.5.3.3 Solid Fuel Applications

The oldest and most common method of size enlargement and densification of solid fuels is pressure agglomeration. The growing demand for solid fuels in the 19th century led to a drastic increase in coal production throughout the western world, which in turn generated large quantities of unmarketable coal fines. In light of this development and the high cost of coal mining in Europe, significant effort was directed to the development of novel high-quality products from coal fines. Many different methods were developed to convert coal fines into marketable products by pressure agglomeration. These products, commonly referred to as briquettes, featured many advantages over particulate coal fines, including enlarged particle size, reduced dust losses, improved flow properties and increased bulk density (Pietsch, 2005). Coal briquette production reached a peak in the western world shortly after World War II. Due to growing environmental concerns surrounding smoke and other air pollution that resulted from the high content of tar and/or pitch used to bind coal fines together, a steep decline in coal briquette production occurred. Although several new applications for briquetting technology are currently being considered, industrial briquetting of solid fuels is at a historic low in the developed world (Pietsch, 2005).

Nonetheless, research interest in briquetting solid fuels has remained strong as the production of unmarketable coal fines has increased rapidly in the past 50 years. In addition, a tremendous emphasis has been placed on energy production from renewable resources throughout Europe and North America as traditional fossil fuel resources continue to deplete and greenhouse gas emissions continue to rise. As a result, hundreds of papers have been published over the past century that address the application of roll press briquetting to the densification of coal and biomass feedstocks. It is well beyond the scope of this review to attempt to summarize all of the studies that have been conducted on these topics. Therefore, the following section will address select findings related to the influence of material variables and operating conditions on the quality of briquettes and recent developments in binder formulations.

Most early studies on coal briquetting focused on the improvement of briquette strength and durability by evaluating different types of binders. For example, Mills (1908) investigated a wide variety of organic and inorganic binders to produce satisfactory quality briquettes at the lowest possible price. The inorganic binders evaluated in this study included clay, lime, magnesia, magnesia cement, plaster of Paris (gypsum), Portland cement, natural cement, slag cement and water gas. Many more organic binders were tested, including wood products, sugar factory residues, starches, slaughter house refuse, tars and pitches from coal, natural asphalts and petroleum products, for a total of 35 different substances. It was found that organic binders generally improve the coherence of coal briquettes more than inorganic binders. However, due to the higher price of most organic binders, it was concluded that the selection of an ideal binder must be made based on the desired briquette quality for every specific application. In a more recent study, Taulbee et al. (2009) evaluated 50 binder formulations in the production of briquettes from blends of fine coal and sawdust. Based on the results of the study, guar gum and wheat starch were identified as the most suitable binders for the pulverized coal market and lignosulfonate/lime was identified as the best binder for the stoker market.

More recent studies have been focused on the effects of material properties and process conditions on the strength and durability of briquettes. For example, Taulbee et al. (2009) evaluated numerous briquetting parameters in the production of briquettes from blends of fine coal and sawdust. The parameters investigated include binder content, sawdust content, sawdust type, briquetting pressure and dwell time, coal and sawdust particle size, clay content, moisture content, cure temperature and cure time. It was found that binder content, sawdust content, sawdust type and curing conditions exerted the greatest influence on the quality of briquettes. In contrast, briquetting pressure and dwell time were found to have the smallest impact on briquette quality. In another study published by the same authors, Patil et al. (2009) investigated the effect of particle-size distribution on the production of briquettes from blends of coal fines and sawdust. Using a modified Proctor density test, it was determined that the packing density of coal-only blends reached a maximum with seventy to eighty percent coarse coal. However, the maximum compressive strength of the briquettes was found with one hundred percent fine flotation coal. The packing density and compressive strength results for briquettes produced with sawdust were very similar. One difference in the results was that the greatest compressive strength of the coal-sawdust briquettes was obtained with twenty to fifty percent fine coal, rather than one hundred percent.

In another study, Mangena & du Cann (2007) investigated the effect of coal properties in binderless briquetting of various South African coking coals and weathered bituminous coals. The vitrinite-rich coking and blend coking coals were found to produce the highest quality binderless briquettes, which is thought to be a result of stronger bonding from the deformation and subsequent consolidation of the vitrinite macerals in the coals. It was also determined that weathering of bituminous coal fines has an adverse effect on the ability to produce good briquettes. The authors suggest that the negative influence of weathered coal fines can be alleviated by the addition of kaolinite to the coal feed prior to briquette production.

Another area of significant interest in recent years is lignite briquetting. Beker (1997) evaluated the effects of moisture content and briquetting pressure in production of briquettes from Turkish lignites and waste materials. The optimum moisture content and briquetting pressure were found to be 15% and 550 Mpa, respectively. At these conditions, sawdust and paper mill waste were found to be good binders that produce briquettes with good strength and high calorific value. Furthermore, Beker et al. (1998) studied the optimization of briquetting conditions for blends of Turkish lignite and bituminous coals with and without binders. It was determined that the addition of bituminous coal decreased the mechanical strength of the lignite briquettes. In an effort to improve the strength of the briquettes, sawdust, sunflower shell and molasses were added as binders, which in turn increased the mechanical stability of the briquettes. Finally, it was found that all of the briquettes produced in this study were not water resistant, which imposes challenges for storage and transportation.

A continual topic of significant interest is the identification of cost-effective binders to improve the strength, durability and other qualities of fuel briquettes. This is largely due to the significant limitations of many traditional binders for solid fuel applications. For example, inorganic binders such as sodium silicate and bentonite increase the ash content and reduce the heating value of feedstocks. However, inorganic binders are generally less expensive than organic materials. Briquettes made using starch-based binders have poor water-proofing properties and tend to fall apart when exposed to moisture during transportation and storage (Taulbee et al., 2010). Further, asphalt-based binders produce additional emissions when heated during thermochemical conversion processes. More importantly, conventional binders require a very high dose (5 to 10 percent by dry weight) to provide adequate strength and durability. These binders are usually derived from useful and often expensive raw materials; therefore, they add significantly to the overall cost of production. The high dose can be attributed to the fact that conventional binders are typically matrix or film type, which only perform an adhesive function by physically binding the coal particles together to form a large mass. No chemical reaction takes place to strengthen the bond between the binder and coal particles (Messman, 1977). Therefore, there is still a need to find improved binders for agglomeration applications.

During the past two decades, efforts to improve the quality of briquettes have been focused on improving the performance of conventional binders. Goleczka et al. (1988) invented a process for cold briquetting by using a binder composed of molasses and an inorganic hardening agent obtained from calcium carbonate, calcium phosphate, iron oxide and aluminum oxide. Hale et al. (1989) also disclosed a binder incorporating molasses/phosphoric acid and magnesium oxide. The briquettes produced with these mixtures showed good initial shatter resistance, improved hot compressive strength and excellent water resistance. Major and Radu (1998) disclosed a new synergistic binder composition composed of asphalt, sodium carbonate pulping liquor and nonylphenol ethoxylate that can produce a waterproof, self-curing briquette. White (1999) invented a binder that is produced by direct liquefaction of biomass with the addition of pyrolysis tar, petroleum asphalt, reinforcing fibers, extender, fillers, and cross-linking agents if necessary. Kriech and Dobbs (2003) recently disclosed a binder composition including a distillable petroleum hydrocarbon emulsified with a surfactant and water. This binder can increase the hydrophobic characteristics of coal particles and bring about a significant change in their chemistry. Grigorova and Kuzev (2003) tested starch modified with cophony as a brown coal briquetting binder for improved water resistance.

More recently, new methods for reducing binder dosage and for improving the bond strength at the binder-particle interface have been explored by some researchers. For example, Miller and Martin (1980) patented a new briquetting process that uses organic Lewis-base solvents to pretreat coal fines prior to compaction to produce coal briquettes without adding additional binders. The solvents claimed in this patent are capable of electron donor action, and include acetone, methyl ethyl ketone, and ethylene diamine. It is believed that an unassociated electron pair may perform an important function in the interaction between the coal and the solvent. However, a large amount of solvent (20-50% by dry weight) is required for this process, which must be recovered and reused for the process to remain cost-effective. Studies have also been performed by adding liquid oxidants (e.g. H_2O_2) to coal tar to promote the release of oxygen radicals during curing and to strengthen the interfacial bonds between the binder and coal. The interfacial bonds can also be improved by adding other types of additives such as phosphoric acid (Plancher et al., 2002).

Another limitation to coal briquette production is the absorption of water and subsequent disintegration of briquettes during storage and transportation. In light of this difficulty, there is a growing interest in the development of economically feasible methods to sustain the physical and mechanical integrity of fuel briquettes in the presence of water, as evidenced by a number of publications on this topic (Wang et al., 2011; Motaung et al., 2007; Saglam et al., 1990). Several different methods have been investigated to improve the water resistance of fuel briquettes. The most commonly employed method is coating individual fuel particles with a chemical binder prior to briquette production. For example, Bratton et al. (2010) evaluated a novel fine coal briquetting process that included the application of a proprietary binder to improve the strength and weathering properties of coal briquettes. It was determined that a wetting and drying cycle had minimal impact on the durability of coal briquettes produced with the proprietary binder. However, the cost of the novel binder is not discussed and thus is likely a limiting factor to this approach. Furthermore, Taulbee et al. (2009) investigated twelve different binders including molasses, guar gum, corn starch, wheat starch and paper sludge to improve the strength and water resistance of briquettes produced with fine coal and sawdust. The study found that the compressive strength of the coal-sawdust briquettes was significantly reduced after submergence in water for eight hours. These and other water soluble binders are generally not recommended to improve the water resistance of fuel briquettes (Mills, 1908).

Another method that has been investigated to improve the water resistance of fuel briquettes is coating with water insoluble chemicals. Coating materials can be applied by many different techniques including dipping, brushing, flow coating, roller coating and spraying (Freitag, 1996). Of these methods, dipping and spraying present the greatest opportunity for fuel briquette coating due to the size and shape of briquettes. Both methods generally require heating the material to reduce the viscosity, which leads to a reduction in film thickness and thus a reduction in chemical consumption. When the materials are heated prior to application, these techniques are referred to as hot dipping and hot spraying (Freitag, 1996).

Specific techniques for coating briquettes have been disclosed in patents filed in the United States and Australia. Goss (1938) patented a hot spraying mechanism for applying paraffin wax to wood briquettes for the purpose of protecting against the absorption of moisture. Lundwall (1939) developed a machine that employs the dipping technique to coat briquettes composed of metal cuttings with a mixture of water and Portland cement. Furthermore, Trechock (1973) described a spray coating method to overcome the problem of airborne dust associated with rail shipment of coke briquettes. Using this method, the briquettes are treated with an aqueous dispersion of solid film former such as sodium silicate, blackstrap molasses, turpentine resins and pitches derived from black coal or petroleum. Bates et al. (1988) disclosed a method of coating briquettes composed of brown coal, bituminous coal, anthracite or other carbonaceous materials such as wood. The patent describes a water based emulsion comprising an acrylic polymer based on acrylic ester monomer that can be applied by spraying or dipping. Finally, Shimasaki et al. (2003) developed a method of producing coal briquettes with high strength and excellent water resistance by mixing starch with the coal particles prior to briquette production and coating the surface of the briquettes with a heavy oil component simultaneously with or after briquette formation.

2.6 References

Ahmed, S., & Whalley, B. (1978). Analytical procedures for sulfur in coal desulfurization products. In Karr, C., Jr. (Ed.), *Analytical methods for coal and coal products.* San Diego, CA: Academic Press.

Allardice, D., & Evans, D. (1978). Moisture in coal. In Karr, C., Jr. (Ed.), *Analytical methods for coal and coal products.* San Diego, CA: Academic Press.

ANSI/ASAE S424.1 (1992). *Method of determining and expressing particle size of chopped forage materials by screening.* St. Joseph, MI: American Society of Agricultural and Biological Engineers.

ASAE D274.1 (1992). *Flow of grain and seeds through orifices.* St. Joseph, MI: American Society of Agricultural and Biological Engineers.

ASAE S358.3 (2012). *Moisture measurement − Forages.* St. Joseph, MI: American Society of Agricultural and Biological Engineers.

ASTM C518-10 (2010). *Standard test method for steady-state thermal transmission properties by means of the heat flow apparatus.* West Conshohocken, PA: ASTM International.

ASTM D167-12a (2012). *Standard test method for apparent and true specific gravity and porosity of lump coke.* West Conshohocken, PA: ASTM International.

ASTM D1875/D1875M-04 (2010). *Standard test method for fusibility of coal and coke ash.* West Conshohocken, PA: ASTM International.

ASTM D2639-08 (2008). *Standard test method for plastic properties of coal by the constant-torque Gieseler plastometer.* West Conshohocken, PA: ASTM International.

ASTM D2766-95 (2009). *Standard test method for specific heat of liquids and solids.* West Conshohocken, PA: ASTM International.

ASTM D291-07 (2012). *Standard test method for cubic foot weight of crushed bituminous coal.* West Conshohocken, PA: ASTM International.

ASTM D3172-07a (2007). *Standard practice for proximate analysis of coal and coke.* West Conshohocken, PA: ASTM International.

ASTM D3173-11 (2011). *Standard test method for moisture in the analysis sample of coal and coke.* West Conshohocken, PA: ASTM International.

ASTM D3174-12 (2012). *Standard test method for ash in the analysis sample of coal and coke.* West Conshohocken, PA: ASTM International.

ASTM D3175-11 (2011). *Standard test method for volatile matter in the analysis sample of coal and coke.* West Conshohocken, PA: ASTM International.

ASTM D3176-09 (2009). *Standard practice for ultimate analysis of coal and coke.* West Conshohocken, PA: ASTM International.

ASTM D3177-02 (2007). *Standard test methods for total sulfur in the analysis sample of coal and coke.* West Conshohocken, PA: ASTM International.

ASTM D3302/D3302M-12 (2012). *Standard test method for total moisture in coal.* West Conshohocken, PA: ASTM International.

ASTM D3682-01 (2006). *Standard test method for major and minor elements in combustion residues from coal utilization processes.* West Conshohocken, PA: ASTM International.

ASTM D409/D409M-12 (2012). *Standard test method for grindability of coal by the Hardgrove-machine method.* West Conshohocken, PA: ASTM International.

ASTM D4208-02 (2007). *Standard test method for total chlorine in coal by the oxygen bomb combustion/ion selective electrode method.* West Conshohocken, PA: ASTM International.

ASTM D440-07 (2012). *Standard test method of drop shatter test for coal*. West Conshohocken, PA: ASTM International.

ASTM D5373-08 (2008). *Standard test methods for instrumental determination of carbon, hydrogen, and nitrogen in laboratory samples of coal.* West Conshohocken, PA: ASTM International.

ASTM D5865-12 (2012). *Standard test method for gross calorific value of coal and coke.* West Conshohocken, PA: ASTM International.

ASTM D6128-06 (2006). *Standard test method for shear testing of bulk solids using the Jenike shear cell.* West Conshohocken, PA: ASTM International.

ASTM D6683-08 (2008). *Standard test method for measuring bulk density values of powders and other bulk solids as function of compressive stress.* West Conshohocken, PA: ASTM International.

ASTM D6773-08 (2008). *Standard shear test method for bulk solids using the Schulze ring shear tester.* West Conshohocken, PA: ASTM International.

ASTM D7481-09 (2009). *Standard test methods for determining loose and tapped bulk densities of powders using a graduated cylinder.* West Conshohocken, PA: ASTM International.

ASTM E1534-93 (2006). *Standard test method for determination of ash content of particulate wood fuels.* West Conshohocken, PA: ASTM International.

ASTM E1755-01 (2007). *Standard test method for ash in biomass.* West Conshohocken, PA: ASTM International.

ASTM E775-87 (2008). *Standard test method for total sulfur in the analysis sample of refuse-derived fuel.* West Conshohocken, PA: ASTM International.

ASTM E777-08 (2008). *Standard test method for carbon and hydrogen in the analysis sample of refuse-derived fuel.* West Conshohocken, PA: ASTM International.

ASTM E778-08 (2008). *Standard test method for nitrogen in the analysis sample of refuse-derived fuel.* West Conshohocken, PA: ASTM International.

ASTM E870-82 (2006). *Standard test methods for analysis of wood fuels.* West Conshohocken, PA: ASTM International.

ASTM E871-82 (2006). *Standard test method for moisture analysis of particulate wood fuels.* West Conshohocken, PA: ASTM International.

ASTM E872-82 (2006). *Standard test method for volatile matter in the analysis of particulate wood fuels.* West Conshohocken, PA: ASTM International.

Basu, P. (2010). *Biomass gasification and pyrolysis: Practical design and theory*. Burlington, MA: Academic Press.

Basu, P., Butler, J., & Leon, M. (2011). Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. *Renewable energy*, *36*(1), 282-288.

Bates, A., Heng, S., & Perry, G. (1988). *Australian Patent No. 1988016577*. Wooden, ACT: Australian Patent Office.

Baughman, G. (1978). *Synthetic fuels data handbook: U.S. oil shale, U.S. coal, oil sands.* Denver, CO: Cameron Engineers.

Beker, U. (1997). Briquetting of Afsin-Elbistan lignite of Turkey using different waste materials. *Fuel processing technology, 51*(1-2), 137-144.

Beker, U., Kucukbayrak, S., & Ozer, A. (1998). Briquetting of Afsin-Elbistan lignite. *Fuel processing technology, 55*(2), 117-127.

Bell, D., Towler, B., & Fan, M. (2011). *Coal gasification and its applications.* London, England: William Andrew.

Bennett, R. (1981). Gas conditioning. In T. Reed (Ed.), *Biomass gasification: Principles and technology*. Park Ridge, NJ: Noyes Data Corporation.

Berenbaum, R., & Brodie, I. (1959). Measurement of the tensile strength of brittle materials. *British journal of applied physics, 10*(6), 281-287.

Berkowitz, N. (1994). *An introduction to coal technology.* (2nd ed.). San Diego, CA: Academic Press.

Boley, C. & Rice, N. (1949). Methods of evaluating briquet quality. *Proceedings of a coal briquetting conference*, 31-47, Laramie, WY: University of Wyoming.

Boylan, D. (1996). Southern company tests of wood/coal cofiring in pulverized coal units. *Biomass and bioenergy, 10*(2-3), 139-147.

Brar, J., Singh, K., Wang, J., & Kumar, S. (2012). Cogasification of coal and biomass: A review. *International journal of forestry research, 2012*(1), 1-10.

Brown, D., & Atkin, B. (2000). A method for the rapid on-site assessment of handleability. *Coal preparation, 21*(3), 299-313.

Brown, D., Atkin, B., Miles, N., & Creasey, D. (1997). Determination of the handleability of a coal blend using an extrusion trough. *Fuel, 76*(13), 1183-1186.

Brown, D., & Miles, N. (2004). Assessment of coal handleability. *Coal preparation, 24*(3-4), 99-122.

Browning, J. (1967). Agglomeration. *Chemical Engineering, 74*(25), 147-170.

Capes, C. (1980). Particle size enlargement. In J. Williams & T. Allen (Eds.), *Handbook of powder technology* (Vol. 1). Amsterdam, Netherlands: Elsevier Scientific Publishing Company.

Carpenter, A. (2008). Polygeneration from coal. London, England: IEA Clean Coal Centre.

Carslaw, H., & Jaeger, J. (1959). *Conduction of heat in solids.* (2nd ed.). Oxford, England: Oxford University Press.

CEN/TS 15370-1 (2006). *Solid biofuels − Method for the determination of ash melting behavior − Part 1: Characteristic temperatures method.* Brussels, Belgium: European Committee for Standardization.

Cercone, K., Deming, D., & Pollack, H. (1996). Insulating effect of coals and black shales in the Appalachian Basin, Western Pennsylvania. *Organic chemistry, 24*(2), 243-249.

Channiwala, S., & Parikh, P. (2002). A unified correlation for estimating HHV of solid, liquid, and gaseous fuels. *Fuel, 81*(8), 1051-1063.

Chen, Y., Adams, T., II, & Barton, P. (2011). Optimal design and operation of flexible energy polygeneration systems. *Industrial & engineering chemistry research, 50*(8), 4553-4566.

Collazo, J., Pazo, J., Granada, E., Saavedra, A., & Eguia, P. (2012). Determination of the specific heat of biomass materials and the combustion energy of coke by DSC analysis. *Energy, 45*(1), 746-752.

Collot, A. (2002). *Matching gasifiers to coals*. London, England: IEA Clean Coal Centre.

Collot, A. (2006). Matching gasification technologies to coal properties. *International journal of coal geology, 65*(3), 191-212.

Couch, G. (2008). *Coal to liquids*. London, England: IEA Clean Coal Centre.

Cummer, K., & Brown, R. (2002). Ancillary equipment for biomass gasification. *Biomass and bioenergy, 23*(2), 113-128.

Demirbas, A. (2003). Sustainable cofiring of biomass with coal. *Energy conversion and management, 44*(9), 1465-1479.

Desrosiers, R. (1981). Thermodynamics of gas-char reactions. In T. Reed (Ed.), *Biomass gasification: Principles and technology*. Park Ridge, NJ: Noyes Data Corporation.

Doroodchi, E., Zulfiqar, H., & Moghtaderi, B. (2013). A combined experimental and theoretical study on laboratory-scale comminution of coal and biomass blends. *Powder technology, 235*(1), 412-421.

Drzymala, Z. (1993). *Industrial briquetting: Fundamentals and methods*. Warsaw, Poland: Polish Scientific Publishers.

Eckerd, J. (1967). Development of standard procedures for testing fuel briquets. *Proceedings of the 10th biennial briquetting conference*, 95-99, Albuquerque, NM: Institute for Briquetting and Agglomeration.

EN 14774-1 (2009). *Solid biofuels − Determination of moisture content − Oven dry method − Part 1: Total moisture − Reference method.* Brussels, Belgium: European Committee for Standardization.

EN 14774-2 (2009). *Solid biofuels − Determination of moisture content − Oven dry method − Part 2: Total moisture − Simplified method.* Brussels, Belgium: European Committee for Standardization.

EN 14774-3 (2009). *Solid biofuels − Determination of moisture content − Oven dry method − Part 3: Total moisture − Moisture in general analysis sample.* Brussels, Belgium: European Committee for Standardization.

EN 14775 (2009). *Solid biofuels − Determination of ash content.* Brussels, Belgium: European Committee for Standardization.

EN 14918 (2009). *Solid biofuels − Determination of calorific value.* Brussels, Belgium: European Committee for Standardization.

EN 15103 (2009). *Solid biofuels − Determination of bulk density.* Brussels, Belgium: European Committee for Standardization.

EN 15104 (2011). *Solid biofuels − Determination of total content of carbon, hydrogen and nitrogen − instrumental methods.* Brussels, Belgium: European Committee for Standardization.

EN 15148 (2009). *Solid biofuels − Determination of the content of volatile matter.* Brussels, Belgium: European Committee for Standardization.

EN 15149-2 (2010). *Solid biofuels − Determination of particle size distribution − Part 2: Vibrating screen method using sieve apertures of 3,15 mm and below.* Brussels, Belgium: European Committee for Standardization.

EN 15150 (2011). *Solid biofuels − Determination of particle density.* Brussels, Belgium: European Committee for Standardization.

EN 15289 (2011). *Solid biofuels − Determination of total content of sulfur and chlorine.* Brussels, Belgium: European Committee for Standardization.

Ergun, S. (1951). Determination of particle density of crushed porous solids. *Analytical chemistry, 23*(1), 151-156.

Ettinger, I., & Zhupakhina, E. (1960). Method of determining porosity of mineral coals. *Fuel, 39*(5), 387-392.

Fell, J., & Newton, J. (1968). The tensile strength of lactose tablets. *Journal of pharmacy and pharmacology, 20*(8), 657-659.

Fernando, R. (2005). *Fuels for biomass cofiring*. London, England: IEA Clean Coal Centre.

Fernando, R. (2008). *Coal gasification*. London, England: IEA Clean Coal Centre.

Fernando, R. (2009). *Co-gasification and indirect cofiring of coal and biomass*. London, England: IEA Clean Coal Centre.

Freitag, W. (1996). Principles of application. In D. Stoye & W. Freitag (Eds.), *Resins for coatings: Chemistry, properties and applications*, 40-44. Cincinnati, Ohio: Hanser/Gardner Publications.

Gan, H., Nandi, S., & Walker, P., Jr. (1972). Nature of the porosity in American coals. *Fuel, 51*(4), 272-277.

Gaston, K., Jarvis, M., Pepiot, P., Smith, K., Frederick, W., Jr., & Nimlos, M. (2011). Biomass pyrolysis and gasification of varying particle sizes in a fluidized-bed reactor. *Energy & fuels, 25*(8), 3747-3757.

Geyer, W., DeWyke, J., & Walawender, W. (2000). Biomass and gasification properties of young populous clones. *Wood and fiber science, 32*(3), 375-384.

Goleczka, J., Harris, W., & Pringle, J. (1988). *U. S. Patent No. 4,738,685*. Washington, DC: U.S. Patent and Trademark Office.

Gomez-Barea, A., & Leckner, B. (2010). Modeling of biomass gasification in fluidized bed. *Progress in energy and combustion science, 36*(4), 444-509.

Gorbaty, M., Kelemen, S., George, G., & Kwiatek, P. (1992). Characterization and thermal reactivity of oxidized organic sulphur forms in coals. *Fuel, 71*(11), 1255-1264.

Goss, W. (1938). *U.S Patent No. 2,114,377*. Washington, DC: U.S. Patent and Trademark Office.

Graboski, M. (1981). Kinetics of char gasification reactions. In T. Reed (Ed.), *Biomass gasification: Principles and technology*. Park Ridge, NJ: Noyes Data Corporation.

Graboski, M., & Bain, R. (1981). Properties of biomass relevant to gasification. In T. Reed (Ed.), *Biomass gasification: Principles and technology*. Park Ridge, NJ: Noyes Data Corporation.

Grigorova, I., & Kuzev, L. (2003). Briquetting of brown coals with a binding agent modified amylum with soluble colophony, Annual of University of Mining and Geology “St. Ivan Rilski”, *Mining and Mineral Processing, 46*(II).

Guigon, P., & Simon, O. (2003). Roll press design – influence of force feed systems on compaction. *Powder technology, 130*(1-3), 41-48.

Hale, S., Kelly, S., & Tayler, R. (1989). *European Patent Application No. 0377995 A2*. Munich, Germany: European Patent Office.

Hall, D., & Cutress, J. (1960). The effect of fines content, moisture and added oil on the handling of small coal. *Journal of the institute of fuel, 33*(1), 63-72.

Hanson, S., Patrick, J., & Walker, A. (2002). The effect of coal particle size on pyrolysis and steam gasification. *Fuel, 81*(5), 531-537.

Hattingh, B., Everson, R., Neomagus, H., & Bunt, J. (2011). Assessing the catalytic effect of coal ash constituents on the CO_2 gasification rate of high ash, South African coal. *Fuel processing technology, 92*(10), 2048-2054.

Herrin, J., & Deming, D. (1996). Thermal conductivity of U.S. coals. *Journal of geophysical research, 101*(B11), 25381-25386.

Higman, C., & van der Burgt, M. (2003). *Gasification*. Burlington, MA: Gulf Professional Publishing.

Holley, C., & Antonetti, J. (1977). Agglomeration of coal fines. *Proceedings of the 15th biennial conference of the Institute for Briquetting and Agglomeration*, 1-12, Albuquerque, NM: Institute for Briquetting and Agglomeration.

Honaker, R., Parekh, B., Taulbee, D., & Tao, D. (2005). *Premium fuel production from mining and timber waste using advanced separation and pelletizing technologies*. Washington, DC: U.S. Department of Energy.

Hunt, E., Prinzing, D., Battista, J., & Hughes, E. (1997). The shawville coal/biomass cofiring test: A coal/power industry cooperative test of direct fossil-fuel CO_2 mitigation. *Energy conversion and management, 38*(Supplement), S551-S556.

Hurst, H., Novak, F., & Patterson, J. (1999). Viscosity measurements and empirical predictions for some model gasifier slags. *Fuel, 78*(4), 439-444.

Jenike, A. (1964). Storage and flow of solids, *University of Utah engineering experiment station, Bulletin number 123*.

Jenkins, B. (1989). Physical properties of biomass. In O. Kitani & C. Hall (Eds.), *Biomass handbook.* New York, NY: Gordon and Breach Science Publishers.

Jenkins, B., Baxter, L., Miles, T., Jr., Miles, T. (1998). Combustion properties of biomass. *Fuel processing technology, 54*(1-3), 17-46.

Kaliyan, N., & Morey, R. (2008). *Binding mechanisms of corn stover and switchgrass in briquettes and pellets*. ASABE Paper No. 084282. St. Joseph, MI: ASABE.

Khambeckar, J., Barnum, R., & Hossfeld, R. (2010). Achieving reliable material flow in coal preparation plants. *CPSA journal, 9*(2), 12-15.

Kim, Y., Seo, D., & Hwang, J. (2011). Study of the effect of coal type and particle size on char-CO_2 gasification via gas analysis. *Energy & fuels, 25*(11), 5044-5054.

Kriech, A., & Dobbs, T. (2003). *U. S. Patent No. 6,530,966*. Washington, DC: U.S. Patent and Trademark Office.

Kristiansen, A. (1996). *Understanding coal gasification*. London, England: IEA Clean Coal Centre.

Kumabe, K., Hanaoka, T., Fujimoto, S., Minowa, T., & Sakanishi, K. (2007). Co-gasification of woody biomass and coal with air and steam. *Fuel, 86*(5-6), 684-689.

Kumar, A., Jones, D., & Hanna, M. (2009). Thermochemical biomass gasification: A review of the current status of the technology. *Energies, 2*(3), 556-581.

Liang, C., Chen, X., Xu, P., Liu, B., Zhao, C., & Xu, C. (2011). Effect of moisture content on conveying characteristics of pulverized coal for pressurized entrained flow gasification. *Experimental thermal and fluid science, 35*(6), 1143-1150.

Long, H., III, & Wang, T. (2011). *Case studies for biomass/coal co-gasification in IGCC applications*. Vancouver, Canada: ASME Turbo Expo 2011.

Lundwall, A. (1939). *U.S. Patent No. 2,155,500*. Washington, DC: U.S. Patent and Trademark Office.

Luo, S., Xiao, B., Guo, X., Hu, Z., Liu, S., & He, M. (2009). Hydrogen-rich gas from catalytic steam gasification of biomass in a fixed bed reactor: Influence of particle size on gasification performance. *International journal of hydrogen energy, 34*(3), 1260-1264.

Mahajan, O., & Walker, P., Jr. (1978). Porosity of coals and coal products. In Karr, C., Jr. (Ed.), *Analytical methods for coal and coal products.* San Diego, CA: Academic Press.

Major, B., & Radu, G. (1998). *U. S. Patent No. 6,013,116*. Washington, DC: U.S. Patent and Trademark Office.

Mangena, S., & du Cann, V. (2007). Binderless briquetting of some selected South African prime coking, blend coking and weathered bituminous coals and the effect of coal properties on binderless briquetting. *International journal of coal geology, 71*(2-3), 303-312.

Mehrotra, V. (1980). *Pelletization of coal fines - kinetic and strength aspects*. (Doctoral dissertation), Available from ProQuest Dissertations and Theses. (UMI No. 8113129).

Messman, H. (1977). Introduction. In H. Messman & T. Tibbetts (Eds.), *Elements of briquetting and agglomeration*. Las Cruces, NM: Institute for Briquetting and Agglomeration.

Mikka, A., & Smitham, J. (1985). Coal handleability assessment. *Proceedings of the third Australian coal preparation conference*, 12-27.

Miller, M., & Martin, D. (1980). *U. S. Patent No. 4,235,603*. Washington, DC: U.S. Patent and Trademark Office.

Mills, J. U.S. Department of the Interior, United States Geological Survey. (1908). Binders for coal briquets: *Investigations made at the fuel-testing plant: St. Louis, Mo.* (Bulletin 343).

Mills, K., & Rhine, J. (1989a). The measurement and estimation of the physical properties of slags formed during coal gasification. 1. Properties relevant to fluid flow. *Fuel, 68*(2), 193-200.

Mills, K., & Rhine, J. (1989b). The measurement and estimation of the physical properties of slags formed during coal gasification. 2. Properties relevant to heat transfer. *Fuel, 68*(7), 904-910.

Minchener, A. (2005). Coal gasification for advanced power generation. *Fuel, 84*(17), 2222-2235.

Moore, J. (1957). Proposals of the standards committee. *Proceedings of the 5th biennial briquetting conference*, 37-40, Laramie, WY: International Briquetting Association.

Mondal, P., Dang, G., & Garg, M. (2011). Syngas production through gasification and cleanup for downstream applications − Recent developments. *Fuel processing technology, 92*(8), 1395-1410.

Montagnaro, F., Brachi, P., & Salatino, P. (2011). Char-wall interaction and properties of slag waste in entrained-flow gasification of coal. *Energy & fuels, 25*(8), 3671-3677.

Motaung, S., Mangena, S., de Korte, G. (2007). Effects of coal composition and flotation reagents on the water resistance of binderless briquettes. *Coal preparation, 27*(4), 230-248.

Mulvaney, D., & Robbins, P. (Eds.). (2011). *Green energy: An a-to-z guide.* Thousand Oaks, CA: SAGE Publications.

Nattermann, C., & Hutinger, K. (1994). Correlations between coal reactivity and inorganic matter content for pressure gasification with steam and carbon dioxide. *Fuel, 73*(10), 1682-1684.

Nowok, J. (1994). Viscosity and phase transformation in coal ash slags near and below the temperature of critical viscosity. *Energy & fuels, 8*(6), 1324-1336.

Ozum, B., Kovacik, G., & Chambers, A. (1993). Coal gasification gas cleanup. *International journal of hydrogen energy, 18*(10), 847-851.

Pan, Y., Velo, E., Roca, X., Manya, J., & Puigjaner, L. (2000). Fluidized-bed co-gasification of residual biomass/poor coal blends for fuel gas production. *Fuel, 79*(11), 1317-1326.

Patil, D., Taulbee, D., Parekh, B., & Honaker, R. (2009). Briquetting of coal fines and sawdust – Effect of particle-size distribution. *International journal of coal preparation and utilization, 29*(1), 251-264.

Perry, R., & Chilton, C. (1973). *Chemical engineer's handbook.* (5th ed.). Tokyo, Japan: McGraw-Hill Kogakusha.

Petrakis, L., & Grandy, D. (1980). Coal analysis, characterization and petrography. *Journal of chemical education, 57*(10), 689-694.

Pickard, E., Roll, W., & Ramser, J. (1961). Fundamentals of hay wafering. *Transactions of the American Society of Agricultural Engineers, 4*(1), 65-68.

Pietsch, W. (2002). *Agglomeration processes: Phenomena, technologies, equipment*. Weinheim, Germany: Wiley-VCH.

Pietsch, W. (2005). *Agglomeration in industry: Occurrence and applications*. Weinheim, Germany: Wiley-VCH.

Pinto, F., Andre, R., Franco, C., Lopes, H., Carolino, C., Costa, R., & Gulyurtlu, I. (2010). Co-gasification of coal and wastes in a pilot-scale installation. 2: Effect of catalysts in syngas treatment to achieve sulphur and nitrogen compounds abatement. *Fuel, 89*(11), 3340-3351.

Plancher, H., Agarwal, P., & Severns, R. (2002). Improving form coke briquette strength. *Fuel processing technology, 79*(2), 83-92.

Prescott, J., & Barnum, R. (2000). On powder flowability. *Pharmaceutical technology, 24*, 60-84.

Prostel, E., (1953). Report on physical tests used by operating briquetting plants. *Proceedings of the 3rd biennial briquetting conference*, 67-70, Laramie, WY: International Briquetting Association.

Rabier, F., Temmerman, M., Bohm, T., Hartmann, H., Jensen, P., Rathbauer, J., & Fernandez, M. (2006). Particle density determination of pellets and briquettes. *Biomass and bioenergy, 30*(11), 954-963.

Rastogi, S., & Klinzing, G. (1994). Characterizing the rheology of powders by studying dynamic avalanching of the powder. *Particle and particle systems characterization, 11*(6), 453-456.

Ratafia-Brown, J., Manfredo, L., Hoffmann, J., & Ramezan, M. (2002). *Major environmental aspects of gasification-based power generation technologies*. Washington, DC: U.S. Department of Energy.

Richards, S. (1990). Physical testing of fuel briquettes. *Fuel processing technology, 25*(2), 89-100.

Rumpf, H. (1962). The strength of granules and agglomerates. In W. Knepper (Ed.), *Agglomeration*, 379-418. New York, NY: John Wiley and Sons.

Saglam, M., Yuksel, M., Yanik, J., Tutas, M., Karaduman, M., & Ustun, G. (1990). Production of water-resistant briquettes from Turkish lignites using sulphite liquor binders. *Fuel, 69*(1), 60-64.

Sami, M., Annamalai, K., & Wooldridge, M. (2001). Co-firing of coal and biomass fuel blends. *Progress in energy and combustion science*, *27*(2), 171-214.

Schulze, D. (2008). *Powders and bulk solids: Behavior, characterization, storage and flow.* Berlin, Germany: Springer-Verlag.

Schwedes, J., & Schulze, D. (1990). Measurement of flow properties of bulk solids. *Powder technology, 61*(1), 59-68.

Scott, G., & Kilgour, D. (1969). The density of random close packing of spheres. *Journal of physics D: Applied physics, 2*(6), 863-866.

Seggiani, M. (1998). Modelling and simulation of time varying slag flow in a Prenflo entrained-flow gasifier. *Fuel, 14*(14), 1611-1621.

Shimasaki, K., Deguchi, T., Sugita, S., & Makino, E. (2003). *U.S. Patent No. 6,626,966*. Washington, DC: U.S. Patent and Trademark Office.

Simbeck, D., Korens, D., Biasca, F., Vejtasa, S., & Dickenson, R. (1993). *Coal gasification guidebook: Status, applications, and technologies*. Palo Alto, CA: Electric Power Research Institute.

Sjostrom, K., Chen, G., Yu, Q., Brage, C., & Rosen, C. (1999). Promoted reactivity of char in co-gasification of biomass and coal: Synergies in the thermochemical process. *Fuel*, *78*(10), 1189-1194.

Smith, I. (2001). *Potential for economic greenhouse gas reduction in coal-fired power generation.* London, England: IEA Clean Coal Centre.

Smith, I., & Rousaki, K. (2002). *Prospects for co-utilization of coal with other fuels − GHG emissions reduction.* London, England: IEA Clean Coal Centre.

Song, W., Sun, Y., Wu, Y., & Zhu, Z. (2011). Measurement and simulation of flow properties of coal ash slag in coal gasification. *AIChE journal, 57*(3), 801-818.

Song, W., Tang, L., Zhu, X., Wu, Y., Zhu, Z., & Koyama, S. (2010a). Effect of coal ash composition on ash fusion temperatures. *Energy & fuels, 24*(1), 182-189.

Song, W., Tang, L., Zhu, X., Wu, Y., Zhu, Z., & Koyama, S. (2010b). Flow properties and rheology of slag from coal gasification. *Fuel, 89*(7), 1709-1715.

Speight, J. (1994). *The chemistry and technology of coal.* (2nd ed.). New York, NY: Marcel Dekkar.

Speight, J. (2005). *Handbook of coal analysis.* Hoboken, NJ: John Wiley and Sons.

Speight, J. (2008). *Synthetic fuels handbook: Properties, process, and performance.* New York, NY: McGraw-Hill.

Standish, N., Yu, A., & Zou, R. (1991). Optimization of coal grind for maximum bulk density. *Powder technology, 68*(2), 175-186.

Taulbee, D. (2012). *U.S Patent Application Pub. No. US 2012/0317878 A1*. Washington, DC: U.S. Patent and Trademark Office.

Taulbee, D., Neather, J., Patil, D., Sowder, N., O'Daniel, B., & Montross, M. (2010). Combustion of briquettes and fuel pellets prepared from blends of biomass and fine coal. In R. Honaker (Ed.), *International coal preparation congress 2010 conference proceedings*. Littleton, CO: Society for Mining, Metallurgy, and Exploration.

Taulbee, D., Patil, D., Honaker, R., & Parekh, B. (2009). Briquetting of coal fines and sawdust Part I: Binder and briquetting-parameters evaluations. *International journal of coal preparation and utilization, 29*(1), 1-22.

Trechock, J. (1973). *U.S. Patent No. 3,711,318*. Washington, DC: U.S. Patent and Trademark Office.

Tremel, A., Haselsteiner, T., Nakonz, M., & Spliethoff, H. (2012). Coal and char properties in high temperature entrained flow gasification. *Energy, 45*(1), 176-182.

U.K. Department of Trade and Industry, Cleaner Coal Technology Programme. (2002). *Guaranteed bunker flow using the Edinburgh Cohesion Tester, Case study 008,* London, England.

van Heek, K., & Muhlen, H. (1987). Effect of coal and char properties on gasification. *Fuel processing technology, 15*(1), 113-133.

van Heek, K., & Muhlen, H. (1985). Aspects of coal properties and constitution important for gasification. *Fuel, 64*(10), 1405-1414.

Voitkevich, O., Kabo, G., Blokhin, A., Paulechka, Y., & Shishonok, M. (2012). Thermodynamic properties of plant biomass components. Heat capacity, combustion energy, and gasification equilibria of lignin. *Journal of chemical and engineering data, 57*(7), 1903-1909.

Waitzman, D., Faucett, H., Kindahl, E., Tomlinson, S., & Nichols, D. (1975). *Evaluation of fixed-bed, low-BTU coal gasification systems for retrofitting power plants*. Palo Alto, CA: Electric Power Research Institute.

Wang, H., Zhu, S., Bai, Z., & Yang Y. (2011). Effect of heat treatment on water resistance of lignite briquettes. *Power and energy engineering conference (APPEEC)*, 2011 Asia-Pacific, 1-3.

Weast, R. (Ed.) (1960). *Handbook of chemistry and physics.* Cleveland, OH: The Chemical Rubber Company.

White, D. (1999). *U.S. Patent No. 5,916,826*. Washington, DC: U.S. Patent and Trademark Office.

Yin, R., Liu, R., Wu, J., Wu, X., Sun, C., & Wu, C. (2012). Influence of particle size on performance of a pilot-scale fixed-bed gasification system. *Bioresource technology, 119*(1), 15-21.

Zhou, J., Masutani, S., Ishimura., Turn, S., & Kinoshita, C. (2000). Release of fuel-bound nitrogen during biomass gasification. *Industrial & engineering chemistry research, 39*(3), 626-634.

Chapter 3

Briquette Characterization Methods

3.1 Abstract

A major limitation to industrial utilization of coal-biomass briquette feedstocks is the absence of standard methods to characterize important physical and mechanical properties of coal-biomass briquettes. To address this challenge, a detailed review of briquette properties was conducted to determine the most important properties for characterization of coal-biomass briquettes. The briquette properties that were identified as most significant are: (1) tensile strength, (2) crushing strength, (3) elasticity, (4) mechanical durability, (5) attritability, (6) friability, (7) water content, (8) particle density, (9) bulk density and (10) water resistance. Crushing strength and mechanical durability appear to be the most important of these properties, and thus should be measured for all experimental and industrial coal-biomass briquette formulations. The other identified properties are still very important and should be considered in detailed evaluations of coal-biomass briquettes when requested by a client or customer. Experimental evaluations were conducted to adapt, evaluate and refine established methods that appeared suitable for coal-biomass briquette evaluations by directly testing coal-biomass briquettes and analyzing the results. Additionally, work was conducted to develop novel characterization methods to quantify briquette properties when suitable established methods were not applicable or available. Recommendations are provided for specific methods and procedures to characterize coal-biomass briquettes based on the results of this study.

3.2 Introduction

3.2.1 Problem Statement

Co-utilization of biomass with coal in existing coal-fired facilities presents a unique opportunity to reduce greenhouse gas emissions and increase energy production from renewable resources. Significant interest in this opportunity has led to more than 150 coal-fired power stations across the world co-firing biomass with coal on a commercial or trial basis as of 2009 (Fernando, 2009). These co-firing experiences have revealed a number of technical challenges including upstream issues, such as biomass availability, transportation, storage, and handling, as well as problems encountered during energy conversion, such as fouling, corrosion, inconsistent feeding and segregation (Basu et al., 2011; Sami et al., 2001). Recent studies suggest that many of these challenges can be mitigated by reconstituting coal-biomass mixtures into larger particles. Specifically, roll press briquetting has been investigated to produce homogeneous, free-flowing feedstocks that minimize handling and segregation problems often encountered with combustion and gasification systems (Taulbee et al., 2010; Honaker et al., 2005). However, a major limitation to industrial utilization of these feedstocks is the absence of standard methods to characterize important physical and mechanical properties of coal-biomass briquettes.

3.2.2 Briquette Properties

3.2.2.1 Strength and Durability

The most important and widely used indicator of briquette quality is the strength of bonds between particles (Pietsch, 2002). The only scientifically defined method to characterize the strength of briquettes that provides information on the fundamental nature of interparticle bonds is tensile strength measurement. Tensile strength is defined as the tensile force at failure divided by the cross-sectional area of the briquette. In cases where the briquette does not have a uniform shape, the area of the failure plane that results from this test can be used in place of cross-sectional area. Universal equations and theoretical models for approximation of the tensile strength of briquettes is discussed in detail by Pietsch (2002).

In practice, the tensile strength of briquettes can be accurately and reproducibly measured with a variety of specially designed and general purpose devices. Typically these devices are comprised of three main components for (1) gripping the sample, (2) applying a deforming load and (3) measuring the applied deforming load (Capes, 1980). Tensile strength measurement devices can include other features to measure deformation and peak load during testing, which can provide additional information about the strength and durability of particle bonds within a briquette. However, there is no standard device or procedure for measuring tensile strength due to the many different shapes and sizes of briquettes. In any case, the major issue concerning tensile strength measurement is the difficulty involved in mounting and gripping individual briquettes without impacting the strength or integrity of the sample. Due to this difficulty, tensile strength measurement is rarely used to characterize briquettes in laboratory and industrial applications. Instead, a wide variety of industry-specific methods have been developed to simulate the forces that briquettes are subjected to during handling, transportation and storage. Unfortunately, the results obtained from these types of tests are empirical and not theoretically predictable because the fundamental failure mechanisms are not understood. Nonetheless, these types of strength and durability measurements are important to consider because of their simplicity and industrial acceptance.

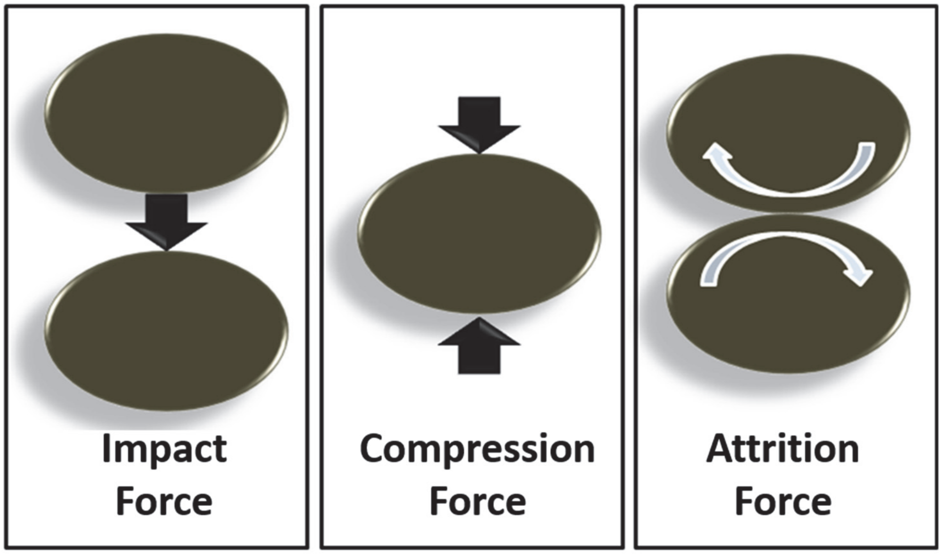


Figure 3-1. Forces briquettes encounter in handling, storage and transportation

Over the past several decades, researchers involved in the development of fuel briquette formulations and processes have reached a consensus regarding the most important physical properties that should be measured to indicate the quality of briquettes. The identified physical properties are friability, crushing (or break) strength, and attritability (Taulbee et al., 2010; Honaker et al., 2005; Richards, 1990; Eckerd, 1967; Moore, 1957; Prostel, 1953; Boley & Rice, 1949). The measurement of these three parameters can be used to indicate the extent to which briquettes will degrade during handling, transportation and storage. Briquettes continually experience impact forces, compression forces and attrition forces from production to utilization (Figure 3-1). Impact forces cause sudden breakage into small pieces from a sudden impact. These forces are encountered when briquettes drop in stockpiling, at conveyor transfer points and from bins and chutes. Friability is the term used to describe the tendency of an object to resist impact forces. Briquettes can be crushed by compression forces encountered in bins, stockpiles and railcars from the load applied by other briquettes. Attrition is defined as wearing or grinding down by friction. Briquettes are subjected to attrition forces during transportation and at loading and unloading points.

Although researchers generally agree on the most important physical properties concerning briquette strength and durability, specific test methods to quantify these parameters are highly variable. It is common for researchers to independently develop assessment procedures appropriate to the nature of the particular investigations performed at their laboratories. For example, many researchers have designed assessment procedures for attritability and friability to mirror existing ASTM procedures for coal and coke, yet there is still very little consistency between the procedures employed at separate laboratories.

The only documented procedures that have been used to quantify the durability of coal-biomass briquettes are those that have been in use at the University of Kentucky's Center for Applied Energy Research (CAER) over the last decade. Taulbee et al. (2010) and Patil et al. (2009) describe methods to quantify the crushing strength and attritability of briquettes prepared from blends of biomass and fine coal. Patil et al. (2009) and Honaker et al. (2005) describe a drop test method that is used to determine the friability of briquettes made from blends of coal fines and sawdust. This method consists of averaging the number of drops to failure for four briquettes dropped from a height of 18 inches onto a steel plate. However, this method was eventually abandoned due to an inherently high level of data scatter and the time consuming nature of these evaluations. In addition, this method requires the technician to visibly determine when the briquette has split into two or more significant pieces, which is a subjective decision that could vary from one person to another.

The importance of friability measurement has also been realized by the coal industry. ASTM D440-07 (2012) describes a drop-shatter test for coal that was established to indicate the extent to which lump coal will break in conventional transit and handling operations. This standard specifies dropping 50 kilograms of coal from a box equipped with a false bottom that is positioned six feet above a steel plate. The coal is dropped from the box by releasing the false bottom, recovered from the steel plate and dropped a second time to further break the coal. The broken coal is then hand screened through nested sieves (8, 6, 4, 3, 2, 1½, 1, ¾, ½, ¼, and ⅛ inch apertures). The results are reported as the mass percentage in each size class and the friability of each size class.

Taulbee et al. (2010) and Patil et al. (2009) describe a method to measure briquette crushing strength using either a Mark-10 EG-200 force gauge (200 lb_f capacity) or a Lloyd Instruments LRX Plus load cell (1,000 lb_f capacity). Each gauge is mounted to an automated test stand and equipped with a 0.75-inch diameter plunger which travels downward at a rate of one inch per minute. This ability to control the rate of loading is very important to ensure the accuracy and reproducibility of test results (Capes, 1980). The force gauges are configured with a break detect feature which stops the movement of the plunger once the applied force drops to 95 percent of the maximum force attained during the test. The plunger then reverses direction and the maximum force attained during the test is designated as the "compressive strength" of the briquette. Measurements are recorded along the axis used to apply force during briquette formation and reported values represent the average of a minimum of 15 measurements. Values less than 50 lb_f are classified as poor, between 50 and 100 lb_f as marginal, between 100 and 150 lb_f as good, and greater than 150 lb_f as excellent. Although the measurement recorded following this procedure provides important information regarding the strength of briquettes, the use of the term 'compressive' strength is not scientifically valid (Pietsch, 2002). A more appropriate term for this type of characterization method is crushing strength.

This test procedure can be easily adapted to measure the elasticity of individual briquettes, which is directly related to the application of compression forces. The elasticity of an object is its tendency to return to original shape after application of a deforming load (Sadd, 2009). When an elastic object is subjected to an external deforming load, the internal structure of the object opposes the deformation, and after the force is removed, restores the object to its original size and shape. Elasticity of a material can be expressed according to various elastic moduli, such as Young's modulus, shear modulus and bulk modulus. Each of these values are indicative of the inherent stiffness of a material for different types of deformation. For instance, the shear modulus applies to deformation in shearing and the Young's modulus applies to deformation that results from uniaxial compression or extension. The elasticity of many materials is defined by the linear relation between stress and strain, known as Hooke's law, which is described by:

$$F = -kx \qquad \text{(Eq. 3-1)}$$

where F is the force applied to an object, x is the resultant internal displacement of the object, and k is the rate or spring constant, which is an inherent material property. Due to the simplicity of this relationship, this appears to be a good approach to measure the elasticity of coal-biomass briquettes.

Taulbee et al. (2010) and Patil et al. (2009) also describe a method to measure forces that coal-biomass briquettes encounter in handling, and transportation, which is considered a measure of attritability. Following this procedure, 20 to 25 briquettes (approximately 200 grams) are placed into a 12-inch diameter Plexiglas cylinder equipped with three, 2-inch lifters and tumbled for five minutes at 40 rotations per minute. The briquettes are then removed from the cylinder and screened through a 4.75-millimeter (U.S. Standard 4 mesh) sieve in a Ro-Tap sieve shaker for two minutes. The attrition index (A_I) is calculated by:

$$A_I = m_r / m_i \tag{Eq. 3-2}$$

where m_r is the mass of briquettes retained on the 4.75-millimeter sieve and m_i is the initial mass of the briquettes prior to testing. By this method, attrition indices less than 0.80 are considered poor, between 0.80 and 0.90 are considered marginally acceptable, between 0.90 and 0.95 are considered good and greater than 0.95 are considered excellent. This method is a good measure of briquette durability but it is not a measure of true attritability. Attrition is defined as wearing or grinding down an object by friction, and this test method incorporates impact forces in addition to attrition forces. Therefore, this test method will be referred to as "mechanical durability" from this point forward to conform with the terminology used in EN 15210-2 (2010), which presents a standard method for determining the mechanical durability of biomass briquettes by tumbling in a similar device. However, an additional method to measure the true attritability of coal-biomass briquettes should still be considered. In addition to these important properties indicative of briquette quality, there are several other feedstock properties that should be considered for co-firing processes.

3.2.2.2 Moisture Content

Moisture content is an important property because the evaporation of moisture during energy conversion consumes a significant amount of the deliverable energy in a feedstock. Therefore, moisture content must be known to properly design a system for minimal energy loss (Basu, 2010). Determination of coal-biomass briquette moisture content is complicated by its presence in two separate forms: surface (free) moisture and inherent (equilibrium) moisture. As the name implies, surface moisture is the moisture present on the surface of the coal or biomass particles, which is ordinarily deposited during processing, transportation and storage. In contrast, inherent moisture is the moisture absorbed within the coal matrix or biomass cell walls (Speight, 2005). Total moisture is defined as the sum of the surface and inherent moisture and can be expressed on a wet basis or a dry basis. The wet basis moisture content of coal and biomass is calculated as:

$$M_{wet} = 100\left(\left(m_{wet} - m_{dry}\right)/m_{wet}\right) \tag{Eq. 3-3}$$

where M_{wet} is the wet basis moisture content expressed as a percentage, m_{wet} is the wet weight and m_{dry} is the dry weight (Basu, 2010). The dry basis moisture content is calculated as:

$$M_{dry} = 100\left(\left(m_{wet} - m_{dry}\right)/m_{dry}\right) \tag{Eq. 3-4}$$

where M_{dry} is the dry basis moisture content expressed as a percentage. Finally, the wet basis and dry basis moisture contents are related as:

$$M_{dry} = M_{wet}/(100 - M_{wet}) \tag{Eq. 3-5}$$

ASTM D3302/D3302M-12 (2012) specifies a standard procedure for determining and reporting the total moisture in coal. In this method, coal samples are dried at 107 ± 3 degrees Celsius in a drying oven until constant mass is achieved. Constant mass is defined as a change in mass less than or equal to 0.1 percent of the total loss in mass over a period of one hour. The total moisture of the coal sample (M) is calculated by:

$$M = [R(100 - ADL)/100] + ADL \tag{Eq. 3-6}$$

where R is the residual moisture weight percent and ADL is the air dry loss weight percent, which is calculated as the loss in weight in air drying divided by the gross sample weight.

Similarly, ASTM E871-82 (2006) specifies a method for determining and reporting the moisture content of wood fuels, wherein a sample is dried in an oven at 103 ± 1 degrees Celsius until the total weight change of the sample varies less than 0.2 percent over a period of two hours. The moisture content of wood fuels (M) is calculated by:

$$M = 100 \times \left(m_i - m_f\right)/(m_i - m_c) \tag{Eq. 3-7}$$

where m_i is the initial sample mass, m_f is the final sample mass and m_c is the mass of the drying container. Finally, EN 14774 (2009) specifies a method for determining and reporting the total moisture content of solid biofuels. In this method, biofuel samples are dried at 105 ± 2 degrees Celsius in a drying oven until constant mass is achieved. Constant mass is defined by this standard as a change in mass less than or equal to 0.2 percent of the total loss in mass over a period of one hour. The total as-received moisture content (M_{ar}) of solid biofuels is calculated by:

$$M_{ar} = 100 \times (m_2 - m_3 + m_4)/(m_2 - m_1 + m_4) \qquad \text{(Eq. 3-8)}$$

where m_1 is the mass of the empty container, m_2 is the mass of the drying container and sample before drying, m_3 is the mass of the drying container and sample after drying and m_4 is the mass of the moisture associated with packing. It is often useful to report moisture content as a fraction rather than a percentage. In such a case, the term 'water content' is used to describe the amount of water present in a sample of interest. Water content (w) is calculated by:

$$w = m_w/m_s \qquad \text{(Eq. 3-9)}$$

where m_w is the mass of water in the sample and m_s is the mass of dry solids. This relationship is particularly useful when examining the relationship between the water content and density of compacted solids. Thus, the total amount of water present in coal-biomass briquettes will be calculated by Equation 3-9 and reported as water content throughout the remainder of this study.

3.2.2.3 Particle and Bulk Density

Density is another important property to consider for briquette production and utilization. This property is particularly important when sizing a gasifier and feed conveyor to meet desired production. Density must also be considered for operations upstream of the gasifier such as fuel transportation, bulk handling and storage (Graboski & Bain, 1981). The density of coal-biomass briquettes can be reported as particle density and bulk density, depending on the method that the volume of the material is calculated and reported. Particle density (or apparent density) of briquettes is a measure of the mass per unit volume occupied by individual briquettes, including pores and cracks (Mahajan & Walker, 1978). This property is particularly important for briquettes and other agglomerates because strength and durability typically increase with particle density (Pietsch, 2002). To calculate particle density, the total mass is divided by the external volume of the briquette (Basu, 2010).

For regularly shaped particles, stereometric methods can be used to approximate the external volume of a sample to calculate particle density. In contrast, the density of irregularly shaped particles can be determined by liquid or solid displacement methods. Density determination by solid displacement can be accomplished with a powder pycnometer, in which the apparent volume of a sample is determined by the displacement of a powder. Liquid displacement methods (hydrostatic and buoyancy) are based on the Archimedes principle, which states that the buoyancy of an object immersed in a fluid is equal to the weight of the fluid that the body displaces. According to the hydrostatic method, the mass of liquid displaced by a sample is recorded and particle density (ρ_p) is calculated by:

$$\rho_p = (m_{air}/m_{dis})\rho_w \qquad \text{(Eq. 3-10)}$$

where m_{air} is the weight of the sample in air, m_{dis} is the weight of the liquid displaced by the sample and ρ_w is the density of the liquid. In the buoyancy method, the buoyancy of a sample is determined by measuring the difference between the mass of the sample in air and the apparent mass of the sample while submerged in a liquid of known density. By this method, particle density (ρ_p) is calculated by:

$$\rho_p = (m_{air}/(m_{air} - m_w))\rho_w \qquad \text{(Eq. 3-11)}$$

where m_{air} is the weight of the sample in air, m_w is the weight of the sample in liquid and ρ_w is the density of the liquid. According to Rabier et al. (2006), liquid displacement methods are more accurate and precise than stereometric methods for the determination of the particle density of fuel briquettes, which often vary in size and shape.

A standard method for measuring the particle density of biomass pellets and briquettes using the buoyancy method is presented in EN 15150 (2011). This standard describes an apparatus and procedures to calculate the particle density of pellets (diameter ≤ 25 millimeters) that is easily adaptable to coal-biomass briquette evaluations. The apparatus consists of a balance, a density determination rig and a glass beaker (Figure 3-2). The density determination rig consists of a bridge platform, a supporting frame and a submergence tray. The supporting frame rests on the weight cell of the balance and the bridge platform is placed over the supporting frame and the balance so that neither are loaded by the bridge. The glass beaker is filled with water, placed on the bridge platform and the submergence tray is hung from the supporting frame into the glass beaker. The bottom of the submergence tray must have perforated openings to allow liquid to fill the dish from below during submergence. In addition, the submergence tray must be positioned so that it does not touch the bottom or sides of the glass beaker. Typically, brackets can be installed along the top of the supporting frame that form a narrow groove for the submergence tray to rest in place.

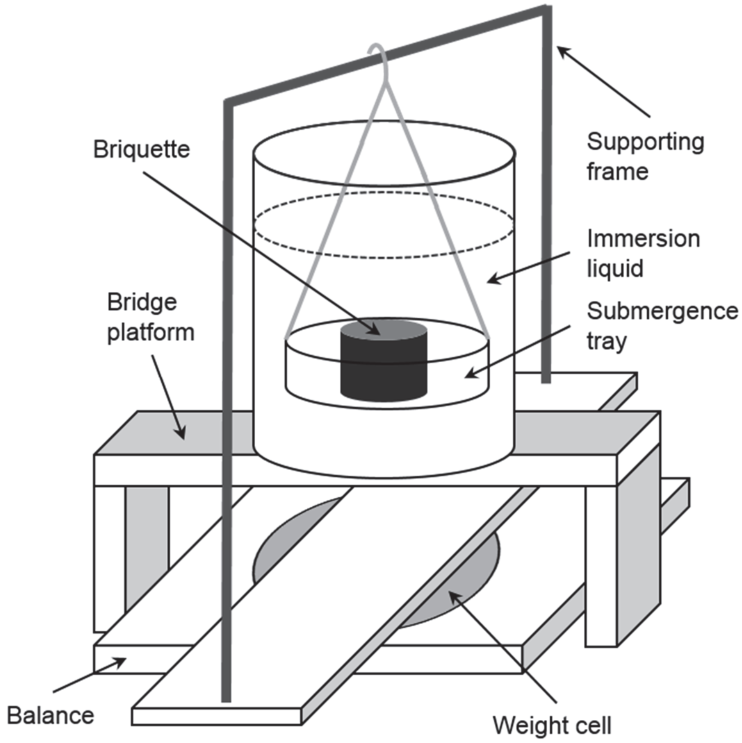


Figure 3-2. Apparatus for measurement of particle density specified in En 15150 (2011)

After assembly of the apparatus is complete, the scale must be tared with the empty submergence tray in place. The mass of four pellets is recorded to the nearest 0.001 grams by placing them on the supporting frame. Next, the submergence tray is removed from the supporting frame and the four pellets are placed in the tray. The tray is then carefully placed back in the groove between the brackets of the supporting frame to submerge the pellets in the liquid. While the pellets are submerged, the mass on the balance display is recorded to the nearest 0.001 grams. Due to the hygroscopic nature of biomass particles, the standard recommends recording the mass reading from the balance immediately after submergence to prevent water absorption and disintegration. The mass should be recorded approximately three to five seconds after placing the tray back on the supporting frame when the reading on the balance display reaches a constant value. Immediately after recording the mass of the submerged pellets, the submergence tray is lifted off of the supporting frame and out of the glass beaker to prevent contamination of the liquid by disintegration of the pellets. This procedure is repeated for nine additional four-pellet samples for a total of ten replications and the moisture content of a portion of the initial sample material is calculated according to EN 14774 (2009). Finally, the particle density of the pellets at a given moisture content (ρ_p) is calculated as:

$$\rho_p = (m_a/(m_a - m_l))\rho_l \quad \text{(Eq. 3-12)}$$

where m_a is the weight of the pellets in air, m_l is the weight of the pellets while submerged in water and ρ_l is the density of the liquid in which the pellets are submerged.

Due to the rapid disintegration of many briquette formulations in water and the surface tension present at the briquette-water interface, it is recommended in EN 15150 that a wetting agent is added to the water and/or a coating agent is applied to the surface of the briquette prior to submergence. The recommended wetting agent is t-Octylphenoxypolyethoxyethanol; polyethylene glycol tertoctylphenyl ether (trade mark Triton X-100®) at a concentration of 1.5 grams per liter of water and the recommended coating agent is paraffin wax with a melting point of 52 to 54 degrees Celsius. However, Rabier et al. (2006) determined that if a coating agent is applied before submersion in liquid, a correction for the amount of the coating agent penetrating the sample is required. A simple assumption that all of the coating agent remains outside of the briquette is unacceptable. Therefore, a correction factor must be derived using a powder pycnometer or similar device. However, the authors did not find any improvement in the precision or accuracy of results when using paraffin wax to coat samples. Therefore, it was concluded that applying the coating agent and correcting for the amount that penetrates the sample is not worth the additional effort.

Bulk density is a measure of the mass per unit volume occupied by a group of particles, including interstitial volume between the particles (Berkowitz, 1994). Many factors influence bulk density, including particle density, particle size and shape, surface and inherent moisture, and degree of compaction (Speight, 2005). The bulk density of coal-biomass briquettes is an important property to consider from a materials handling and storage perspective. This property is used to predict the required size of bins and hoppers and to predict the flow behavior of solids. Contrary to the common misconception in many industries, bulk solids do not simply have loose and packed densities. Rather, they exhibit a range of bulk densities that is a function of the consolidating pressure applied to the material. For highly compressible materials, this range of values is often expressed as a straight line on a log-log plot of consolidating pressure versus bulk density, where the slope of the line is the compressibility of the material. The results obtained from this test can be used to properly design processing, storage and transfer equipment to accommodate desired production capacities.

Several different standard methods are available for measuring bulk density that could be applicable to coal-biomass briquette evaluations. These methods include ASTM D291-07 (2012), which covers the determination of cubic foot weight of crushed bituminous coal, ASTM E873-82 (2013), which covers the determination of bulk density of densified particulate biomass, and ASTM D6683-08 (2008), which covers the measurement of bulk density of powders and other bulk solids as a function of compressive stress. The concept of bulk density measurement is fairly simple in all of these methods: the mass of bulk solids that occupies a standard volume container (i.e. one cubic foot) is measured and the bulk density is calculated as mass divided by volume. This relationship is formally written as:

$$\rho_b = m_t / v_c \tag{Eq. 3-13}$$

where ρ_b is the bulk density, m_t is the total mass and v_c is the total volume of the container. According to ASTM D291-07 (2012), the uncompacted bulk density of coal samples is determined by discharging coal into a one cubic foot box from a conical hopper situated one foot and ten inches above the bottom of the box. Excess material is removed from the box using a straight edge and the bulk density is determined by measuring the weight of the filled box. Similarly, ASTM E873-82 (2006) specifies the measurement of bulk density of densified particulate biomass fuels, in which material is poured into a one cubic foot box from a height of two feet above the top edge. The box is then dropped five times onto a nonresilient surface from a height of six inches and excess material is removed from the box using a straight edge. Finally, the bulk density of the biomass fuel is calculated by dividing the net weight of the sample by the volume of the measuring box.

3.2.2.4 Water Resistance

The absorption of water and subsequent disintegration of coal-biomass briquettes is a major limitation to the design of low-cost storage and transportation systems for co-firing operations. As a result, water resistance is a very important property to consider for the production and utilization of coal-biomass briquettes. Over the years, many methods have been reported in the literature for measuring the water resistance of fuel briquettes. For example, Wright (1911) measured the water absorption tendency of coal briquettes by immersing them in water for varying time periods up to several weeks. The results of this test are reported as the time immersed, the total percentage of water absorbed and the percentage of water absorbed in the first four days of the test. Similarly, Richards (1990) adopted a water immersion test to evaluate the water absorption and disintegration of coal briquettes. By this method, briquettes are immersed in water for thirty minutes and then weighed to measure the mass of water absorbed. The results are reported qualitatively with respect to tendency and time to disintegrate, in addition to percent absorption. Yildirim & Ozbayoglu (2002) measured the water resistance of coal briquettes by immersing briquettes in water for 24 hours. After drying, the percentage of minus ten millimeter material was reported as the water disintegration index. Finally, Taulbee et al. (2009) measured the water resistance of briquettes composed of fine coal and sawdust by submerging four briquettes in water for eight hours, curing overnight in an environmental chamber and measuring the compressive strength the following day. Each of these methods involve submerging briquettes in water for an extended period of time. While these provide a good foundation for further development of water resistance test methods for coal-biomass briquettes, it is unlikely that briquettes will ever be fully submerged in water. Further, it is unlikely that there will ever be an economically feasible method to waterproof briquettes, which is what these multi-hour submergence tests truly measure. Therefore, efforts of this study will be directed toward development of a method to measure water resistance during some type of simulated rain fall event.

3.2.3 Research Objective

Many different methods are reported in the literature to characterize various physical and mechanical properties of coal and biomass feedstocks. However, a major limitation to industrial utilization of coal-biomass briquette feedstocks is the absence of standard characterization methods. Therefore, the objective of this research was to adapt, evaluate and refine established methods that appear suitable for coal-biomass briquette evaluations by directly testing coal-biomass briquettes and analyzing the results. Additionally, work was conducted to develop novel characterization methods to quantify briquette properties when suitable established methods were not applicable or not available. Ultimately, the results of this study will be used to develop a manual of standard test methods and procedures to guide industrial characterization of coal-biomass briquette formulations.

3.3 Experimental

3.3.1 Materials

All briquettes produced for this study were composed of bituminous coal and milled biomass. The two bituminous coals used in this study were obtained from preparations plants in the Appalachian coal basin of the eastern United States. Specifically, the coal samples were obtained from Alpha Natural Resources' Emerald mine preparation plant in Waynesburg, Pennsylvania (referred to as Emerald coal) and Alpha Natural Resources' McClure River preparation plant in McClure, Virginia (referred to as McClure River coal). The Emerald coal was obtained from the clean coal stockpile at the preparation plant and was subjected to further processing prior to briquette production. Size reduction of the Emerald coal was accomplished by successive crushing in a jaw crusher, roll crusher and grinder. The coal was then screened to a top size of one millimeter using a Uniflex two-deck screen, air-dried for one week, split into two-kilogram lots and stored in sealed plastic bags. The moisture content of the coal prior to briquette production was 1.60% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The size distribution of the crushed coal was measured by wet screening and analyzed using the Rosin-Rammler equation (Figure 3-3). Based on this analysis, the Emerald coal was found to have a mass median diameter of 301 microns, a size modulus of 0.43 and a distribution modulus of 1.02. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the Emerald coal (Table 3-1). Notable results of the analyses include a moisture and ash free heating value of 15,268 Btu/lb, an ash content of 9.37% (dry basis) and a sulfur content of 3.04% (dry basis).

The McClure River coal was a clean coal flotation product sampled from a vacuum disk filter in the preparation plant. This coal was air-dried for one week prior to briquette production to reach a total moisture content of 1.10% (dry basis). The size distribution of this coal was also measured by wet screening and analyzed using the Rosin-Rammler equation (Figure 3-3). Based on this analysis, the McClure River coal was found to have a mass median diameter of 73 microns, a size modulus of 0.10 and a distribution modulus of 1.09. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the McClure River coal (Table 3-1). Notable results of the analyses include a moisture and ash free heating value of 15,724 Btu/lb, an ash content of 10.50% (dry basis) and a sulfur content of 0.88% (dry basis).

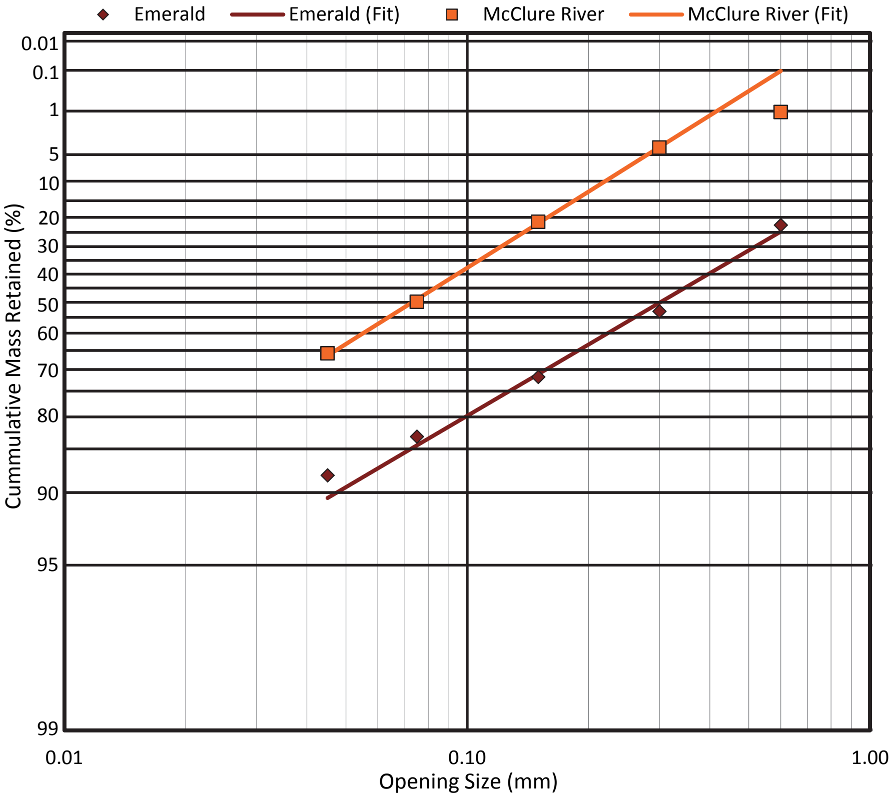


Figure 3-3. Particle-size distribution of bituminous coals

Table 3-1. Chemical properties of coal and biomass feedstocks

Chemical Property	**Emerald Coal**		**McClure River Coal**		**Corn Stover**		**Switchgrass**	
	As Received	**Dry Basis**	**As Received**	**Dry Basis**	**As Received**	**Dry Basis**	**As Received**	**Dry Basis**
Moisture (%)	4.28	--	28.38	--	12.95	--	14.79	--
Ash (%)	8.97	9.37	7.52	10.50	4.36	5.01	2.44	2.86
Sulfur (%)	3.04	3.18	0.63	0.88	0.09	0.10	0.07	0.08
Volatiles (%)	37.59	39.27	20.25	28.28	71.49	82.13	70.37	82.58
Fixed Carbon (%)	49.16	51.36	43.85	61.22	11.19	12.86	12.41	14.56
Carbon (%)	74.26	77.58	58.91	82.26	46.37	53.27	41.59	48.81
Hydrogen (%)	4.91	5.13	6.58	4.75	4.94	5.67	6.32	7.04
Nitrogen (%)	1.39	1.45	1.12	1.56	0.54	0.62	0.35	0.30
Oxygen (%)	3.15	3.29	25.24	0.05	30.75	35.33	41.58	48.57
HHV (Btu/lb)	13,245	13,837	10,079	14,073	7,028	8,073	6,914	8,114
MAF HHV (Btu/lb)	--	15,268	--	15,724	--	8,499	--	8,353

The biomass used for this study was milled switchgrass and corn stover. The switchgrass sample was obtained as large round bales from Piedmont Bioproducts in Gretna, Virginia. The bales were successively processed through a Sperry New Holland tub grinder (Figure 3-4a) and a Bliss Industries hammer mill (Figure 3-4b) equipped with a 6.35-millimeter screen, and stored in a sealed bulk bag prior to use. Particle-size distribution was not determined for the switchgrass sample because previous attempts to collect this information has indicated that the results are skewed due to the elongated particle shape of milled grass (i.e. elongated particles tend to screen differently than round particles). Prior to briquette production the moisture content of the switchgrass was 17.50% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. Ultimate and proximate analyses were conducted on the switchgrass sample with the results presented in Table 3-1. Notable results of the analyses include a moisture and ash free heating value of 8,353 Btu/lb, an ash content of 2.86% (dry basis) and a sulfur content of 0.08% (dry basis).

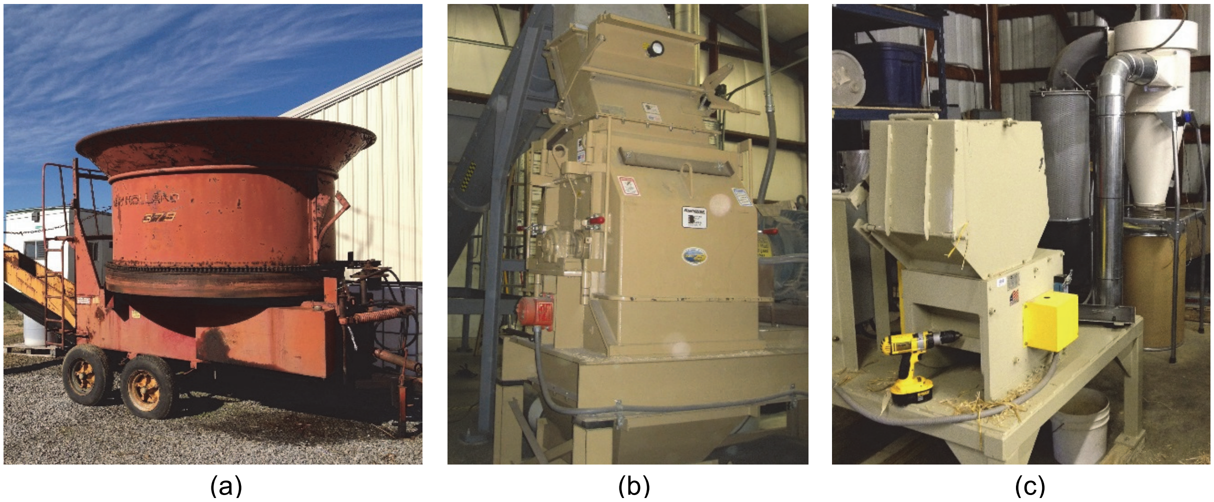
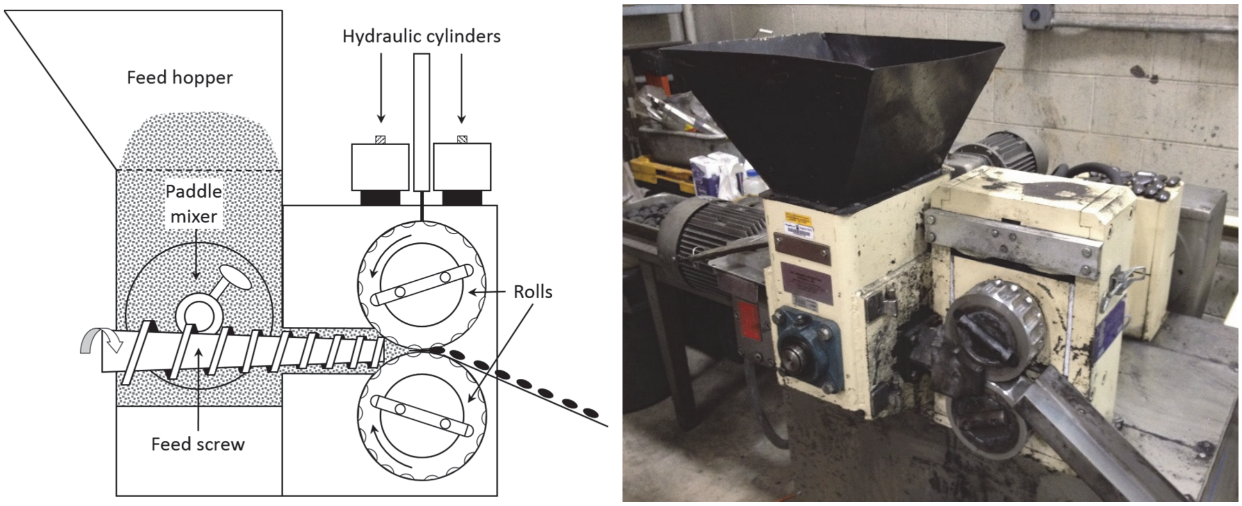

(a) (b) (c)

Figure 3-4. Equipment used for biomass size reduction: (a) tub grinder (b) hammer mill and (c) knife mill

The corn stover used for this study was obtained as large round bales from a farm in Blacksburg, Virginia operated by Virginia Tech. The bales were processed in a Jordan Reduction Solutions knife mill (Figure 3-4c) equipped with a 4.76-millimeter screen and stored in a sealed bulk bag prior to use. Again, particle-size distribution was not determined due to the inherently low accuracy of the procedure. Prior to briquette production the moisture content of the corn stover was 11.35% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The ultimate and proximate analyses results for the corn stover sample are also displayed in Table 3-1. Notable results of the analyses include a moisture and ash free heating value of 8,499 Btu/lb, an ash content of 5.01% (dry basis) and a sulfur content of 0.10% (dry basis).

3.3.2 Briquette Production

Pill-shaped briquettes (approximately 43 x 19 x 14 mm) were produced with a Komarek B-100R laboratory roll press equipped with 13-centimeter diameter rolls. The machine is comprised of two counter-rotating rolls, two hydraulic cylinders, a horizontal tapered screw and a paddle feeder (Figure 3-5). The hydraulic cylinders control the position of the upper roll and thus control the gap between the rolls. The paddle feeder is driven by a fixed speed motor and distributes the material to the horizontal screw that in turn feeds material to the rolls. The counter-rotating rolls and the horizontal screw are driven by variable speed motors, which enable adjustment of the torque applied to the material from the rolls and screw.



(a) (b)

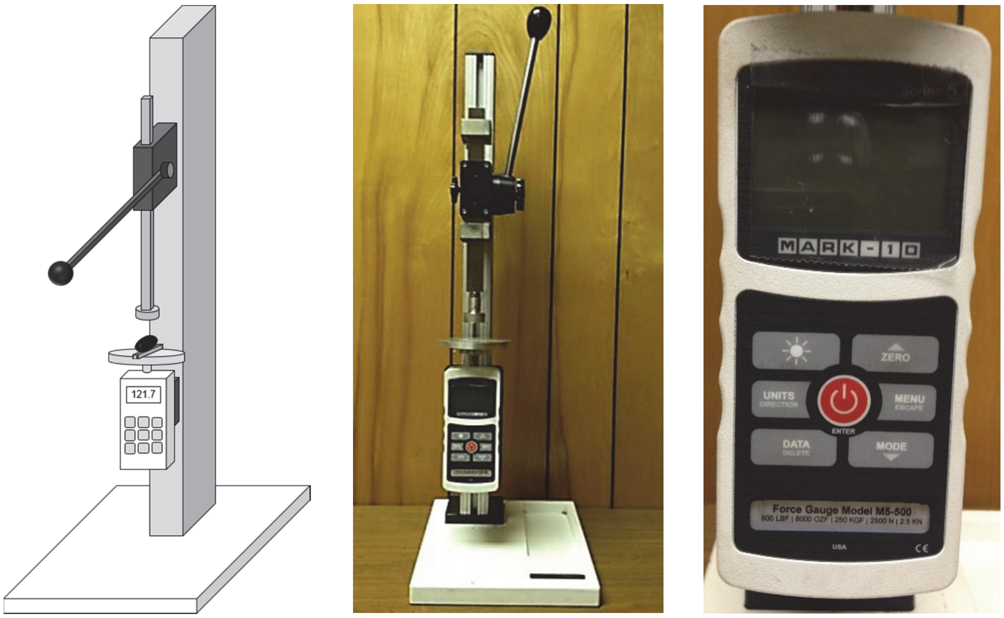
Figure 3-5. Komarek B-100R roll press (a) schematic diagram (modified from Guigon & Simon, 2003) and (b) laboratory installation

For all laboratory experiments, the rolls of the B-100R were driven at a motor speed of 450 rotations per minute with a hydraulic force of 100 kilonewtons. The horizontal screw speed was adjusted during briquette production to maintain a roll torque of approximately 1,500 to 1,800 newton-meters. Two types of briquettes were produced for this study, based on the availability of materials at the time of evaluations: (1) Emerald coal – corn stover briquettes (referred to as EM-CS) and (2) McClure River coal – switchgrass briquettes (referred to as MR-SG). In both cases, the briquettes were produced in five-kilogram batches with 20% biomass (dry basis) and 80% bituminous coal (dry basis). The coal and biomass were mixed for five minutes in a Hobart A200 20-quart commercial mixer and directly co-briquetted in the Komarek B-100R. Immediately after formation, the briquettes were screened across a Sweco vibrating separator equipped with a 0.5-inch screen to remove excess fines. Finally, the briquettes were stored in sealed five-gallon buckets for 24 hours prior to use for evaluating the configuration of several characterization methods.

3.3.3 Evaluation and Refinement Procedures

3.3.3.1 Tensile Strength

A Mark-10 M5-500 digital force gauge with a 500 lb_f capacity and 0.1 lb_f resolution was used to evaluate several indirect tensile strength measurement techniques. As shown in Figure 3-6, the force gauge was fitted with a four-inch diameter aluminum plate and mounted to a Mark-10 TSA750 manual test stand. The manual test stand offers the advantage of lower capital investment, but the precision of such a device is inferior to an automated test stand. For evaluations, the digital force gauge was configured with a break detect feature that stopped data acquisition once the applied force dropped to 95 percent of the maximum force attained during each test. The tensile strength of each briquette was then reported as the maximum force attained during each test. Evaluations were performed on 25 EM-CS briquettes for each indirect tensile test and the tensile strength was reported as the average of the 25 values.



(a) (b) (c)

Figure 3-6. (a) Mark-10 force gauge and test stand schematic drawing, (b) Mark-10 TSA750 manual test stand and force gauge installation and (c) Mark-10 M5-500 digital force gauge

Several different plungers and briquette configurations were evaluated to determine the most significant and repeatable method to indirectly measure the tensile strength of coal-biomass briquettes. Figure 3-7 shows each configuration that was tested with different plunger types and briquette orientations. Initially, two diametrical compression tests were performed on the EM-CS briquettes, in which force was applied between two parallel plates to briquettes along the axis of formation (i.e. the axis between the two roller pockets during formation). The first of these tests was performed with the briquette standing 'tall' with the long axis parallel to the axis of force application during the evaluation (Figure 3-7a). The second test was performed with the briquette standing 'short' with the long axis perpendicular to the axis of force application (Figure 3-7b).

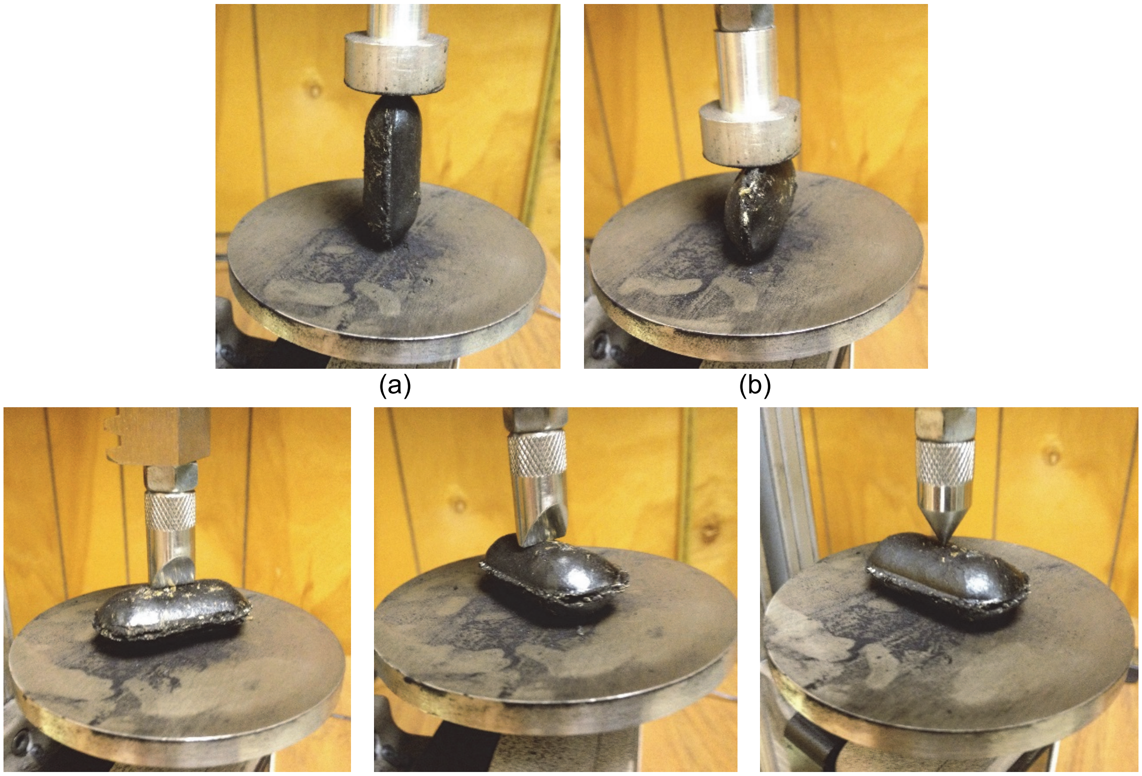

(a) (b)
(c) (d) (e)

Figure 3-7. Briquette orientations and plungers utilized for indirect tensile strength tests: (a) 'tall' diametrical compression, (b) 'short' diametrical compression, (c) parallel wedge indentation, (d) perpendicular wedge indentation and (e) point indentation

In addition, three indention tests were performed by applying a force to the smooth 'pocket' surface of the briquettes. The first two indention tests were performed with a wedge-shaped indention tool that was applied parallel to the long axis of the briquette (Figure 3-7c) and perpendicular to the long axis of the briquette (Figure 3-7d). The final test configuration employed a conical indention tool (Figure 3-7e) to apply a point load to the center of briquettes. Results of these evaluations are presented in Section 3.4.1.

3.3.3.2 Crushing Strength

To evaluate and refine the crushing strength test method reported by Taulbee et al. (2010) and Patil et al. (2009), the Mark-10 digital force gauge and test stand configuration was again utilized. In this instance, the test stand was fitted with a one-inch cylindrical aluminum plunger that was used to apply force to the center of the pocket surface of briquettes until failure (Figure 3-8). The gauge was again configured with a break detect feature that stopped data acquisition once the applied force dropped to 95 percent of the maximum force attained during each test. The crushing strength of each briquette was then reported as the maximum force attained during each test. Evaluations were performed by crushing 50 MR-SG briquettes to determine the precision of results obtained from this method and any improvements that could be made. Results of these evaluations are presented in Section 3.4.2.

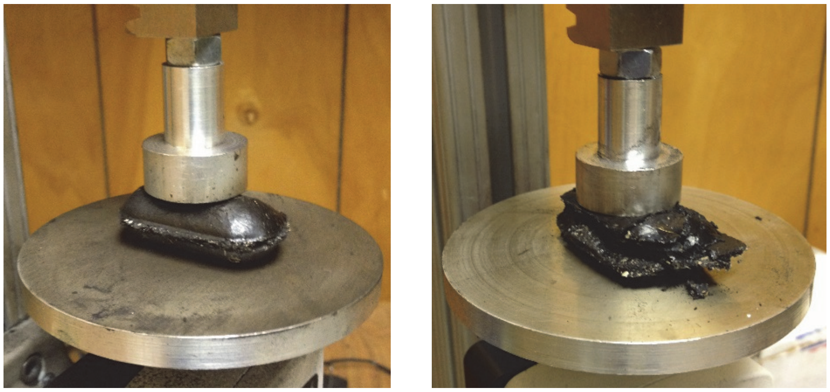

(a) (b)

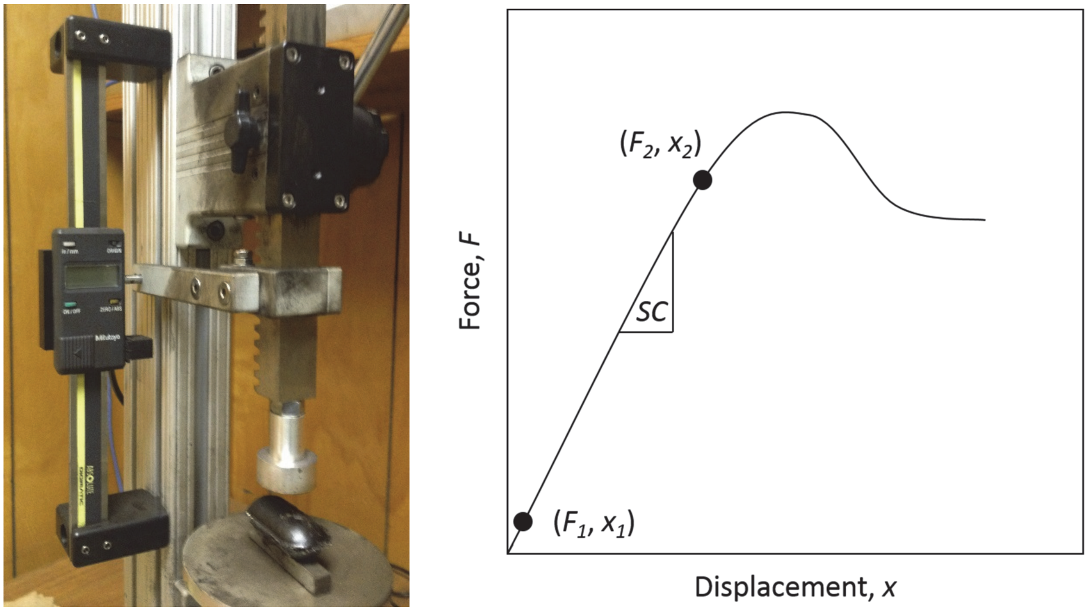
Figure 3-8. Briquette orientation and plunger utilized for crushing strength tests (a) prior to crushing and (b) after crushing

3.3.3.3 Elasticity

To measure the elasticity of coal-biomass briquettes using the fundamental theory presented by Hooke's Law (i.e. Equation 3-1), the same equipment and procedure that was described for crushing strength evaluations was utilized. However, in this instance the test stand was fitted with a Mark-10 ESM001 digital travel display to record the displacement of briquettes while the load was applied by the plunger (Figure 3-9a). This installation was required to determine the spring constant (*SC*) of the briquettes, which is calculated by:

$$SC = (F_2 - F_1)/(x_2 - x_1) \quad \text{(Eq. 3-14)}$$

where F_2 is the maximum force applied during elastic deformation, F_1 is the minimum force applied during elastic deformation, x_2 is the displacement that corresponds with F_2, and x_1 is the displacement that corresponds with F_1 (see Figure 3-9b). These values are obtained from the force versus displacement curve that is produced during testing. The force gauge was configured to record two force and displacement data points per second with the break detect feature activated. To improve the accuracy of readings, an aluminum bar (51 x 8 x 8 millimeters) was placed upon the aluminum plate with each briquette then placed atop and parallel to the bar for testing (the motivation for this approach is discussed in detail in Section 3.4.2).



(a) (b)

Figure 3-9. (a) Mark-10 ESM001 digital travel display fitted to the manual test stand for elasticity tests and (b) force-displacement data point selection example

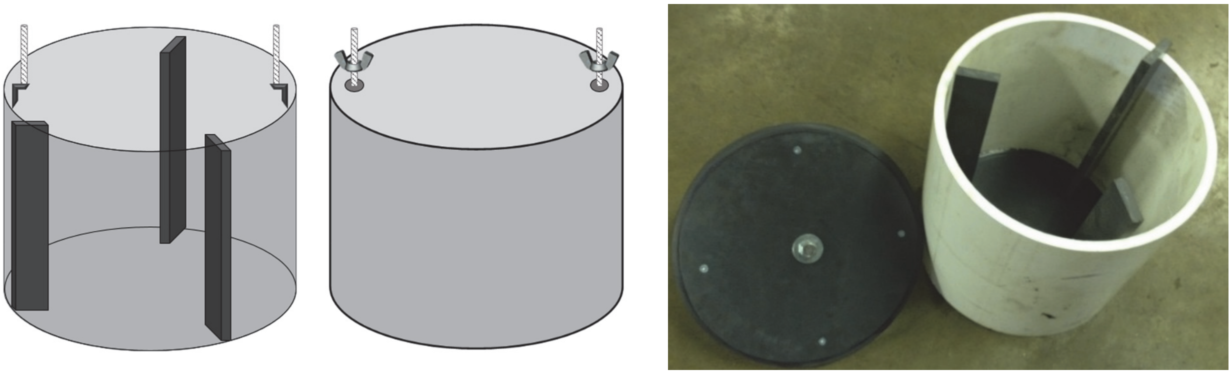
Evaluation of this method was conducted to determine the impact of data point selection on the calculated spring constant values (i.e. selection of F_1 and F_2 from the force-displacement curve in Figure 3-9b). The selection of the (F_2, x_2) data point is complicated because it is often difficult to determine the upper extent of the linear portion of the curve due to the low sampling frequency (i.e. two samples per minute) and the added error from using a manual test stand. Therefore, two separate approaches were evaluated for selection of the (F_2, x_2) data point to determine the method that provides the best combination of accuracy and precision: (1) selection of a force-displacement data point that appears to form the upper extent of the linear portion of the curve (as shown in Figure 3-9b) and (2) selection of the peak force-displacement data point (i.e. yield point). The inherent advantage of the first method is that the calculated spring constant is derived from the elastic deformation (i.e. linear) portion of the force-displacement curve. However, the inherent disadvantage of this approach is the ambiguity of selection of the upper extent of the linear portion of the curve. In contrast, the inherent advantage of the second approach is that the force-displacement data point can be easily selected from identifying the maximum force attained during each individual test. However, the disadvantage associated with this method is that the calculated spring constant values are fundamentally inaccurate because the peak force typically occurs after a period of inelastic deformation that exists beyond the elastic (linear) displacement region. Nonetheless, both methods were evaluated by crushing 25 EM-CS briquettes, recording the two prescribed sets of data points, and calculating the spring constant using Equation 3-14. Finally, each of the 25 values were averaged and the spring constant was reported as the calculated average value. Results of these evaluations are presented in Section 3.4.3.

3.3.3.4 Mechanical Durability

Evaluation of the attritability characterization method reported by Taulbee et al. (2010) and Patil et al. (2009) was performed using a 12-inch diameter PVC cylinder equipped with three 2-inch lifters (Figure 3-10). As previously discussed, this method is a good measure of briquette durability but it is not a measure of true attritability. Therefore, this test method is now referred to as “mechanical durability” to conform to the terminology used in EN 15210-2 (2010) and to differentiate between this briquette characteristic and true attritability. To evaluate the configuration of the mechanical durability test, several series of experiments were designed to determine the influence and optimum conditions of three key process variables. The variables studied were the number of cylinder rotations, the cylinder rotational speed (rpm) and the number of briquettes loaded into the cylinder. For each experiment, MR-SG briquettes were tumbled under prescribed conditions and subsequently screened over a 4.75-millimeter sieve in a Ro-Tap sieve shaker for two minutes. The mechanical durability (MD) of the briquettes was then calculated by:

$$MD = 100 \times \left(m_{final}/m_{initial}\right) \quad \text{(Eq. 3-15)}$$

where m_{final} is the mass of briquettes retained on the 4.75-millimeter sieve and $m_{initial}$ is the initial mass of the briquettes prior to durability testing. Results of these evaluations are presented in Section 3.4.4.



(a) (b)

Figure 3-10. Mechanical durability cylinder (a) schematic drawing and (b) laboratory installation

3.3.3.5 Attritability

Due to the lack any published methods to measure true attritability of briquettes, a novel method was developed to measure the attritability of coal-biomass briquettes. The principle of this method is that a group of briquettes are screened in a Ro-Tap sieve shaker for a prescribed period of time over a specified sieve size. During this screening period in the sieve shaker, the briquettes are subjected to true attrition forces as they continually rub against one another and the inside surface of the sieve. This action produces frictional forces that wear the briquettes down over time. Using this method, the attritability (A) of briquettes is calculated by:

$$A = 100 \times \left(m_{final}/m_{initial}\right) \qquad \text{(Eq. 3-16)}$$

where m_{final} is the mass of briquettes retained on the sieve after the screening period and $m_{initial}$ is the initial mass of the briquettes prior to attritability testing. Optimization of this method was accomplished by conducting evaluations on MR-SG briquettes to determine the ideal configuration of three key variables: (1) the number of briquettes loaded on the sieve during testing, (2) the screening time employed and (3) the sieve size used for screening. Results of these evaluations are presented in Section 3.4.5.

3.3.3.6 Friability

A modified version of the ASTM shatter test device was built to evaluate the applicability of ASTM D440-07 (2012) to characterize the friability of coal-biomass briquettes (Figure 3-11). The machine was built with a PVC box (8 x 8 x 8 inches) equipped with a false bottom that held the briquettes prior to drop testing. The box rests above a one-inch thick, 22.5-inch diameter steel plate with a wooden frame placed on it. The wooden frame (14 inches tall x 15.25 inches long x

15.25 inches wide) is used to contain the briquettes after contact with the steel plate. Evaluations were performed with MR-SG briquettes to maximize the precision and significance of the results obtained from this method by evaluating the influence of various drop heights and the number of briquettes dropped. After two sequential drops the MR-SG briquettes were screened over a 4.75-millimeter sieve in a Ro-Tap sieve shaker for two minutes to determine the friability of the briquettes (F), which was calculated by:

$$F = 100 \times \left(m_{final}/m_{initial}\right) \quad \text{(Eq. 3-17)}$$

where m_{final} is the mass of briquettes retained on the 4.75-millimeter sieve and $m_{initial}$ is the initial mass of the briquettes prior to friability testing. Results of these evaluations are presented in Section 3.4.6.

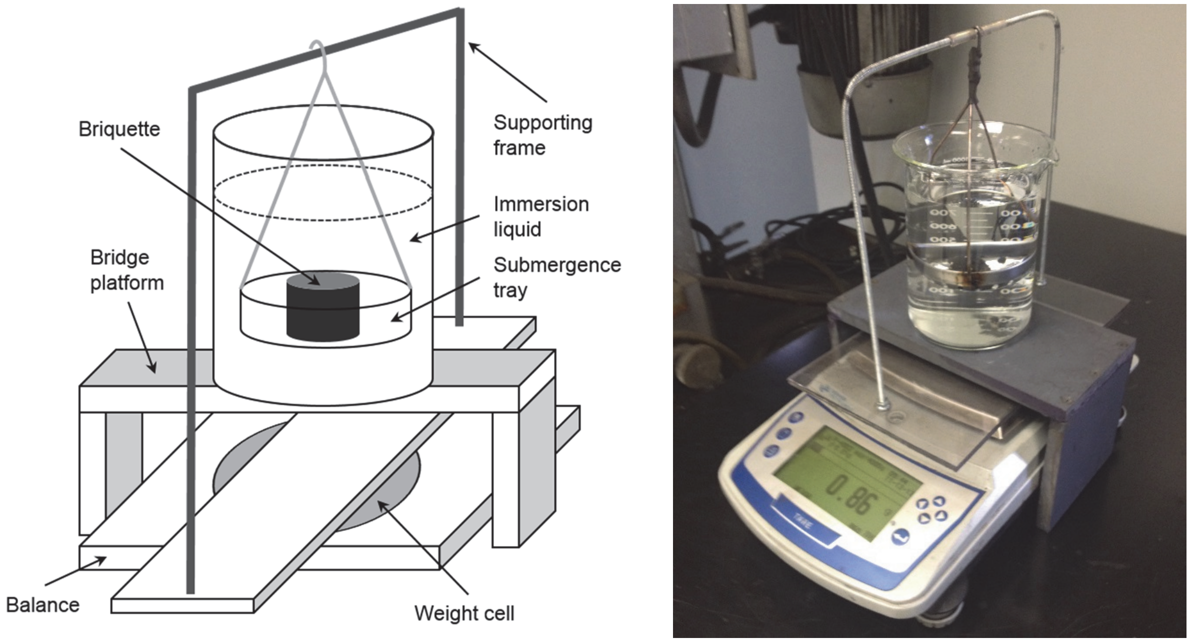
Figure 3-11. Modified ASTM shatter test device for friability testing

3.3.3.7 Water Content

Since each of the identified standard methods for determining water content are based on the same fundamental principle and employ very similar methods, the decision was made to measure the water content of coal-biomass briquettes by drying at 105 ± 4 degrees Celsius in a drying oven for 24 hours. To evaluate the precision of such measurements, the water content of six EM-CS briquettes was calculated after 24 hours using Equation 3-9, and the standard deviation of the results was determined. To evaluate the accuracy of water content measurements after a period of 24 hours, the six briquettes were placed back into the oven for an additional two hours to determine the change in the calculated water content value with additional drying time. After this period of time, the briquettes were reweighed and the water content was again calculated. Finally, the results of this second measurement (i.e. 26 hour drying period) and the 24 hour drying period were compared. These results are presented and discussed in Section 3.4.7.

3.3.3.8 Particle Density

To measure particle density of briquettes, an apparatus was constructed to record the apparent weight of an individual briquette while submerged in a liquid of known density (Figure 3-12). The design of this apparatus and the procedure followed were adapted from the buoyancy method outlined in EN 15150 (2011). The rig constructed for briquette evaluations is slightly larger than that described in EN 15150, but is composed of the same three major components: (1) a frame that rests on the weight cell of a balance and supports a submergence tray, (2) a submergence tray with perforations in the bottom to allow the liquid to fill the dish, and (3) a bridge platform that supports a glass beaker filled with liquid that overstretches the weight cell of the balance to prevent loading by the beaker. To measure the particle density of briquettes, the scale was tared with the empty submergence tray in place and the mass of individual briquettes was determined by placing them on the supporting frame. Next, the submergence tray was removed from the supporting frame and the briquette was placed in the tray. The tray was then carefully placed back in the groove between the brackets of the supporting frame to submerge the briquette in the liquid. During the first three to five seconds of submergence when the reading on the balance display reached a constant value, the mass on the balance display was recorded to the nearest 0.01 grams. Immediately after recording the mass of the submerged briquette, the submergence tray was lifted off of the supporting frame and out of the glass beaker to prevent contamination of the liquid by disintegration of the briquette.



(a) (b)

Figure 3-12. Particle density apparatus (a) schematic drawing and (b) laboratory installation

The buoyancy of each briquette was calculated by subtracting the sample's apparent mass in water from its measured mass in air. The particle density (ρ_p) is then calculated by:

$$\rho_p = \rho_w \times m_a/(m_a - m_b) \quad \text{(Eq. 3-18)}$$

where m_a is the mass of the briquette in air, m_b is the mass of the briquette in water and ρ_w is the density of the immersion liquid. A number of configurations were evaluated to determine the most accurate and precise method to measure particle density of coal-biomass briquettes. For each configuration, the mass of 12 EM-CS briquettes was recorded in air and apparent mass was measured in water to calculate the average wet particle density, the standard deviation and the relative standard deviation. Initially, water was used as the submergence liquid to determine if any wetting agent or coating was necessary. Next, Triton® X-100 was added to the water at a concentration of 1.5 grams per liter to determine if any improvement could be made by adding a wetting agent. Due to the complexity of continually heating paraffin wax for coating briquettes, an aerosol polyurethane was evaluated instead for its potential applicability. A final set of tests was conducted with the combination of water, Triton® X-100 and the polyurethane. Results of these evaluations are presented in Section 3.4.8.

3.3.3.9 Bulk Density

A major problem with adapting standard bulk density measurement methods to laboratory evaluations of coal-biomass briquettes is the large amount of briquettes required to occupy a one cubic foot container. This corresponds to a substantial amount of materials, which require time-consuming preparation (i.e. crushing, screening and drying) prior to briquette production. As a result, three wooden containers were constructed with varying volumes (0.24 ft^3, 0.50 ft^3, 1.00 ft^3) to determine if a smaller container can be used to obtain accurate bulk density measurements for coal-biomass briquettes (Figure 3-13). Each containers was designed with cubic interior dimensions for simplicity (i.e. 0.24 $ft^3 = 7.5^3$ in^3, 0.50 $ft^3 = 9.5^3$ in^3, 1.00 $ft^3 = 12.0^3$ in^3). For each container size, multiple measurements were recorded to determine the precision of the bulk density results.

Figure 3-13. Boxes of varying size for bulk density measurement: (left) 1 ft^3, (middle) 0.50 ft^3 and (right) 0.24 ft^3

To measure bulk density, EM-CS briquettes were poured into the wooden containers of known mass from a height of two feet above the bottom of the interior of the container. As shown in Figure 3-14a, sufficient material was poured so that the briquettes overflowed the top of the container. Next, a straight edge was used to remove the overflowing material from the top of the container. This was accomplished by swiping the straight edge along the top of the container from left to right, top to bottom, right to left and bottom to top until the straight edge no longer came into contact with any briquettes (Figure 3-14b). The container was then reweighed and the bulk density was calculated by:

$$\gamma = (m_f - m_e)/V_c \qquad \text{(Eq. 3-19)}$$

where γ is bulk density, m_f is the mass of the filled container, m_e is the mass of the empty container and V_c is the volume of the container. This procedure was repeated a minimum of six times to measure the apparent bulk density of the EM-CS briquettes for each container size. Results of these evaluations are presented in Section 3.4.9.

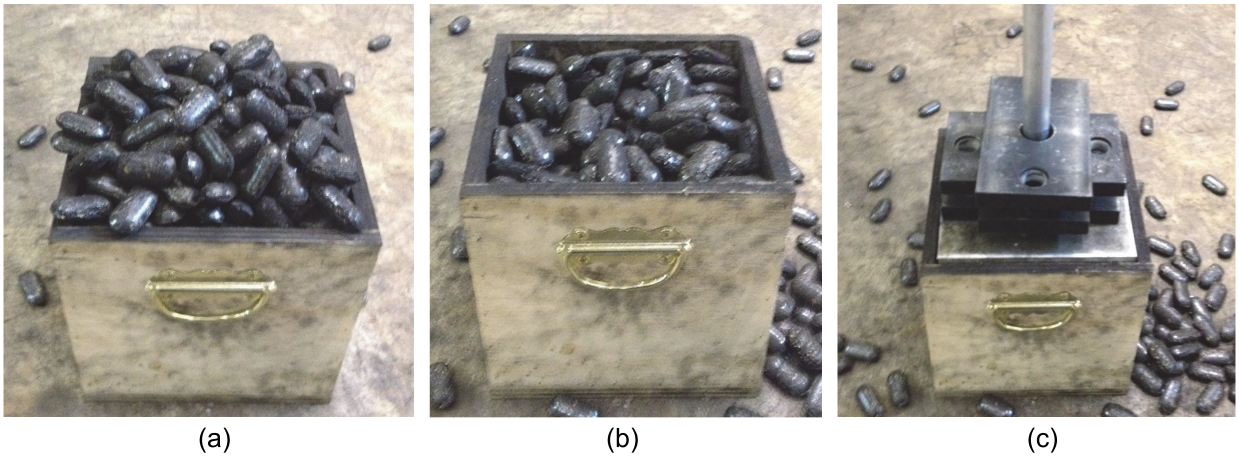

(a) (b) (c)

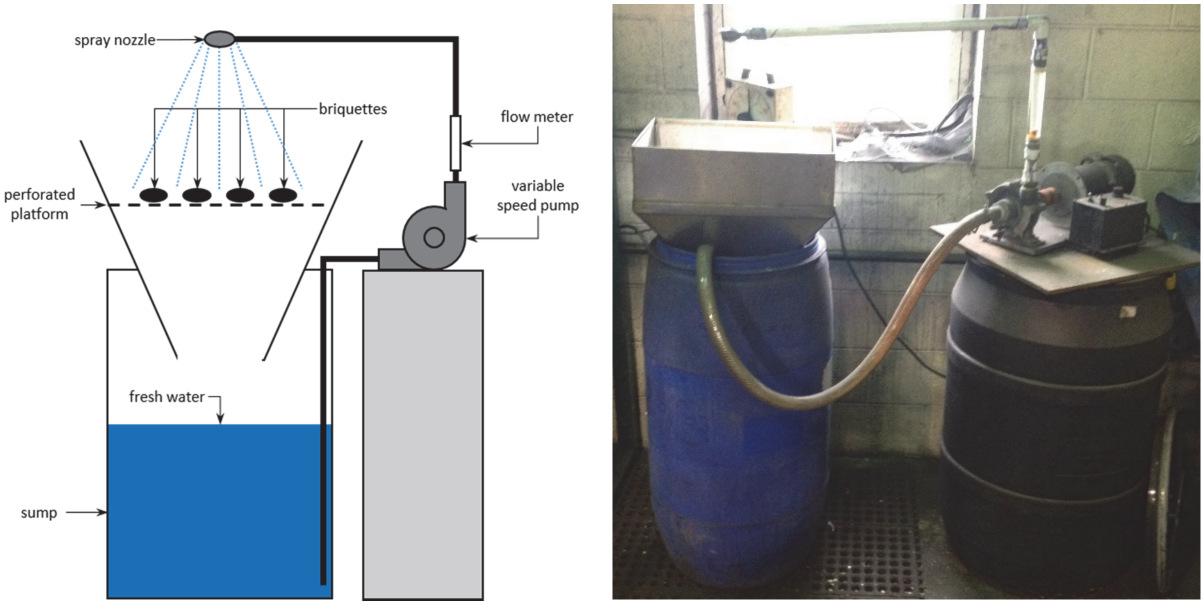
Figure 3-14. (a) Initial briquette overflow for bulk density measurement (b) bulk density container after removing excess briquettes with a straightedge and (c) weight platform assembly for compressibility measurement

Bulk compressibility was measured by applying an increasing consolidation pressure to EM-CS briquettes loaded into the 0.24-ft^3 container. To accomplish this, the briquettes were initially poured into the container from a height of two feet above the bottom of the interior of the container. Next, a straight edge was used to remove the overflowing material from the top of the container as previously described. Weights were then added in five pound increments to a platform that rests on top of the briquettes and fits inside the cubic container as the briquettes are compressed (Figure 3-14c). The container was then topped off with additional briquettes by again pouring from a height of two feed above the bottom of the interior of the container and the straight edge was again used to remove the overflowing material in the same manner described above. To calculate the compressibility of the briquettes, the container was reweighed after each successive five pound addition to determine the apparent change in bulk density with confining pressure. Results of these evaluations are also presented in Section 3.4.9.

3.3.3.10 Water Resistance

A device was constructed to measure the water resistance of coal-biomass briquettes that simulates precipitation that briquettes may encounter during storage and transportation (Figure

3-15). The device consists of a perforated stainless steel platform upon which briquettes are placed. The platform sits above a sump which contains fresh water. A pump was used to cycle the water from the sump through a pipe and out a spray nozzle located approximately 18 inches above the briquettes. The pump was equipped with a variable frequency drive so the flow rate of water onto the briquettes could be controlled. Finally, a flow meter was installed in the pipe to enable the measurement of the water flow rate.



(a) (b)

Figure 3-15. Water resistance apparatus (a) schematic drawing and (b) laboratory installation

Using this device, the water resistance of coal-biomass briquettes was defined as the water absorbed during a specified duration of water spray (i.e. water uptake), which is reported as a percentage of the initial mass of briquettes. To measure water uptake, the mass of a specified number of briquettes was initially recorded. Next, the briquettes were placed on a filter paper which was then placed on the perforated platform of the device (Figure 3-16). The filter paper was used to retain any pieces of the briquettes that become loose during the simulated precipitation that would otherwise wash down into the sump. The pump was then started at a specified speed to achieve a desired flow rate through the spray nozzle. After a specified period of time, the pump was turned off and the filter paper with the briquettes was removed from the perforated platform. Finally, the briquettes were removed from the filter paper and the wet mass of the briquettes was recorded after a period of one minute. The water uptake (*WU*) is then calculated by:

$$WU = 100 \times (m_{wet} - m_{dry})/m_{dry} \quad \text{(Eq. 3-20)}$$

where m_{dry} is the initial mass of the briquettes prior to testing and m_{wet} is the final mass of briquettes after the spraying period.

Figure 3-16. Example of briquette arrangement on filter paper for water resistance measurement

A series of tests were conducted to determine the optimal spray duration, water flow rate and number of briquettes for water uptake evaluations. The first group of tests was conducted on lots of 5, 10, 20 and 40 EM-CS briquettes at a water flow rate of three gallons per minute with a spray duration of 15 seconds to determine the effect of the number of briquettes tested on water uptake measurements. The next series of tests were conducted on lots of five briquettes with spray durations of 5, 15, 30, 60 and 120 seconds at a water flow rate of three gallons per minute to determine the impact of spray duration on water uptake measurements. The final series of tests were conducted on lots of five briquettes with water flow rates of one, two, three, four and five gallons per minute with a spray duration of 15 seconds to analyze the impact of water flow rate on water uptake measurements. Results of these evaluations are presented in Section 3.4.10.

3.4 Results and Discussion

3.4.1 Tensile Strength

The recorded strength values for each of the five indirect tensile strength tests are presented in Figure 3-17. The average force reading was 55.0 lb_f for the tall diametrical compression tests, 53.9 lb_f for the short diametrical compression tests, 130.0 lb_f for the parallel wedge tests, 112.6 lb_f

for the perpendicular wedge tests and 47.8 lb_f for the point indention tests. The average force reading from the point indentation test and the two diametrical compression tests were very similar. In contrast, the results from the two wedge indention tests were very different from the other three tests, yet similar to one another. None of the distributions of results presented in Figure 3-17 closely resemble a normal distribution. However, the results of the tall diametrical compression tests are most similar to a normal distribution, which indicates that this method gives the most precise results. At this point, it is unknown whether or not any of the values obtained from these indirect tensile strength tests fundamentally describe the cohesive strength of individual particles within the briquettes. Nonetheless, it is possible that the true tensile strength of the tested briquettes falls within one of the ranges of similar values (i.e. 47.8-55.0 lb_f or 112.6-130.0 lb_f).

If tensile strength measurement of coal-biomass briquettes is desired in future applications, the tall diametrical compression test would be recommended. However, additional investigations should be conducted to develop a more suitable method to obtain theoretically significant tensile strength results and to determine if any data manipulation could improve the measured results. Although tensile strength is the only material property that describes the fundamental nature of bonds between particles in a material, this property is rarely measured in practical and industrial applications. As a result, a wide variety of industry-specific methods have been developed to simulate the forces that briquettes are subjected to during handling, transportation and storage, which are important to consider because of their simplicity and industrial acceptance.

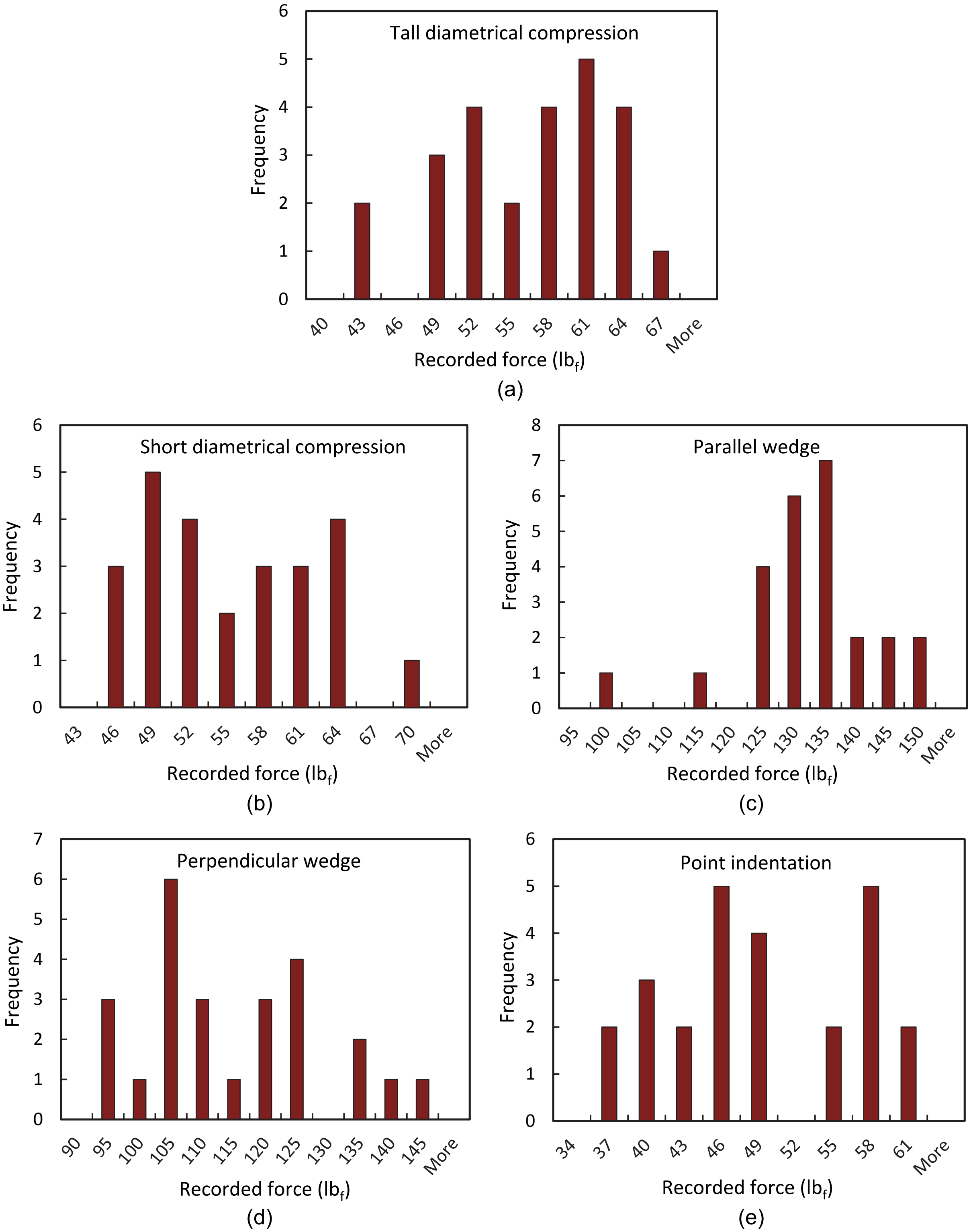


Figure 3-17. Distribution of indirect tensile strength results for (a) point indentation test, (b) parallel wedge indentation test, (c) perpendicular wedge indentation test, (d) tall diametrical compression test and (e) short diametrical compression test

3.4.2 Crushing Strength

To evaluate the precision of the crushing strength test method reported by Taulbee et al. (2010) and Patil et al. (2009) when conducted with a manual test stand rather than an automated test stand, 50 MR-SG briquettes were tested. The distribution of recorded briquette crushing strength values are presented in Figure 3-18. It can be seen that there is considerable scatter in the data and the results do not fit a normal distribution. The crushing strength values ranged from 10.4 to 551.7 lb_f with a mean of 255.0 lb_f and a standard deviation of 171.5 lb_f. The block of 27 data points depicted on the right side of Figure 3-18 represent the large number of briquettes for which the break detect feature of the machine did not detect briquette failure. When failure was not detected by the force gauge, the briquette was further compressed and the value obtained from the test was much higher than the true crushing strength of the briquette.

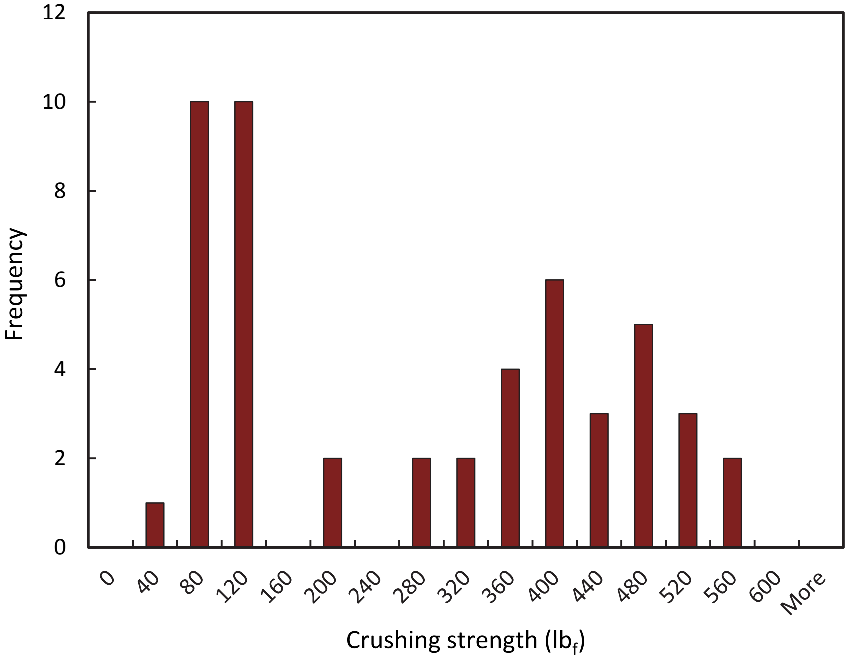


Figure 3-18. Distribution of crushing strength data recorded with the manual test stand

Although it is difficult to see in Figure 3-18, the true distribution of crushing strength values exists between 0 and 200 lb_f. In practice, a technician performing this test would reject the measurements greater than 240 lb_f because the briquette would have visibly fractured prior to the completion of the test (i.e. Figure 3-19). The number of data points that would be rejected is thought to be a function of the elasticity of briquettes. For example, a very inelastic briquette will tend to fail very suddenly once the force applied by the plunger exceeds the load that the briquette can support. In this case, the break detect feature is able to clearly detect when the applied force drops to 95 percent of the maximum force attained during the test. Therefore, very few (if any) data points would be rejected. In contrast, a very elastic briquette will not fail suddenly. Instead, it will compress between the plunger and plate as the force is increased until the briquette is visibly destroyed. Consequently, the applied force never drops to 95 percent of the maximum force attained during the test and the data point must be rejected. This case is particularly apparent with uncured briquettes and briquettes produced with high biomass content.

Figure 3-19. Example of briquette compression beyond the break point with the manual test stand

The constant compression speed of an automated test stand alleviates this problem to a large extent. When using an automated test stand, crushing strengths for coal-biomass briquettes typically exhibit relative standard deviations in the range of 10 to 20 percent. Similarly, the portion of briquettes which do not trigger a break point range from zero percent for most samples to less than 10 percent for worst-case scenarios. This is in stark contrast to the results obtained with the use of a manual test stand, in which a break point was not detected for more than half the briquettes tested. While an automated test stand may improve the sensitivity to break-point detection, such units are expensive and not always readily available. In the absence of such an apparatus, a simple, cost-effective solution was developed to improve the sensitivity to break point detection that can be easily incorporated into any force gauge-manual test stand arrangement. An aluminum bar (51 x 8 x 8 millimeters) was placed on the four-inch diameter aluminum plate with each briquette then placed atop and parallel to the bar for testing (see Figure 3-20a). This configuration was then used with the break detect feature enabled to determine the crushing strength of 50 MR-SG briquettes from the same batch that was tested without the aluminum bar. The distribution of briquette crushing strength values recorded with the new configuration is displayed in Figure 3-21. These values ranged from 19.7 to 232.8 lb_f, with a mean of 114.1 lb_f and a standard deviation of 40.6 lb_f.

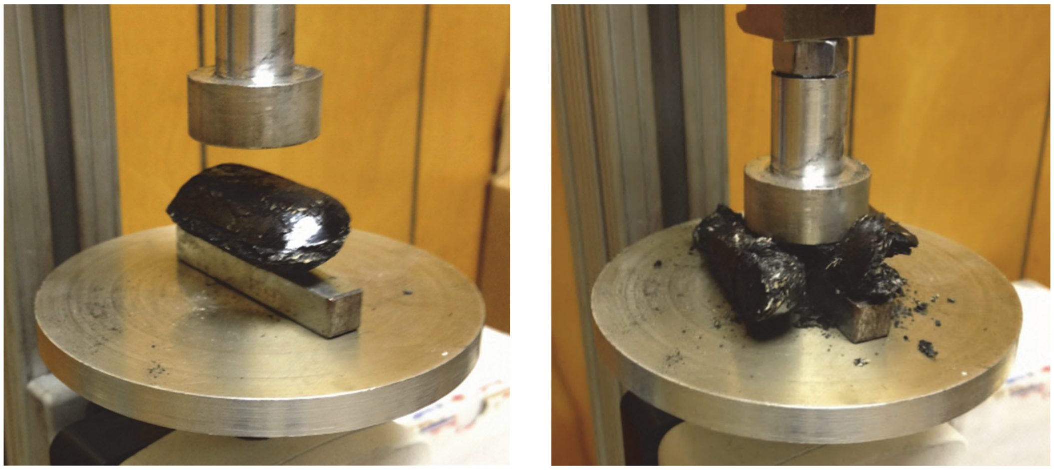

(a) (b)

Figure 3-20. Example of briquette compression with the aluminum bar incorporated to the manual test stand configuration (a) prior to crushing and (b) beyond the break point

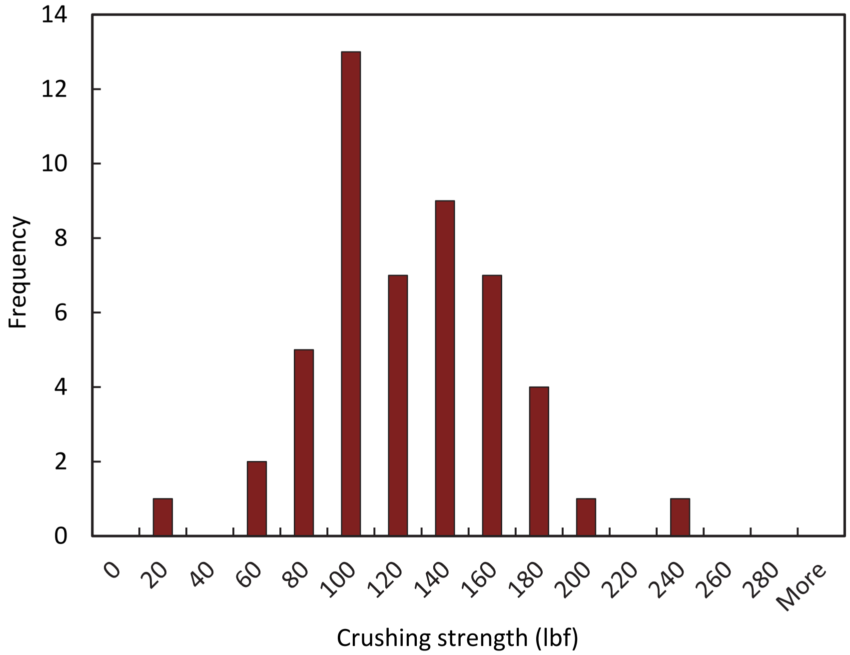
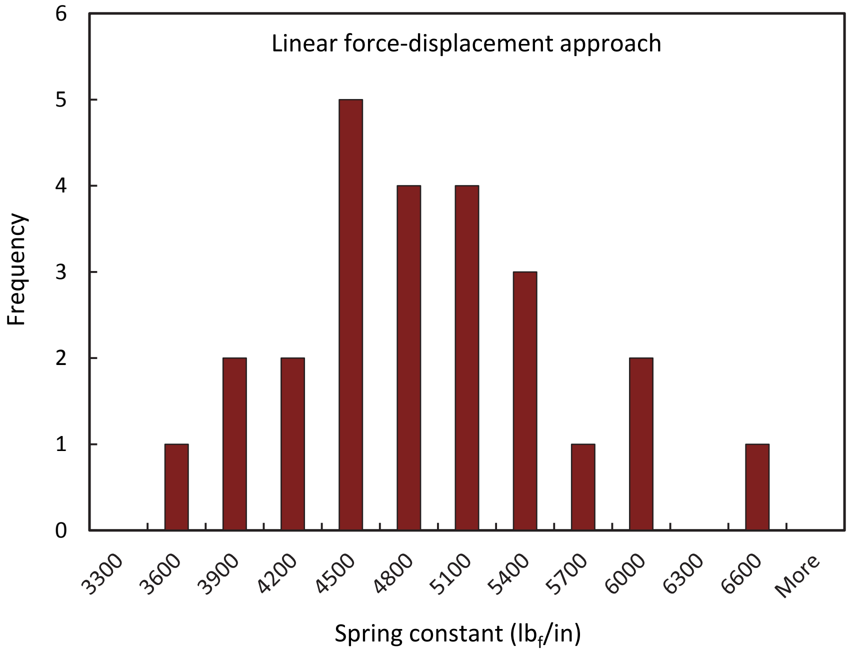


Figure 3-21. Distribution of crushing strength data recorded by incorporating the aluminum bar to the manual test stand configuration

It is evident from Figure 3-18 and Figure 3-21 that the addition of the aluminum bar to the manual test stand configuration resulted in a dramatic increase in the precision of the test results without the rejection of any data points. Specifically, the addition of the aluminum bar reduced the standard deviation of the data by more than 75 percent. This dramatic improvement was realized because the applied force dropped significantly as soon as the briquette reached the break point, as a result of the briquette no longer resting on the aluminum bar (see Figure 3-20b). Figure 3-21 also shows that the crushing strength values fit a normal distribution with the addition of aluminum bar. A similar distribution exists toward the left side of Figure 3-18 for the data obtained without the aluminum bar; however, the data in Figure 3-18 is skewed to lower crushing strength values. This is likely due to the loss of more than half of the data points from the range of true crushing strength values during the tests with the aluminum bar. These results show that this crushing strength method is well suited for coal-biomass briquette evaluations using a manual test stand and an aluminum bar.

3.4.3 Elasticity

A histogram of the results from both sets of elasticity evaluations are provided in Figure 3-22. It is clearly shown by this figure that the spring constant values obtained from the linear force-displacement evaluations (top) closely resemble a normal distribution. In contrast, the spring constants obtained from the peak force-displacement evaluations (bottom) appear to follow a much more random distribution. The result was fairly surprising as the difficulty associated with the selection of the upper extent of the linear portion of the curve did not appear to have any significant impact on the precision of the measurements. As a result of the fundamental significance (i.e. derivation from Hooke’s law) of spring constant results obtained using the linear force-displacement method and the improved precision of the calculated results, the linear force-displacement method appears to be better suited for characterizing the elasticity of coal-biomass briquettes.



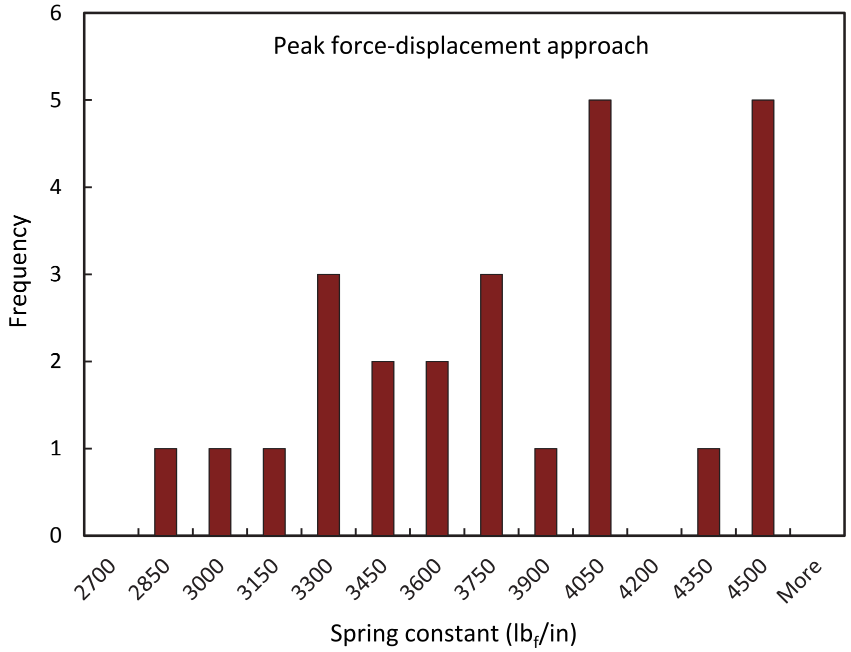
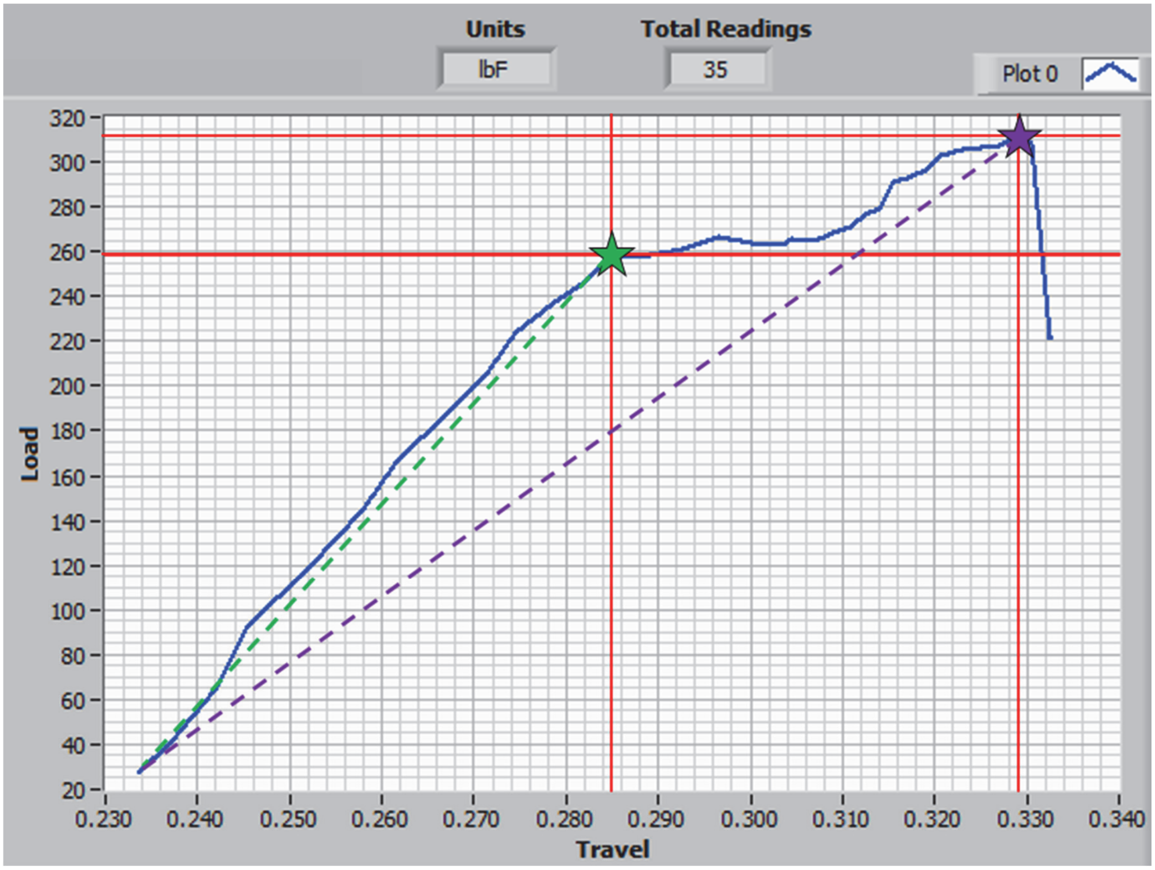


Figure 3-22. Distribution of calculated spring constant values for (top) linear force-displacement evaluations and (bottom) peak force-displacement evaluations

Another interesting observation is the difference in the mean spring constant values for each set of evaluations. The average spring constant for the peak load and displacement evaluations is 3730 lb_f/in, as compared to 4747 lb_f/in for the linear force and displacement evaluations. The reason for this increase in measured spring constant values for the linear force and displacement evaluations can be understood by examining a sample force-displacement diagram, as shown in

Figure 3-23. From this figure, two different sets of force-displacement data can be obtained to calculate the spring constant of a briquette. The data point corresponding to the peak force and displacement is represented by the purple star and the data point corresponding to the linear force and displacement is represented by the green star. Using Hooke's Law, the spring constant corresponding to the peak force and displacement (slope of purple line) is 2679 lb_f/in, and the spring constant corresponding to the linear force and displacement (slope of green line) is 4138 lb_f/in. This example shows why the average spring constant values are considerably larger for the linear force-displacement evaluations than for the peak force-displacement evaluations. Based on these results, this method appears to be acceptable for measuring the spring constant of coal-biomass briquettes.



Units: lbF

Total Readings: 35

Figure 3-23. Sample force-displacement curve for spring constant calculation

3.4.4 Mechanical Durability

The first variable studied to evaluate the mechanical durability method reported by Taulbee et al. (2010) and Patil et al. (2009) was the number of briquettes loaded in the cylinder. Four separate series of tests were performed by tumbling different numbers of briquettes for five minutes at 40 rotations per minute to determine how mechanical durability results are impacted by cylinder loading (i.e. volume of briquettes to volume of the cylinder). It is important to note that the moisture content of the McClure River coal varied for each series of tests (i.e. 0.98 to 1.70%) due to variable drying conditions, which directly impacted the measured mechanical durability values. Figure 3-24 displays the results obtained for the four series of tests. Test 1 was performed with the highest moisture coal, while the lowest moisture coal was used for Test 4. For each of the four series of tests, the measured mechanical durability of the briquettes increased with a cylinder loading greater than 60 briquettes.

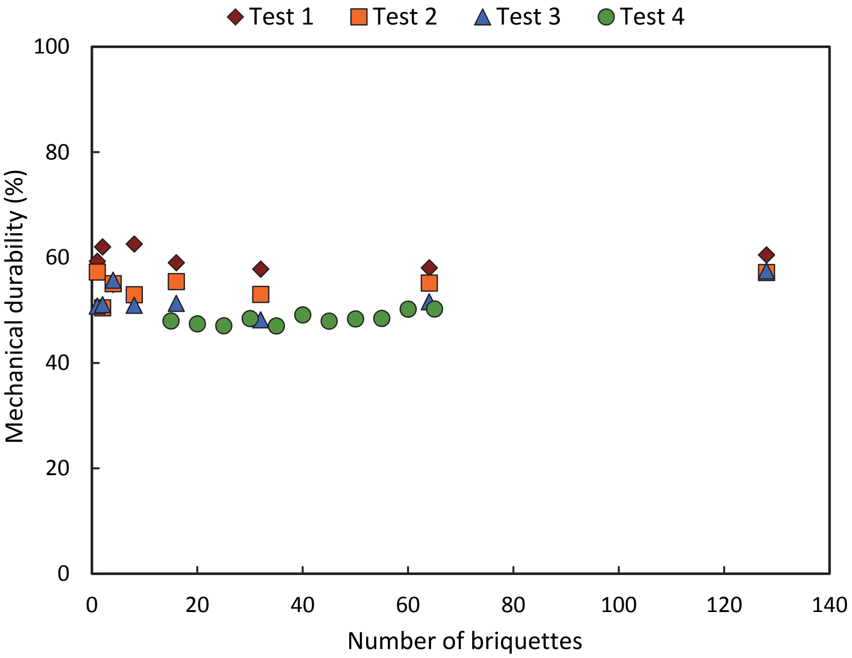


Figure 3-24. Mechanical durability results for different numbers of briquettes tested

This trend can be seen more clearly with the mechanical durability residual values plotted as a function of the number of briquettes loaded in the cylinder (Figure 3-25). The residual value is the difference between the sample and the estimated function value, which is the average of all data points for each test. High residual values represent large deviation from the average while values close to zero represent small deviation. The residual values were very high (-4.38 to 3.56) for cylinder loading between one and eight briquettes but remained close to zero between 16 and 64 briquettes. The increase in mechanical durability with a greater number of briquettes is thought to be the result of a cushioning effect from a high cylinder loading factor. From the data in Figure

3-24 and Figure 3-25, the ideal cylinder loading for measurement of mechanical durability was determined to be 20 briquettes. This is supported by the low residual values calculated in the range of 16 to 64 briquettes and the desire to limit the number of briquettes required for each evaluation.

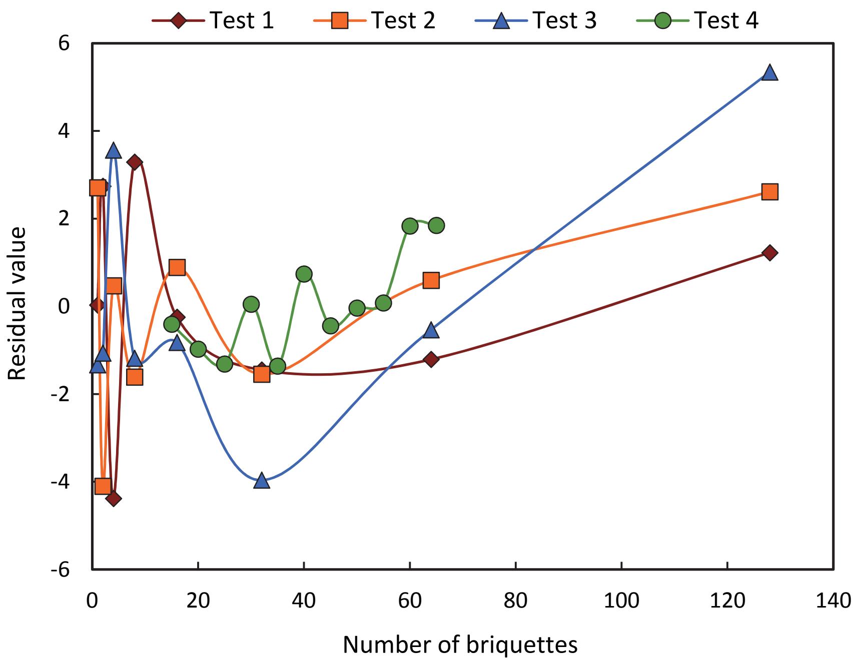


Figure 3-25. Mechanical durability residual values for different numbers of briquettes tested

The other variables examined to evaluate and refine the mechanical durability method were the number of cylinder rotations and the rotational speed of the cylinder (rpm). Evaluations were performed on 20 MR-SG briquettes at cylinder rotational speeds of 10, 20, 40 and 60 rpm. For each speed, five different numbers of rotations were examined (i.e. 20, 40, 80, 160 and 320 rotations). The results of these evaluations are displayed in Figure 3-26. Through 80 rotations, mechanical durability decreased with a corresponding decrease in the rotational speed of the cylinder. For example, the most minus 4.75-millimeter material was produced from tumbling at 10 rpm, while the least minus 4.75-millimeter material was produced from tumbling at 60 rpm. This occurred because at higher rotational speeds the briquettes are carried by the lifters inside the cylinder so they do not experience as many drops as briquettes tumbled at lower speeds. However, there was some variation in this trend once the number of rotations was increased to 160 and 320. The least breakage still occurred at 60 rpm while the most breakage unexpectedly occurred at 20 rpm.

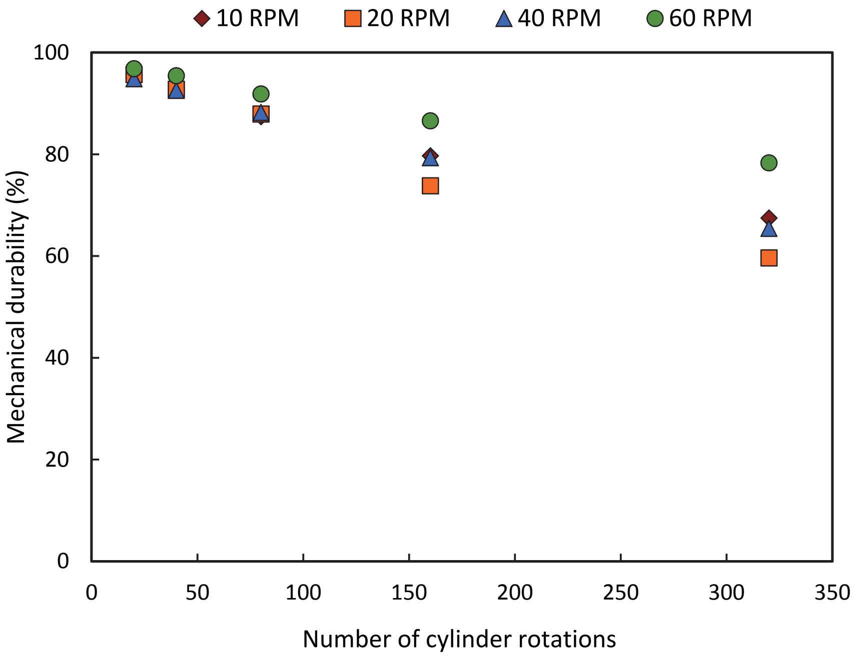


Figure 3-26. Mechanical durability results for different rotational speeds and different numbers of cylinder rotations

An exponential statistical model was fitted to the data which relates the mechanical durability of the briquettes to the number of cylinder rotations for each rotational speed (Figure 3-27). The exponential model was selected because the briquette particles that are most easily removed come off quickly while the remaining particle becomes more resistant to degradation over time, which is indicative of exponential decay. The coefficient of determination (R^2) was calculated for each exponential regression curve and is displayed in Figure 3-27. The coefficient of determination provides a measure of how likely future outcomes will be predicted by a statistical model, with values ranging from zero to one. In this case, a high coefficient of determination means that for an individual rotational speed, data is more likely to fall in line with the statistical model that describes briquette decay over time. The rotational speed with the highest coefficient of determination was 40 rpm, with an R^2 value of 0.9997. In contrast, the 60 rpm statistical model has the lowest R^2 value at 0.9945. Due to the highest R^2 value and to align with the method reported in the literature, a rotational speed of 40 rpm is suggested for coal-biomass briquette evaluations. It can also be observed from Figure 3-27 that greater differentiation between individual mechanical durability values is achieved when briquettes are subjected to larger numbers of rotations. Therefore, 200 cylinder rotations should be performed to reduce the time required for evaluations while still maintaining sufficient sample differentiation and alignment with the method reported in the literature. An additional outcome of this study was the decision to only screen briquettes in the Ro-Tap sieve shaker for 30 seconds after mechanical durability testing. This decision was made due to the realization that briquettes experience additional degradation during screening, which is discussed in Section 3.4.5. A screening time of 30 seconds was chosen because this amount of time ensured all of the broken particles passed through the sieve without producing a significant quantity of additional fine material.

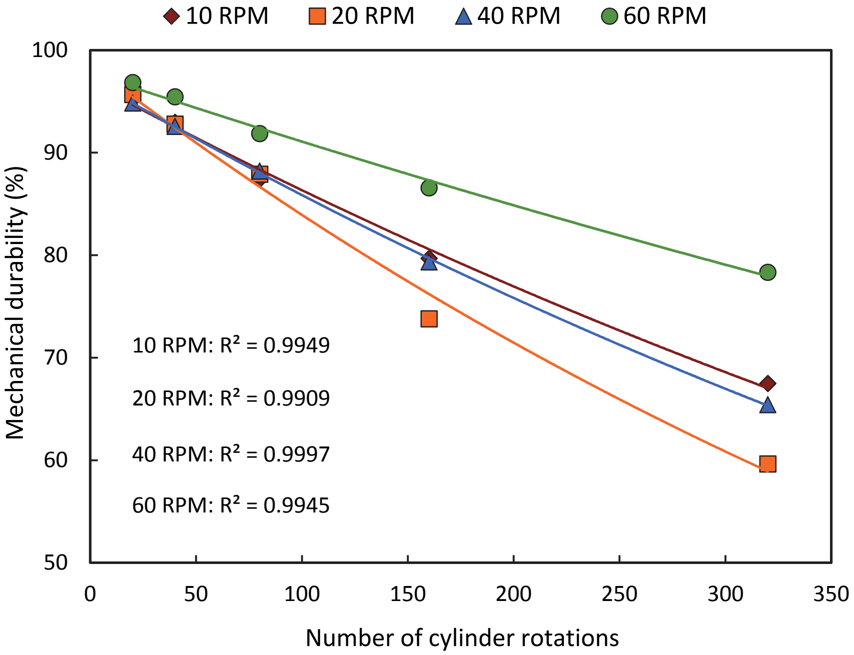


Figure 3-27. Exponential regression line fitted to mechanical durability results for different rotational speeds and different numbers of cylinder rotations

3.4.5 Attritability

To optimize the screening time and number of briquettes for the attritability evaluation method, a series of tests were conducted in which different numbers of MR-SG briquettes (i.e. 5, 10, 15, 20, 25, and 30) were screened for different periods of time (i.e. 10, 20, 40, 80, 160, and 320 seconds). This was accomplished by weighing a specified number of briquettes and then initially screening them in a Ro-Tap sieve shaker over a 4.75-millimeter sieve for 10 seconds. The sieve was then removed from the Ro-Tap and the mass of briquettes retained on the sieve was recorded. Next, the sieve was placed back in the Ro-Tap and the briquettes were screened for an additional 10 seconds. The sieve was again removed from the Ro-Tap and the mass of the briquettes retained on the screen was recorded. This value was designated the 20 second screening time value since the briquettes were subjected to a total of 20 seconds throughout the course of the two tests. Again, the sieve was placed back in the Ro-Tap and the briquettes were screened for an additional 20 seconds (i.e. a total screening time of 40 seconds). This screening and weighing procedure was continued until the briquettes were screened for a total of 320 seconds. The results of these evaluations for each screening time with different numbers of briquettes are presented in Figure 3-28.

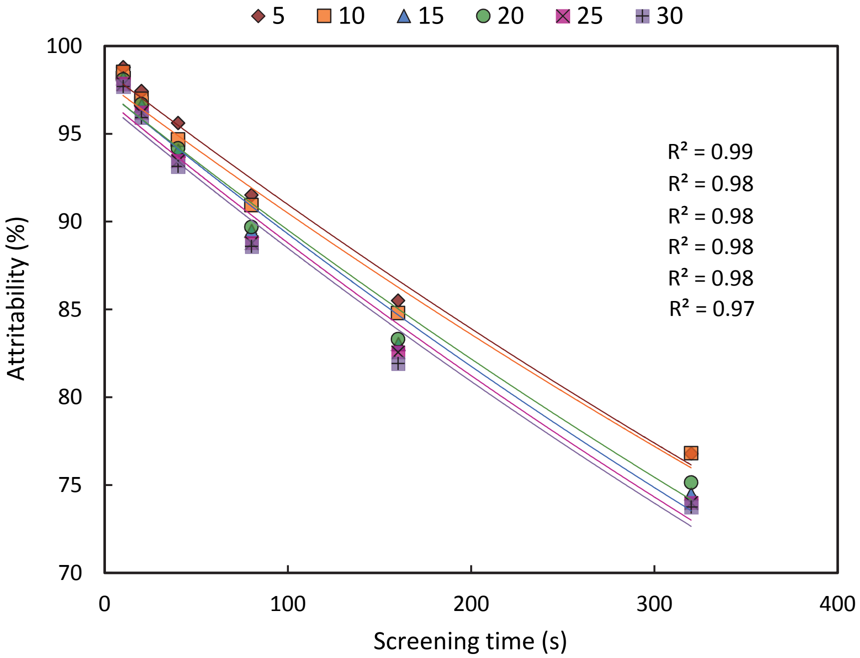


Figure 3-28. Attritability results for different screening times with different numbers of briquettes

To analyze the relationship between the measured attritability of the briquettes over time, an exponential regression line was fitted to the data for each number of briquettes tested. This type of regression was chosen because attrition is thought to be an exponential decay process, wherein the outer surface of the briquettes is removed most easily and the attrition rate decreases with time. This relationship proved to be quite accurate, which is demonstrated by the high coefficient of determination (R^2) values calculated for each data set. It can also be observed from Figure 3-28 that the differentiation between individual attritability results is greater when briquettes are subjected to a longer screening duration. Therefore, it is suggested that briquettes are screened for 300 seconds (i.e. 5 minutes) to provide a significant differentiation between the results for different briquette formulations.

To provide additional insight into the relationship between attritability values and the number of briquettes tested, attritability is plotted versus number of briquettes in Figure 3-29. For this example, the screening time was held constant at three minutes and a 4.75-millimeter sieve was utilized. Evaluations were performed with 1, 2, 4, 8, 16 and 32 briquettes, each of which was repeated three times. The standard deviation of the results is also provided in Figure 3-29 as error bars. The lowest standard deviation (0.39%) was found for evaluations with 16 briquettes. This value increased to 0.70% when the number of briquettes tested was increased to 32. As a result, it is suggested that evaluations are performed with 20 briquettes due to the low standard deviation in this region and because 20 is a good sample size for statistically significant results. Another interesting finding was that the attritability values and the number of briquettes tested were found to be related to one another by a power law. In this instance, the data fit a power function extremely well (i.e. $R^2 = 1.00$). The power determined by the regression (i.e. 0.02) relates the attritability of one briquette to that of any number of briquettes (*x*) for the three minute screening time evaluated.

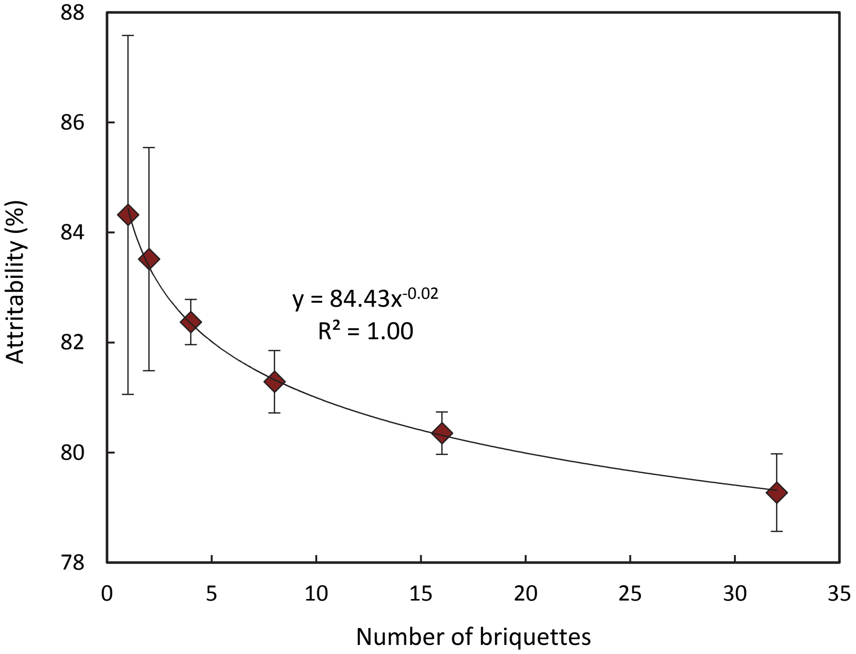


Figure 3-29. Attritability results for different numbers of briquettes

The final set of evaluations were performed to determine the impact of sieve size on the measured attritability values. This was accomplished by screening 20 MR-SG briquettes for three minutes in the Ro-Tap sieve shaker using 10 different sieve sizes (i.e. 6.70, 4.75, 3.35, 2.36, 1.70, 1.18, 0.84, 0.59, 0.43 and 0.21 mm). The results of these evaluations are provided in Figure 3-30, which clearly shows that an increase in sieve size leads to a decrease in attritability values. This finding stands to reason since more broken particles can fall through a larger sieve than a smaller one. For example, a very high attritability value (96.9%) was measured for the 0.21-millimeter sieve size, which indicates that only a small percentage of minus 0.21-millimeter particles were produced from attrition. In contrast, the attritability value was substantially lower (87.7%) for briquettes screened over the 6.70-millimeter sieve because all of the particles with an effective diameter less than 6.70 millimeters fell through the sieve openings. The results of this series of tests suggest that sieve size should be selected based on the minimum acceptable size of particles for downstream handling and processing. Therefore, a sieve size of 4.75 millimeters is recommended for coal-biomass briquettes because this particle size is often referred to as the minimum desirable particle size for downstream handling and processing operations in the coal industry.

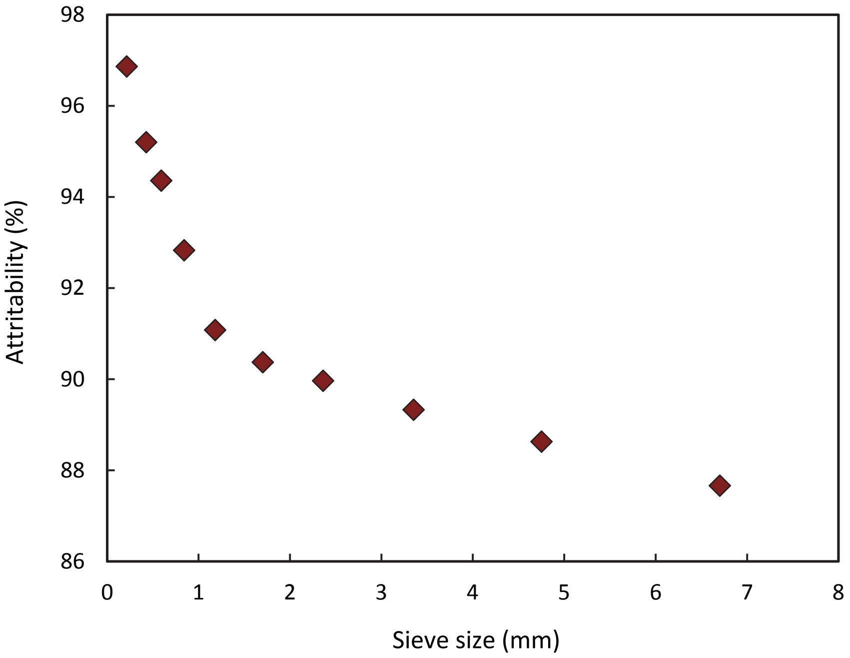


Figure 3-30. Attritability results for different sieve sizes

3.4.6 Friability

Evaluations were performed to determine the optimum drop height and number of briquettes to use for the modified drop-shatter test that was modified from ASTM D440-07 (2012). This method specifies dropping 50 pounds of material, which is not practical for laboratory-scale briquette evaluations. Therefore, the decision was made to examine the difference in briquette friability measurements when different numbers of briquettes are tested (i.e. 10, 20, 40 and 80 briquettes). Each number of briquettes was dropped twice from a height of 4, 6 and 8.4 feet to determine the drop height with the most consistent results. The data from these evaluations is displayed in Figure 3-31 as a function of drop height and in Figure 3-32 as a function of the number of briquettes dropped.

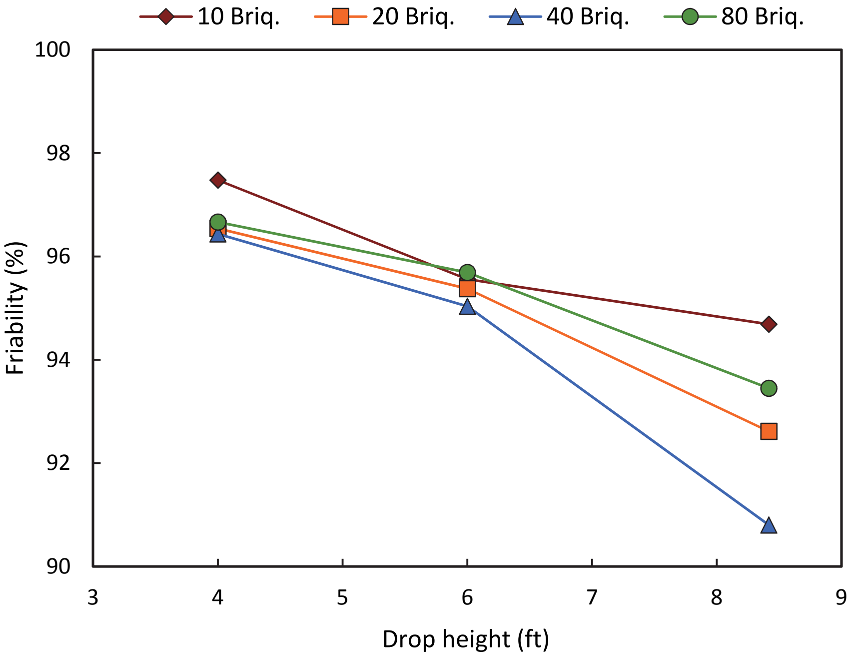


Figure 3-31. Friability results for different drop heights

From Figure 3-31 and Figure 3-32, it can be observed that the least breakage occurred at a drop height of four feet with a sample size of 10 briquettes, while the most breakage occurred at a drop height of 8.4 feet with a sample size of 40 briquettes. An interesting observation was that an increase in the briquette sample size could not be directly correlated to the friability results (i.e. the most breakage occurred with 40 rather than 80 briquettes). However, it can be seen that an increase in drop height directly corresponds to more breakage. The drop height with the most consistent results regardless of the number of briquettes dropped was six feet. At this height, friability measurements ranged from 95.03 to 95.69%. In contrast, the most scatter of results was seen at a drop height of 8.4 feet with a friability range of 90.80 to 94.69%. Therefore, it appears that briquettes should be dropped from a height of six feet to reduce the influence of drop height on the friability results.

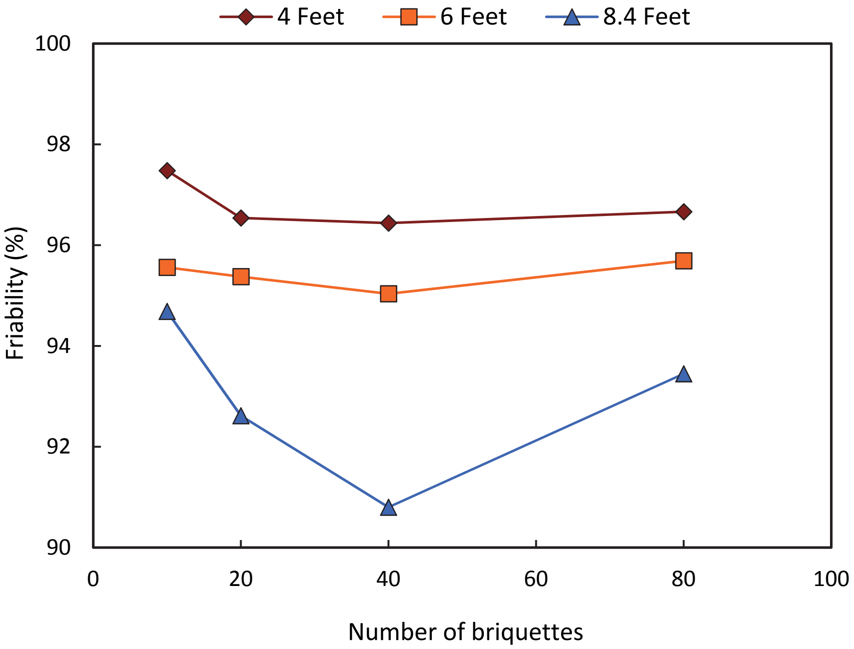


Figure 3-32. Friability results for different numbers of briquettes tested

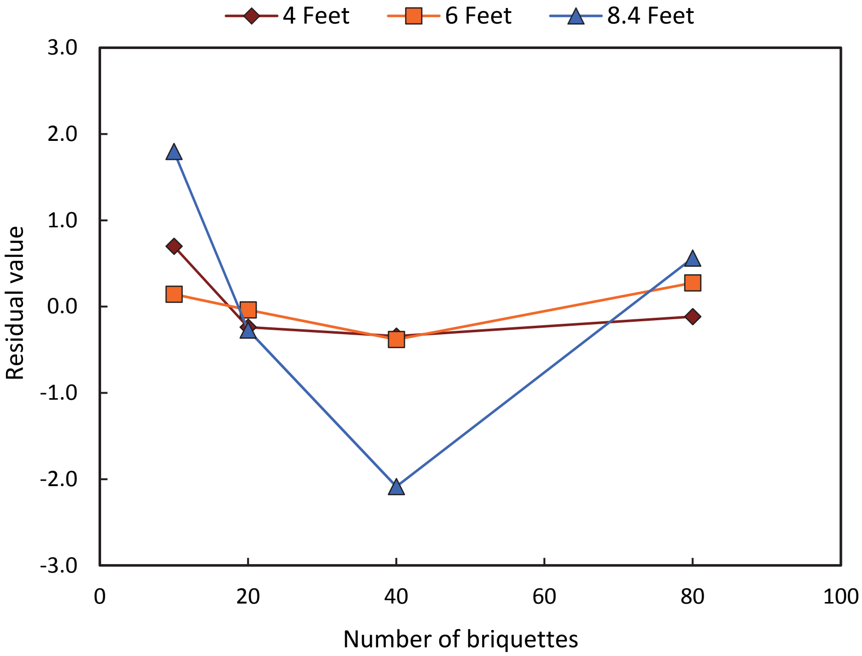


Figure 3-33. Friability residual values for different numbers of briquettes tested

From Figure 3-33, it is clear that a sample size of 20 briquettes produced residual values closest to zero (-0.04 to -0.27). It can also be seen that with 10 and 80 briquettes the residual value is typically greater than zero (-0.12 to 1.80), while with 40 briquettes the residual is much lower than zero (-0.34 to -2.09). Therefore, it appears that 20 briquettes should be used for friability evaluations to minimize the influence of the number of briquettes tested on the results of this test. An additional outcome of this study was the decision to only screen briquettes in the Ro-Tap sieve shaker for 30 seconds after friability testing. This decision was made due to the realization that briquettes experience additional degradation during screening, which is discussed in Section 3.4.5.

3.4.7 Water Content

To evaluate the accuracy and precision of the proposed water content evaluation procedure, six EM-CS briquettes were dried at 105 ± 4 degrees Celsius in a drying oven for 24 hours. The results of these evaluations are presented in Table 3-2. In addition, the standard deviation and relative standard deviation were calculated for the group of six measurements to determine the precision of the method. The average water content value for the six measurements was 0.0382 and the standard deviation was 0.0030. This equated to a relative standard deviation of 7.78%. The low relative standard deviation result indicates that this method is very precise, especially considering the inherent variability among individual products of agglomeration processes.

Table 3-2. Water content accuracy and precision results

Measurement Number	**Initial Wet Mass (g)**	**24 hours**			**26 hours**			**Change in Water Content (%/hr)**
		Dry Mass (g)	**Water Mass (g)**	**Water Content**	**Dry Mass (g)**	**Water Mass (g)**	**Water Content**	
1	9.844	9.463	0.381	0.0403	9.462	0.382	0.0404	0.14
2	9.651	9.299	0.352	0.0379	9.298	0.353	0.0380	0.15
3	9.771	9.470	0.301	0.0318	9.469	0.302	0.0319	0.17
4	9.418	9.055	0.363	0.0401	9.054	0.364	0.0402	0.14
5	9.595	9.226	0.369	0.0400	9.224	0.371	0.0402	0.28
6	9.572	9.213	0.359	0.0390	9.212	0.360	0.0391	0.14
Avg.				0.0382			0.0383	0.17
Std. Dev.				0.0030			0.0033	0.05
Std. Dev. (%):				7.78			7.79	29.75

To evaluate the accuracy of water content measurements after a period of 24 hours, each of the briquettes were dried for an additional two hours to determine the change in the calculated water content value with additional drying time. As presented in Table 3-2, the average change in the calculated water content of the six briquettes over the additional two hour period was found to be 0.17% per hour of the total loss in mass. This value is less than the value commonly recommended by the existing standards for moisture content determination (i.e. 0.2% per hour of the total loss in mass). For this reason, the prescribed period of 24 hours is certainly acceptable for accurately measuring the water content of coal-biomass briquettes.

3.4.8 Particle Density

For each particle density test configuration, the mass of 12 EM-CS briquettes was recorded in air and the apparent mass was measured in water. The calculated particle densities and standard deviations for each set of tests are presented numerically in Table 3-3 and graphically in Figure 3-34. One clear observation is that the particle density value was found to be lowest with the water-only evaluations. This was most likely due to the adherence of air bubbles on the surface of the briquettes, which reduced the effective mass of the briquettes in water, thereby reducing the calculated particle density.

Table 3-3. Particle density results for different test configurations

Test Configuration	**Number of Evaluations**	**Average Particle Density (g/cm^3)**	**Standard Deviation (g/cm^3)**	**Standard Deviation (%)**
Water only	12	1.105	0.010	0.883
Water and polyurethane	12	1.120	0.006	0.575
Water and detergent	12	1.132	0.010	0.846
Water, detergent and polyurethane	12	1.128	0.009	0.808

The lowest standard deviation (0.006) and relative standard deviation (0.575%) values were found with the polyurethane coated samples tested in water. However, since this coating method is not recommended by EN 15150 (2011) and because of the necessity to account for the amount of polyurethane that penetrates the sample, this method is not ideal. The samples tested with the detergent added to the water were found to have a higher particle density (1.132 g/cm^3) and lower relative standard deviation (0.846%) than the samples tested in water alone (1.105 g/cm^3; 0.883%). The higher particle density is believed to be more accurate than the density calculated in water alone because the adherence of air bubbles to the surface of the briquettes was eliminated by incorporating the detergent. Due to the high degree of precision associated with the water and detergent test configuration and the conformity with EN 15150 (2011), this configuration appears to be the best method for measuring the particle density of coal-biomass briquettes.

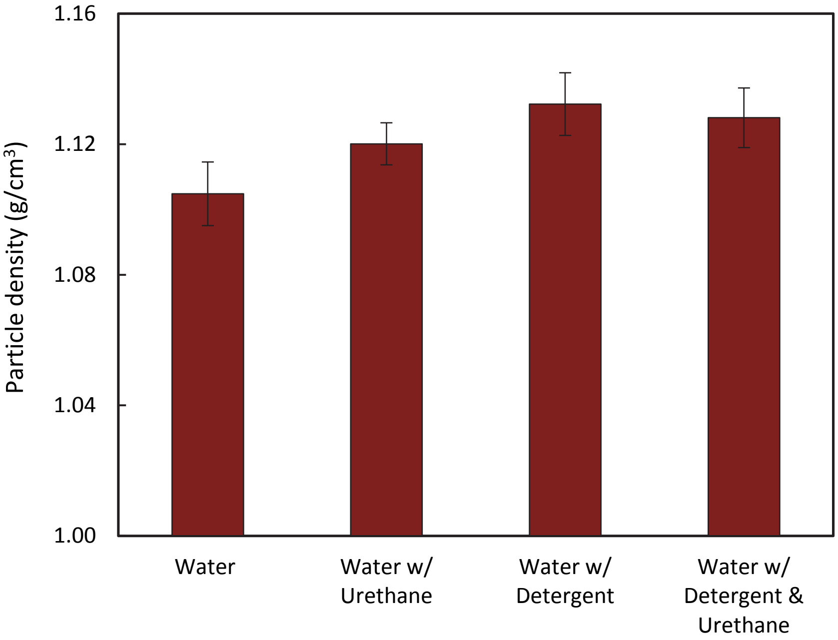


Figure 3-34. Graphical representation of particle density results for different test configurations [Error bars indicate plus and minus one standard deviation from the mean]

3.4.9 Bulk Density

Figure 3-35 shows the experimentally determined bulk density values and standard deviations for EM-CS briquettes corresponding to each container size. From this figure, it can be observed that the bulk density values increased slightly with an increase in container volume. For example, the average bulk density of briquettes in the 0.24-ft^3 container was 40.45 lb/ft^3, as compared to 40.78 lb/ft^3 and 40.84 lb/ft^3 in the 0.50 ft^3 and 1.00-ft^3 containers, respectively. Although there was a measurable difference in the apparent bulk density of briquettes when the container size was increased from 0.24 to 1.00 ft^3, the increase was very small, accounting for less than a one percent increase in apparent bulk density. The standard deviation of the bulk density measurements was 0.49 lb/ft^3 for the 0.24-ft^3 container, 0.73 lb/ft^3 for the 0.50 ft^3 container and 0.25 lb/ft^3 for the 1.00-ft^3 container. Although the best precision was found with the 1.00-ft^3 container, there was no clear trend indicating that the precision of bulk density measurements increases with container size. From these findings it can be concluded that a 0.24-ft^3 container can be used to accurately and precisely measure the bulk density of pill-shaped coal biomass briquettes.

However, if larger briquettes are produced and tested, a larger container may be necessary to accurately measure bulk density.

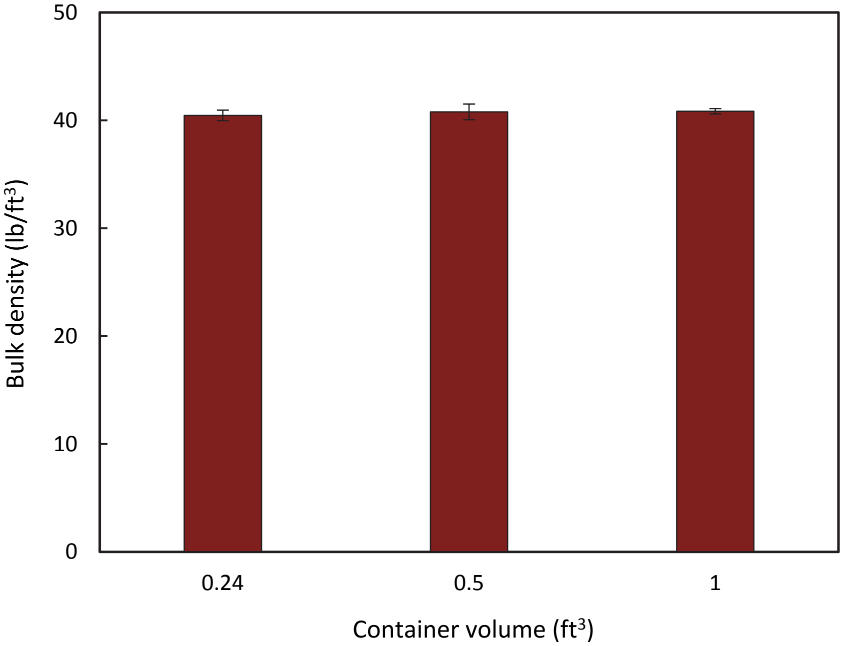


Figure 3-35. Bulk density results for different container volumes [Error bars indicate plus and minus one standard deviation from the mean]

The measured changes in bulk density with consolidation pressure from the compressibility tests are shown in Figure 3-36. From this figure it can be seen that an increase in consolidation pressure led to a slight increase in bulk density from the initial value of 40.58 lb/ft^3 to a final value of 42.00 lb/ft^3. Based on the data collected, the compressibility of the briquettes was found to be 0.01 ft^{-1}. This data suggests that coal-biomass briquettes are generally expected to have low values of bulk compressibility and that this method is acceptable to measure briquette compressibility.

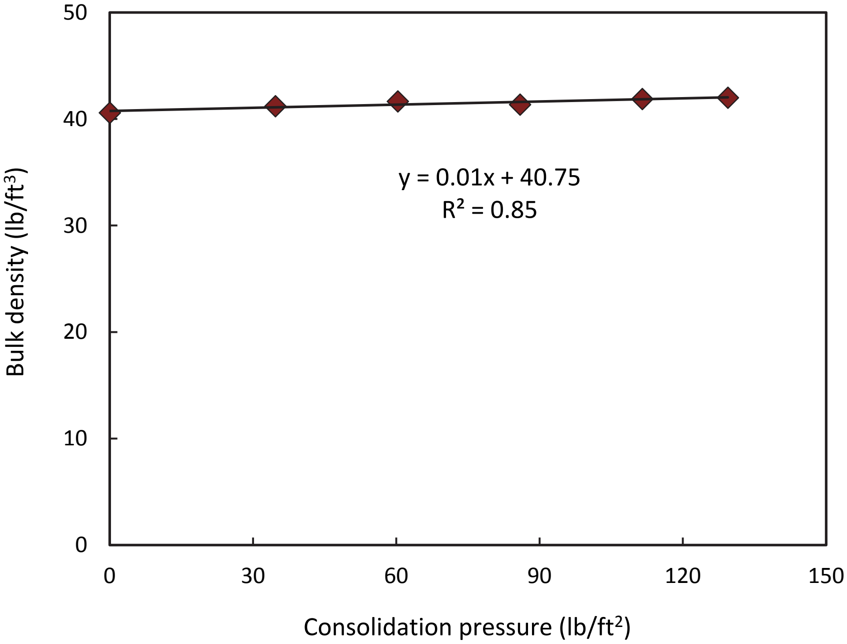


Figure 3-36. Bulk density results for different consolidation pressures

3.4.10 Water Resistance

The results of the first series of tests to determine the effect of the number of briquettes tested on water uptake measurements are presented in Table 3-4. These results suggest that the number of briquettes tested does not have a large impact on water uptake values. This is evident by the narrow range of values (21.68 to 22.89%) and the low relative standard deviation (2.95%) among the conditions evaluated. As a result of these findings, and in an effort to reduce material requirements, five briquettes was selected as the optimal number for water uptake tests. However, this decision is not intended to limit the number of briquettes tested to five if a higher number of briquettes is desired. For example, if it is desirable to evaluate the mechanical durability of briquettes after exposure to water, then it would be suggested to simultaneously test 20 briquettes for water uptake and subsequently test for mechanical durability, rather than testing four separate lots of five briquettes for water uptake.

Table 3-4. Water uptake measurements for all variables studied

Number of Briquettes Tested	Water Uptake (%)	Spray Duration (sec)	Water Uptake (%)	Water Flow Rate (gal/min)	Water Uptake (%)
5	22.87	5	21.46	1	17.89
10	21.79	15	27.21	2	17.47
20	21.68	30	32.06	3	19.84
40	22.89	60	34.34	4	17.98
--	--	120	44.57	5	24.48
Average:	22.31	Average:	31.93	Average:	19.53
Std. Dev:	0.66	Std. Dev:	8.62	Std. Dev:	2.91
Std. Dev (%):	2.95	Std. Dev (%):	27.00	Std. Dev (%):	14.90

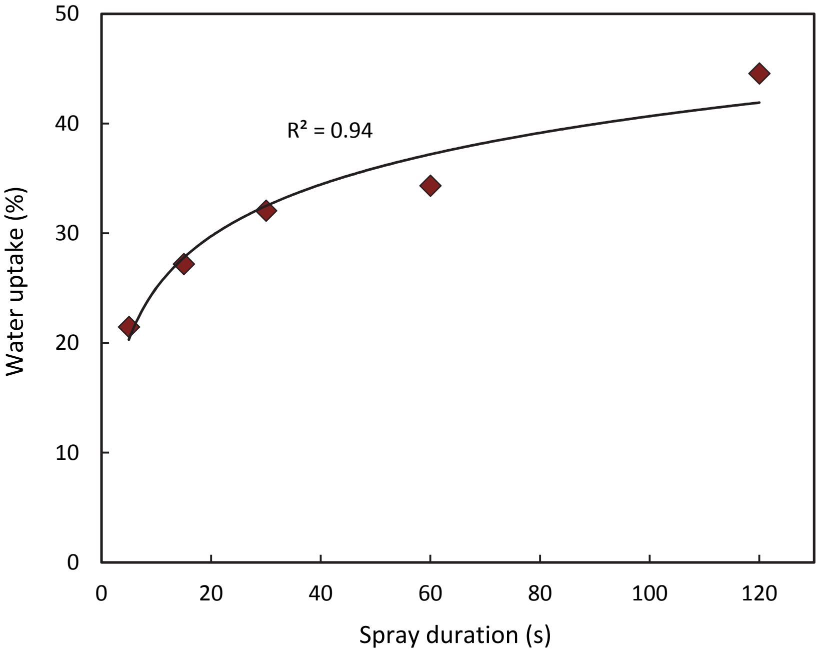


Figure 3-37. Graphical representation of water uptake measurements for different water spray durations

The results of the second series of tests to determine the impact of spray duration on water uptake measurements are also presented in Table 3-4. A very clear and predictable trend ($R^2 = 0.94$) was observed that relates the spray duration to the water uptake measurement, as shown in Figure 3-37. An interesting observation was how quickly these briquettes took up water. After only five seconds, a water uptake greater than 20% was recorded. This implies that a water uptake measurement can be conducted after only a short spray duration without sacrificing a substantial differentiation of results (i.e. if after five seconds the water uptake value was only a small fraction of the value after 120 seconds, then a substantial differentiation of results would be sacrificed by choosing to only spray for five seconds). Therefore, in an effort to minimize the time required for evaluations and achieve statistically significant differentiation of results, a spray duration of 15 seconds appears to be most suitable for coal-biomass briquette water uptake evaluations.

The results of the final series of tests to analyze the impact of water flow rate on water uptake measurements are also displayed in Table 3-4. The measured water uptake values were found to be quite consistent (17.47 to 19.84%) for water flow rates between one and four gallons per minute. However, the measured water uptake at a water flow rate of five gallons per minute was significantly higher (24.48%). It is unknown if this finding is significant or if the variation is a statistical outlier resulting from inconsistent briquettes between tests or loss of material due to the high impact force of the water spray at five gallons per minute. Regardless of the source of this discrepancy, it appears that a water flow rate of three gallons per minute is ideal because at this value the spray profile provided complete coverage of the perforated stainless steel plate and the water pressure did not cause any significant loss of sample into the sump.

3.5 Summary and Conclusions

A major limitation to industrial utilization of coal-biomass briquette feedstocks is the absence of standard methods to characterize important physical and mechanical properties of coal-biomass briquettes. To address this challenge, a detailed review of briquette properties was initially conducted to determine the most important properties for characterization of coal-biomass briquettes. The briquette properties that were identified as most significant are: (1) tensile strength, (2) crushing strength, (3) elasticity, (4) mechanical durability, (5) attritability, (6) friability, (7) water content, (8) particle density, (9) bulk density and (10) water resistance. Crushing strength and mechanical durability appear to be the most important of all these properties, and thus should be measured for all experimental and industrial coal-biomass briquette formulations. The other identified properties are still very important and should be considered in detailed evaluations of coal-biomass briquettes when requested by a client or customer.

Experimental evaluations were conducted to adapt, evaluate and refine established methods that appeared suitable for coal-biomass briquette evaluations by directly testing coal-biomass briquettes and analyzing the results. Additionally, work was conducted to develop novel characterization methods to quantify briquette properties when suitable established methods were not applicable or available. The following section outlines the recommended methods and procedures to characterize coal-biomass briquettes based on the results of this study.

1. Tensile strength – To measure tensile strength, individual coal-biomass briquettes are compressed with the briquette standing tall (i.e. with the long axis of the briquette parallel to the axis of force application) between flat compression plates. This is carried out using a digital force gauge and a manual or automatic test stand. A break detect feature is utilized that stops data acquisition after the applied force drops to 95 percent of the maximum force attained during each test. Tensile strength is then designated as this maximum force. This procedure is repeated for a minimum of 25 briquettes until the relative standard deviation of results is below 20 percent. The average tensile strength of all conducted measurements is reported as the briquette crushing strength, along with the standard deviation of the measured results.

2. Crushing strength – To measure crushing strength, individual coal-biomass briquettes are compressed along the smooth pocket surface (i.e. surface of force application during formation) using a digital force gauge and a manual or automatic test stand equipped with flat compression plates. When using a manual test stand, briquettes are placed atop and parallel to an aluminum bar to improve the accuracy of readings. In both instances, a break detect feature is utilized that stops data acquisition after the applied force drops to 95 percent of the maximum force attained during each test. Crushing strength is then designated as this maximum force. This procedure is repeated for a minimum of 25 briquettes until the relative standard deviation of results is below 20 percent. The average crushing strength of all conducted measurements is reported as the briquette crushing strength, along with the standard deviation of the measured results.

3. Elasticity – To measure elasticity, individual coal-biomass briquettes are compressed following the method outlined for crushing strength measurements. However, force application is measured with respect to briquette displacement using a digital travel display or a similar measurement device. Elasticity is reported as the spring constant of the briquettes, which is calculated as the slope of the linear portion of the force-displacement diagram. This measurement is conducted for a minimum of 25 briquettes until the relative standard deviation

of the results is below 20 percent. The average spring constant of all conducted measurements is reported as the briquette elasticity, along with the standard deviation of the calculated results.

4. Mechanical durability – To measure mechanical durability, 20 coal-biomass briquettes are tumbled for five minutes at 40 rotations per minute in a 12-inch diameter PVC or Plexiglas cylinder equipped with three 2-inch lifters. The briquettes are then removed from the cylinder and screened for 30 seconds over a 4.75-millimeter sieve in a Ro-Tap sieve shaker. Mechanical durability is reported as the percentage of the initial mass of briquettes retained on the 4.75-millimeter sieve.

5. Attritability – To measure attritability, 20 coal-biomass briquettes are screened for five minutes over a 4.75-millimeter sieve in a Ro-Tap sieve shaker. Attritability is reported as the percentage of the initial mass of briquettes retained on the 4.75-millimeter sieve.

6. Friability – To measure friability, 20 coal-biomass briquettes are dropped twice from a height of six feet onto a steel plate using a modified shatter test machine. The briquettes are then screened for 30 seconds over a 4.75-millimeter sieve in a Ro-Tap sieve shaker. Friability is reported as the percentage of the initial mass of briquettes retained on the 4.75-millimeter sieve.

7. Water content – To measure water content, coal-biomass briquettes are dried for 24 hours at 105 ± 4 degrees Celsius in a drying oven. Water content is reported as the fraction of water in the sample on a dry basis.

8. Particle density – To measure particle density, the apparent weight of individual coal-biomass briquettes is measured while submerged in a solution of water and detergent using an apparatus similar to that described in EN 15150 (2011). The detergent to be used is Triton® X-100 at a concentration of 1.5 grams per liter of water. Particle density is calculated by the product of the liquid density and the ratio of the mass of the briquette in air to the difference between the mass of the briquette in air and the mass of the briquette in water. This measurement is conducted for a minimum of 10 briquettes until the relative standard deviation of the results is below 20 percent. The average particle density of all conducted measurements is reported as the briquette particle density, along with the standard deviation of the calculated results.

9. Bulk density – To measure bulk density, coal-biomass briquettes are poured into a 0.24 ft^3 box from a height of two feet above the bottom of the interior of the container so that the briquettes overflow the top of the container. A straight edge is used to remove the overflow material from the top of the container. Bulk density is calculated by dividing the net weight of the briquettes in the filled container by the volume of the container. Variation in bulk density with increasing consolidation pressure, known as compressibility, is measured by incrementally adding weight to a platform that rests on top of the briquettes and calculating the new bulk density for each consolidation pressure. Compressibility is reported as the slope of the line of bulk density versus consolidation pressure.

10. Water resistance – To measure water resistance, five coal-biomass briquettes are subjected to a 15 second water spray at a flow rate of three gallons per minute from a height of 18 inches above the briquettes. Water resistance is reported as the water uptake of the briquettes that results from this spray test, which is reported as the water absorbed as a percentage of the initial mass of the briquettes.

3.6 References

ASTM D291-07 (2012). *Standard test method for cubic foot weight of crushed bituminous coal.* West Conshohocken, PA: ASTM International.

ASTM D3173-11 (2011). *Standard test method for moisture in the analysis sample of coal and coke.* West Conshohocken, PA: ASTM International.

ASTM D3302/D3302M-12 (2012). *Standard test method for total moisture in coal.* West Conshohocken, PA: ASTM International.

ASTM D440-07 (2012). *Standard test method of drop shatter test for coal*. West Conshohocken, PA: ASTM International.

ASTM D7481-09 (2009). *Standard test methods for determining loose and tapped bulk densities of powders using a graduated cylinder.* West Conshohocken, PA: ASTM International.

ASTM E870-82 (2006). *Standard test methods for analysis of wood fuels.* West Conshohocken, PA: ASTM International.

ASTM E871-82 (2006). *Standard test method for moisture analysis of particulate wood fuels.* West Conshohocken, PA: ASTM International.

Basu, P. (2010). *Biomass gasification and pyrolysis: Practical design and theory*. Burlington, MA: Academic Press.

Basu, P., Butler, J., & Leon, M. (2011). Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. *Renewable energy*, *36*(1), 282-288.

Boley, C. & Rice, N. (1949). Methods of evaluating briquet quality. *Proceedings of a coal briquetting conference*, 31-47, Laramie, WY: University of Wyoming.

Capes, C. (1980). Particle size enlargement. In J. Williams & T. Allen (Eds.), *Handbook of powder technology* (Vol. 1). Amsterdam, Netherlands: Elsevier Scientific Publishing Company.

Eckerd, J. (1967). Development of standard procedures for testing fuel briquets. *Proceedings of the 10th biennial briquetting conference*, 95-99, Albuquerque, NM: Institute for Briquetting and Agglomeration.

EN 14774-1 (2009). *Solid biofuels − Determination of moisture content − Oven dry method − Part 1: Total moisture − Reference method.* Brussels, Belgium: European Committee for Standardization.

EN 14774-2 (2009). *Solid biofuels − Determination of moisture content − Oven dry method − Part 2: Total moisture − Simplified method.* Brussels, Belgium: European Committee for Standardization.

EN 14774-3 (2009). *Solid biofuels − Determination of moisture content − Oven dry method − Part 3: Total moisture − Moisture in general analysis sample.* Brussels, Belgium: European Committee for Standardization.

EN 15150 (2011). *Solid biofuels − Determination of particle density.* Brussels, Belgium: European Committee for Standardization.

EN 15210-2 (2010). *Solid biofuels – Determination of mechanical durability of pellets and briquettes – Part 2: Briquettes.* Brussels, Belgium: European Committee for Standardization.

Fernando, R. (2009). *Co-gasification and indirect cofiring of coal and biomass*. London, England: IEA Clean Coal Centre.

Graboski, M., & Bain, R. (1981). Properties of biomass relevant to gasification. In T. Reed (Ed.), *Biomass gasification: Principles and technology*. Park Ridge, NJ: Noyes Data Corporation.

Guigon, P., & Simon, O. (2003). Roll press design – influence of force feed systems on compaction. *Powder technology, 130*(1-3), 41-48.

Honaker, R., Parekh, B., Taulbee, D., & Tao, D. (2005). *Premium fuel production from mining and timber waste using advanced separation and pelletizing technologies*. Washington, DC: U.S. Department of Energy.

Mahajan, O., & Walker, P., Jr. (1978). Porosity of coals and coal products. In Karr, C., Jr. (Ed.), *Analytical methods for coal and coal products.* San Diego, CA: Academic Press.

Moore, J. (1957). Proposals of the standards committee. *Proceedings of the 5th biennial briquetting conference*, 37-40, Laramie, WY: International Briquetting Association.

Patil, D., Taulbee, D., Parekh, B., & Honaker, R. (2009). Briquetting of coal fines and sawdust – Effect of particle-size distribution. *International journal of coal preparation and utilization, 29*(1), 251-264.

Pietsch, W. (2002). *Agglomeration processes: Phenomena, technologies, equipment*. Weinheim, Germany: Wiley-VCH.

Prostel, E., (1953). Report on physical tests used by operating briquetting plants. *Proceedings of the 3rd biennial briquetting conference*, 67-70, Laramie, WY: International Briquetting Association.

Rabier, F., Temmerman, M., Bohm, T., Hartmann, H., Jensen, P., Rathbauer, J., & Fernandez, M. (2006). Particle density determination of pellets and briquettes. *Biomass and bioenergy, 30*(11), 954-963.

Richards, S. (1990). Physical testing of fuel briquettes. *Fuel processing technology, 25*(2), 89-100.

Sadd, M. (2009). *Elasticity – Theory, applications, and numerics.* (2nd ed.). Burlington, MA: Academic Press.

Sami, M., Annamalai, K., & Wooldridge, M. (2001). Co-firing of coal and biomass fuel blends. *Progress in energy and combustion science*, *27*(2), 171-214.

Speight, J. (2005). *Handbook of coal analysis.* Hoboken, NJ: John Wiley and Sons.

Taulbee, D., Neather, J., Patil, D., Sowder, N., O'Daniel, B., & Montross, M. (2010). Combustion of briquettes and fuel pellets prepared from blends of biomass and fine coal. In R. Honaker (Ed.), *International coal preparation congress 2010 conference proceedings*. Littleton, CO: Society for Mining, Metallurgy, and Exploration.

Wright, C. U.S. Department of the Interior, Bureau of Mines. (1911). *Briquetting tests at the United States fuel-testing plant: Norfolk, Virginia, 1907-8.* (Bulletin 385).

Yildirim, M., & Ozbayoglu, G. (2002). Environmentally sound coal-derived binder for coal briquetting. *Coal preparation, 22*(5), 269-276.

Chapter 4

Moisture Optimization in Briquette Production

4.1 Abstract

Existing experimental methodologies to identify optimum moisture levels for briquette production are time consuming, labor intensive and fail to address fundamental theory. To address this challenge, the Briquette Proctor Test was developed, which is a novel low-cost method to quickly determine the optimum water content of coal-biomass mixtures for briquette production. This test is theoretically derived from the Proctor Test for clay soils, but utilizes a hydraulic press and pellet mold to determine optimum water content. The results obtained using the Briquette Proctor Test showed a clear relationship between water content and the dry density of coal-biomass briquettes. Specifically, a clear optimum water content was experimentally determined for each bituminous coal type, and a range of optimum values was identified for the sub-bituminous coal. This influence of water content on briquette production determined by the Briquette Proctor Test proved to be very representative of the results obtained for briquettes produced with a roll press. This suggests that the Briquette Proctor Test can be used to run a preliminary series of scoping tests prior to performing roll press briquetting tests. Additionally, a strong positive correlation was observed between the dry density, mechanical durability, and crushing strength of briquettes, which suggests that an exhaustive experimental study on roll press briquetting coal-biomass mixtures could be streamlined by simply determining the water content that results in the highest dry density, because the maximum strength and durability likely exist at or near this value as well. The Briquette Proctor Test also reduces material requirements, as significantly fewer briquettes are required to locate optimum conditions. Another major implication of these findings is the realization that bituminous coals with similar water contents exhibit very similar compaction behavior regardless of the physical and chemical properties of the coals. However, sub-bituminous coals exhibit very different compaction behavior than bituminous coals, and thus require independent investigation.

4.2 Introduction

4.2.1 Problem Statement

Co-utilization of biomass with coal in existing coal-fired facilities presents a unique opportunity to reduce greenhouse gas emissions and increase energy production from renewable resources. Significant interest in this opportunity has led to more than 150 coal-fired power stations across the world co-firing coal and biomass on a commercial or trial basis as of 2009 (Fernando, 2009). These co-firing experiences have revealed a number of technical challenges including upstream issues, such as biomass availability, transportation, storage, and handling, as well as problems encountered during energy conversion, such as fouling, corrosion, inconsistent feeding and segregation (Basu et al., 2011; Sami et al., 2001). Recent studies suggest that many of these challenges can be mitigated by reconstituting coal-biomass mixtures into larger particles. Specifically, roll press briquetting has been investigated to produce homogeneous, free-flowing feedstocks that minimize handling and segregation problems often encountered with combustion and gasification systems (Taulbee et al., 2010; Honaker et al., 2005).

However, the degradation of coal-biomass briquettes during handling, transportation and storage is a significant limitation to industrial utilization of these feedstocks. As the cost of raw binder materials continues to rise and the outlook for coal prices remains bleak, there is a growing interest in alternative methods to improve the strength and durability of coal-biomass briquettes. With several new technologies to economically dry fine coal on the horizon, moisture optimization of feed materials could emerge as a viable alternative to binder addition in the briquette production process. Unfortunately, existing experimental methodologies to identify optimum moisture levels for briquette production are time consuming, labor intensive and fail to address fundamental aspects of this issue.

4.2.2 Moisture Optimization

In the context of densified products, such as briquettes and pellets, optimum material properties are referred to as the conditions that produce the greatest strength and durability of the final densified product (Kaliyan & Morey, 2009). Strength and durability is very important to consider because briquettes must withstand the forces encountered in handling, storage and transportation operations to justify the cost of briquette production. Many researchers involved in laboratory evaluation of briquette and pellet formulations have noted the significant influence of water content on the strength and durability of densified products (Tumuluru et al., 2011; Kaliyan & Morey, 2009; Taulbee et al., 2009; Mangena & Cann, 2007; Mani et al., 2003). However, there is very little fundamental understanding of the relationship between feedstock moisture content and the strength and durability of briquettes due to the complex mechanics of roll press briquetting and the number of variables present in these systems. As a result, a shotgun approach is commonly used to identify optimum conditions in the laboratory, wherein many batches of briquettes are produced at various conditions, tested for strength and durability, and the optimum is identified by the conditions that exhibit the highest strength and durability. The downside to this approach is that there is no way to verify that the best recorded results are indeed the best possible results. The only solid conclusions that can be drawn using this method are the presence of relative optimum conditions with respect to other conditions tested. Another downside to this approach is the large amount of materials (i.e. coal and biomass) and long time required to perform such an exhaustive experimental study.

An important fundamental characteristic of briquettes and other agglomerates is the significant influence of porosity on strength and durability. Specifically, briquettes exhibit the greatest strength at the lowest achievable porosity, or in other words, at the highest particle density (Pietsch, 2002). Based on this relationship, the standard Proctor Test used in soil mechanics was identified as a potential method to optimize the moisture content of coal-biomass briquettes. The purpose of the Proctor Test is to determine the water content of clay soils that corresponds to the maximum compacted density. In this test, 2.5 kilograms of soil are compacted in a cylindrical mold of known diameter by a specified number of hammer blows. The compacted dry density (ρ_d) of the soil is then calculated by:

$$\rho_d = m_s/V_t \tag{Eq. 4-1}$$

where m_s is the mass of solids and V_t is the total volume (i.e. volume of solid, liquid and gas). This procedure is repeated for various water contents by adding a specified mass of water for each repetition and calculating the precise water content by:

$$w = m_w/m_s \tag{Eq. 4-2}$$

where w is the water content, m_w is the mass of water and m_s is the mass of solids. By measuring the dry density for each calculated water content, a plot can be constructed similar to that shown in Figure 4-1a. The maximum value identified from this plot establishes the maximum dry density (ρ_d^*) and optimum water content (w^*) for the given soil (Lindeburg, 1989).

Complete saturation of the soil occurs with perfect compaction at a given water content since all air is expelled (Lindeburg, 1989). The saturation densities corresponding to each water content can be plotted versus water content to construct a curve known as the zero air voids curve (Figure 4-1b). This curve always lies above the Proctor Test curve since it is not actually possible to expel all air from the compacted material. The theoretical maximum density of the zero air voids curve is calculated as:

$$\rho_z = \rho_w/(w + (1/SG)) \quad \text{(Eq. 4-3)}$$

where ρ_z is the zero air voids density, ρ_w is the density of water, w is the water content and SG is the specific gravity of the solid. The maximum value of the zero air voids density (ρ_{zd}) occurs at a water content of zero. At this point, the maximum dry zero air voids density is equal to the density of the solid itself. It should also be noted that the maximum dry density (ρ_d^*) will always be less than the zero air voids density (ρ_{zd}) since air voids can never be completely eliminated (Lindeburg, 1989).

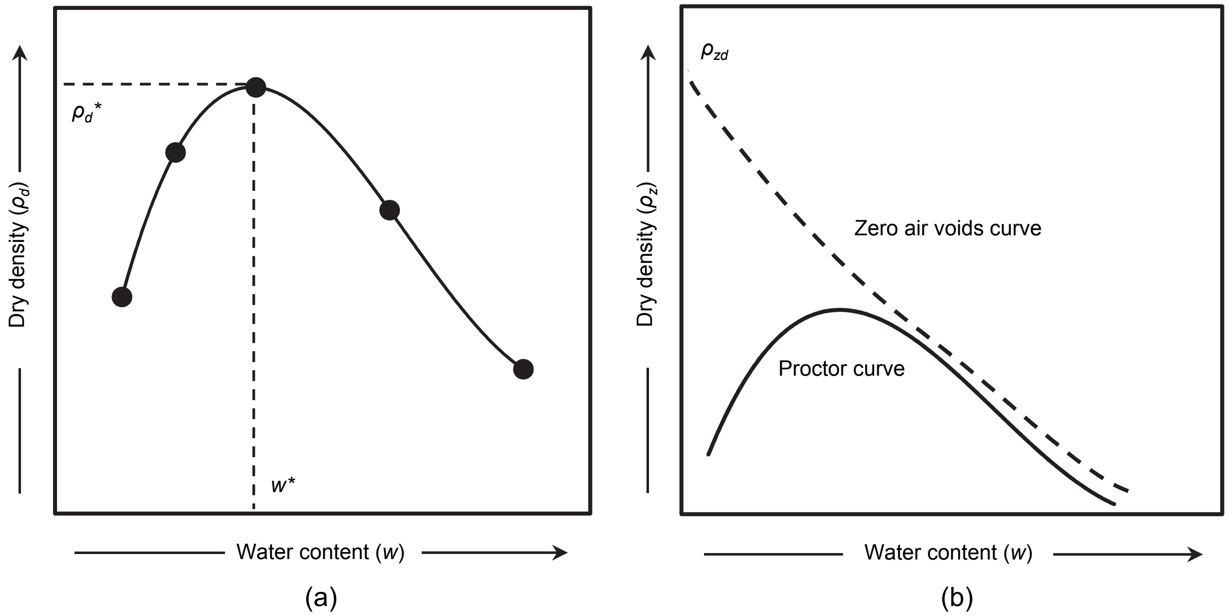


Figure 4-1. (a) Dry density versus water content as determined by the Proctor Test for soils and (b) proctor curve and zero air voids curve for soils

4.2.3 Research Objectives

Existing experimental methodologies to identify optimum moisture levels for briquette production are time consuming, labor intensive and fail to address fundamental aspects of this issue. Therefore, the objective of this study was to develop a methodology that minimizes time and materials required to identify the optimum water content of coal-biomass blends prior to briquette production. The fundamental theory presented in the standard Proctor Test for clay soils was adapted to coal-biomass briquette production to evaluate a number of hypotheses:

1. Water content of coal-biomass blends directly influences the dry density, strength and durability of briquettes;
2. Batch briquette production using a hydraulic press with a pellet mold can be used to predict optimum material properties for continuous roll press briquette production; and
3. Dry density is directly related to the crushing strength and mechanical durability of coal-biomass briquettes.

The secondary objective of this study was to compare and contrast the briquetting performance of three bituminous coals and one sub-bituminous coal. This was accomplished by evaluating the three hypotheses listed above for each of the coals studied, comparing the results of the evaluations and determining the sources of any inconsistencies.

4.3 Experimental

4.3.1 Materials

All briquettes produced for this study were composed of bituminous or sub-bituminous coal and sawdust. The three bituminous coals investigated for this study were obtained from preparations plants operated by Alpha Natural Resources in the Appalachian coal basin of the eastern United States and the sub-bituminous coal was obtained from a mine operated by Alpha Natural Resources in the Powder River Basin in the western United States. Specifically, the coal samples evaluated were:

1. Toms Creek: a high-volatile bituminous coal obtained from the Toms Creek preparation plant in Coeburn, Virginia;
2. McClure River: a medium-volatile bituminous coal obtained from the McClure River preparation plant in McClure, Virginia;

3. Emerald: a high-volatile, high-sulfur bituminous coal obtained from the Emerald mine preparation plant in Waynesburg, Pennsylvania; and
4. Eagle Butte: a sub-bituminous coal obtained from the Eagle Butte mine in Gillette, Wyoming.

The Toms Creek coal was a combined spiral and flotation clean product sampled from a screen bowl centrifuge in the preparation plant. Prior to briquette production, this coal was screened to a top size of one millimeter using a Uniflex two-deck screen, air dried for one week, split into two-kilogram lots and stored in sealed plastic bags. Several evaluations were performed to determine important physical properties of the coal, the results of which are included in Table 4-1. The moisture content of the coal prior to briquette production was 1.03% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The true density of the Toms Creek coal was 1.33 g/cm^3, which was determined by water displacement in a 250 milliliter volumetric flask. The size distribution of the crushed coal was measured by wet screening and analyzed using the Rosin-Rammler equation (Figure 4-2). Based on this analysis, the Toms Creek coal was found to have a mass median diameter of 239 microns, a size modulus of 0.36 and a distribution modulus of 0.88. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the coal (Table 4-2). Notable results of the analyses include a moisture and ash free heating value of 15,250 Btu/lb, an ash content of 11.30% (dry basis) and a sulfur content of 0.93% (dry basis).

Table 4-1. Physical properties of coal feedstocks

Physical Property	Toms Creek	McClure River	Emerald	Eagle Butte
Moisture Content (%)	1.03	0.93	1.60	1.80
True Density (g/cm^3)	1.33	1.27	1.27	1.27
Mass Median Diameter (μm)	239	266	301	295
Size Modulus	0.36	0.40	0.43	0.41
Distribution Modulus	0.88	0.91	1.02	1.16

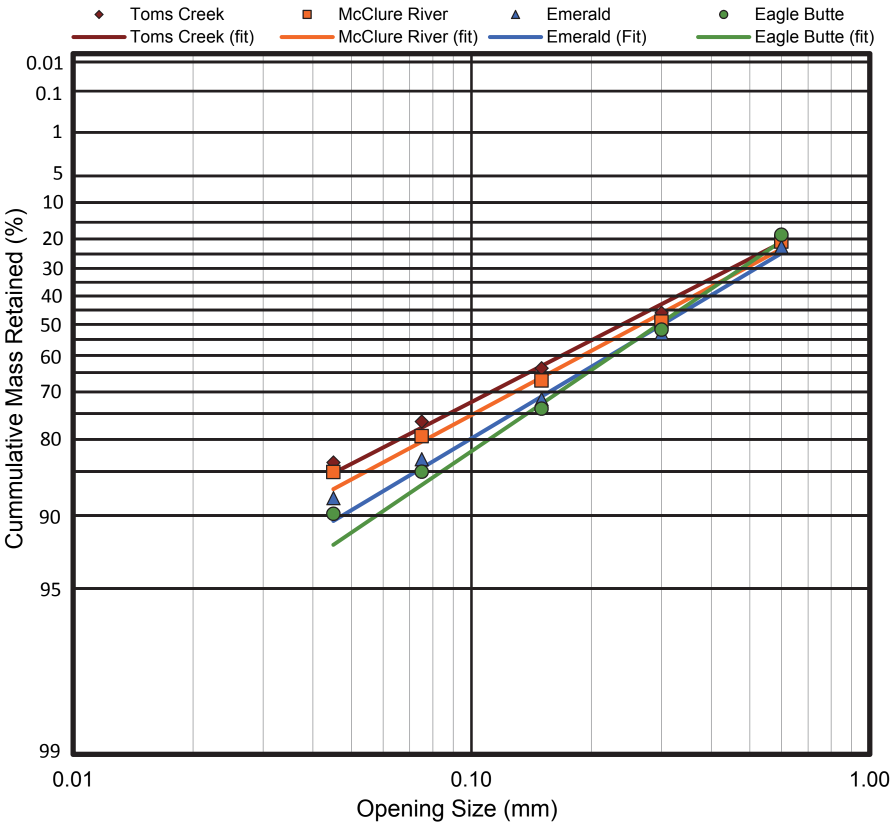


Figure 4-2. Particle-size distribution of coal samples

Table 4-2. Chemical properties of coal and biomass feedstocks

Chemical Property	Toms Creek		McClure River		Emerald		Eagle Butte		Sawdust	
	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis
Moisture (%)	13.73	--	7.89	--	4.28	--	29.08	--	9.42	--
Ash (%)	9.75	11.30	5.73	6.22	8.97	9.37	5.60	7.89	0.87	0.96
Sulfur (%)	0.80	0.93	0.81	0.88	3.04	3.18	0.64	0.90	0.05	0.05
Volatiles (%)	27.24	31.57	26.17	28.41	37.59	39.27	40.89	57.66	83.23	91.89
Fixed Carbon (%)	49.29	57.13	59.80	64.92	49.16	51.36	24.43	34.45	6.48	7.15
Carbon (%)	66.19	76.72	75.77	82.26	74.26	77.58	47.08	66.38	50.23	55.45
Hydrogen (%)	3.85	4.46	4.38	4.75	4.91	5.13	4.00	5.64	5.43	5.99
Nitrogen (%)	1.36	1.58	1.44	1.56	1.39	1.45	0.70	0.99	0.09	0.10
Oxygen (%)	4.32	5.01	0.05	0.05	3.15	3.29	12.91	18.20	33.92	37.45
HHV (Btu/lb)	11,670	13,527	12,963	14,073	13,245	13,837	8,149	11,490	7,718	8,521
MAF HHV (Btu/lb)	--	15,250	--	15,724	--	15,268	--	12,474	--	8,604

The McClure River coal was obtained from the clean coal stockpile at the preparation plant and was subjected to further processing prior to briquette production. Size reduction of the coal was accomplished by successive crushing in a jaw crusher, roll crusher and grinder. The coal was then screened to a top size of one millimeter using a Uniflex two-deck screen, air-dried for one week, split into two-kilogram lots and stored in sealed plastic bags. Again, several evaluations were performed to determine important physical properties of the coal, the results of which are included in Table 4-1. The moisture content of the coal prior to briquette production was 0.93% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The true density of the McClure River coal was 1.27 g/cm^3, which was determined by water displacement in a 250 milliliter volumetric flask. The size distribution of this coal was also measured by wet screening and analyzed using the Rosin-Rammler equation (Figure 4-2). Based on this analysis, the McClure River coal was found to have a mass median diameter of 266 microns, a size modulus of 0.40 and a distribution modulus of 0.91. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the McClure River coal (Table 4-2). Notable results of the analyses include a moisture and ash free heating value of 15,724 Btu/lb, an ash content of 6.22% (dry basis) and a sulfur content of 0.88% (dry basis).

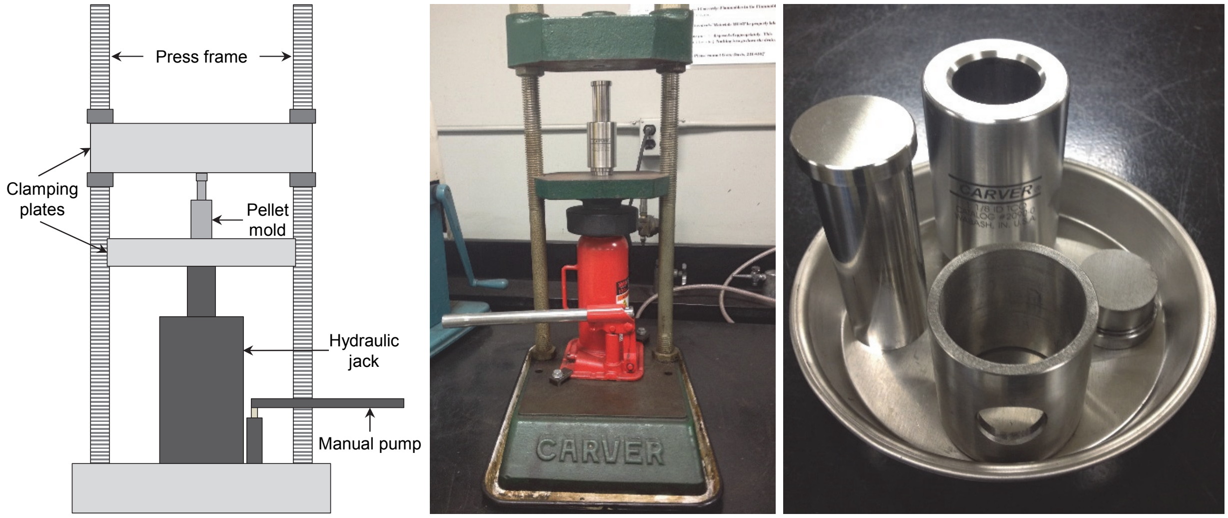
The Emerald coal was obtained from the clean coal stockpile at the preparation plant and was subjected to further processing prior to briquette production. Size reduction of the Emerald coal was accomplished by successive crushing in a jaw crusher, roll crusher and grinder. The coal was then screened to a top size of one millimeter using a Uniflex two-deck screen, air-dried for one week, split into two-kilogram lots and stored in sealed plastic bags. Again, several evaluations were performed to determine important physical properties of the coal, the results of which are included in Table 4-1. The moisture content of the coal prior to briquette production was 1.60% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The true density of the Emerald coal was 1.27 g/cm^3, which was determined by water displacement in a 250 milliliter volumetric flask. The size distribution of the crushed coal was measured by wet screening and analyzed using the Rosin-Rammler equation (Figure 4-2). Based on this analysis, the Emerald coal was found to have a mass median diameter of 301 microns, a size modulus of 0.43 and a distribution modulus of 1.02. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the Emerald coal (Table 4-2). Notable results of the analyses include a moisture and ash free heating value of 15,268 Btu/lb, an ash content of 9.37% (dry basis) and a sulfur content of 3.04% (dry basis).

The Eagle Butte coal was obtained from the raw coal stockpile of the Eagle Butte mine. Prior to briquette production, this coal was successively crushed in a jaw crusher, roll crusher and a grinder. The coal was then screened to a top size of one millimeter using a Uniflex two-deck screen, air dried for one week, oven dried at 105 degrees Celsius for 48 hours, split into two-kilogram lots and stored in sealed plastic bags. Again, several evaluations were performed to determine important physical properties of the coal, the results of which are included in Table 4-1. The moisture content of the Eagle Butte coal prior to briquette production was 1.80% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The true density of the Eagle Butte coal was 1.27 g/cm^3, which was determined by water displacement in a 250 milliliter volumetric flask. The size distribution was again analyzed using the Rosin-Rammler equation (Figure 4-2), which indicated that the coal had a mass median diameter of 295 microns, a size modulus of 0.41 and a distribution modulus of 1.16. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the Eagle Butte coal (Table 4-2). Notable results of the analyses include a moisture and ash free heating value of 12,474 Btu/lb and an ash content of 7.89% (dry basis).

The sawdust used for this study was maple wood obtained from a cabinet manufacturing facility in Christiansburg, Virginia. The sawdust was collected by a vacuum filter during the fine sanding process and was transported to the research laboratory in a sealed bulk bag. A split of the sample was then subjected to moisture analysis using the same procedure specified for the coal sample. The moisture content of the sawdust was found to be 5.45% (dry basis). Particle-size distribution was not determined for the ultra-fine sawdust because previous attempts to collect this information has indicated that the results are lack adequate precision and accuracy. However, ultimate and proximate analyses were conducted on a split of the sawdust sample (Table 4-2). Notable results of the analyses include a moisture and ash free heating value of 8,604 Btu/lb, an ash content of 0.96% (dry basis) and a sulfur content of 0.05% (dry basis).

4.3.2 Briquette Production

The theoretical approach to the standard Proctor Test for soils was adapted to design a procedure to maximize the dry density of coal-biomass briquettes by optimizing the water content of coal-biomass mixtures prior to briquette production. Unfortunately, the Proctor Test procedure was deemed unsuitable for experimental briquette production because it conflicts with several objectives of this study: (1) repeated hammer blows are not representative of the forces present in the roll press; (2) the size of the densified product is not comparable to the size of briquettes produced by the roll press; and (3) the mass of material required (i.e. 2.5 kg) does not minimize material requirements. Therefore, a modified approach to obtaining the plot of dry density versus water content was designed that better conforms to the objectives of this study. This modified approach, referred to as the Briquette Proctor Test, consists of producing individual briquettes in a manual hydraulic press using a pellet mold (Figure 4-3a) and subsequently measuring water content and dry density. The hydraulic press used in this study was a Carver Model C bench-top manual press with a maximum clamping force of 24,000 pounds-force (Figure 4-3b). The pellet mold used in combination with the press was a Carver No. 2090 stainless steel test cylinder with an interior diameter of 1.125 inches, which produces pellets with a surface area of one square inch (Figure 4-3c).



(a) (b) (c)

Figure 4-3. (a) Pellet press schematic drawing, (b) Carver pellet press laboratory installation and (c) Carver pellet mold

To evaluate the applicability of the Briquette Proctor Test, briquettes were produced with a total dry mass of 15 grams with 80 percent coal (dry basis) and 20 percent sawdust (dry basis). The water content of the blend was varied over a range of 0.01 to 0.15 for each of the three sets of bituminous coal-sawdust briquettes and over a range of 0.02 to 0.25 for the sub-bituminous coal-sawdust mixture. The sub-bituminous coal was evaluated over an elevated range of water contents because some preliminary data indicates that the optimum water content for sub-bituminous coal-biomass briquettes is higher than the range studied for bituminous coal-biomass briquettes.

For each individual briquette produced, between 12.11 and 12.22 grams of coal (depending on the water content of the specific coal) were homogenized with 3.16 grams of sawdust and a specified mass of water for five minutes in a KitchenAid five-quart stand mixer. Next, the mixture was carefully poured into the pellet mold and placed onto the Carver hydraulic press. The mold was then compressed until the force reading on the press reached 20,000 pounds-force. The pellet was immediately ejected to simulate a very low dwell time, as is common with roll press briquette production. Immediately after ejection from the mold, the pellet was tested for either water content or wet density, which was later corrected to dry density (ρ_d) by:

$$\rho_d = \rho_{wet}/(1+w) \tag{Eq. 4-4}$$

where ρ_{wet} is the calculated wet density and w is the calculated water content. It should be noted that two identical pellets were produced for each targeted water content because an individual pellet could not be tested for both water content and wet density.

To examine the relationship between results of the Briquette Proctor Test and roll press briquette production, pill-shaped briquettes (approximately 43 x 19 x 14 mm) were produced with a Komarek B-100R laboratory roll press equipped with 13-centimeter diameter rolls. The machine is comprised of two counter-rotating rolls, two hydraulic cylinders, a horizontal tapered screw and a paddle feeder (Figure 5-6). The hydraulic cylinders control the position of the upper roll and thus control the gap between the rolls. The paddle feeder is driven by a fixed speed motor and distributes the material to the horizontal screw that in turn feeds material to the rolls. The counter-rotating rolls and the horizontal screw are driven by variable speed motors, which enable adjustment of the torque applied to the material from the rolls and screw. The hydraulic cylinders control the position of the upper roll and thus control the gap between the rolls. The paddle feeder is driven by a fixed speed motor and distributes the material to the horizontal screw that in turn feeds material to the rolls. The counter rotating rolls and the horizontal screw are driven by variable speed motors, which enable adjustment of the torque applied to the material from the rolls and screw. For all briquettes produced with the B100R throughout this study, the rolls were driven at a motor speed of 450 rotations per minute with 100 kilonewtons of hydraulic force. The horizontal screw speed was adjusted during briquette production to maintain a roll torque of approximately 1000 to 1200 newton-meters.

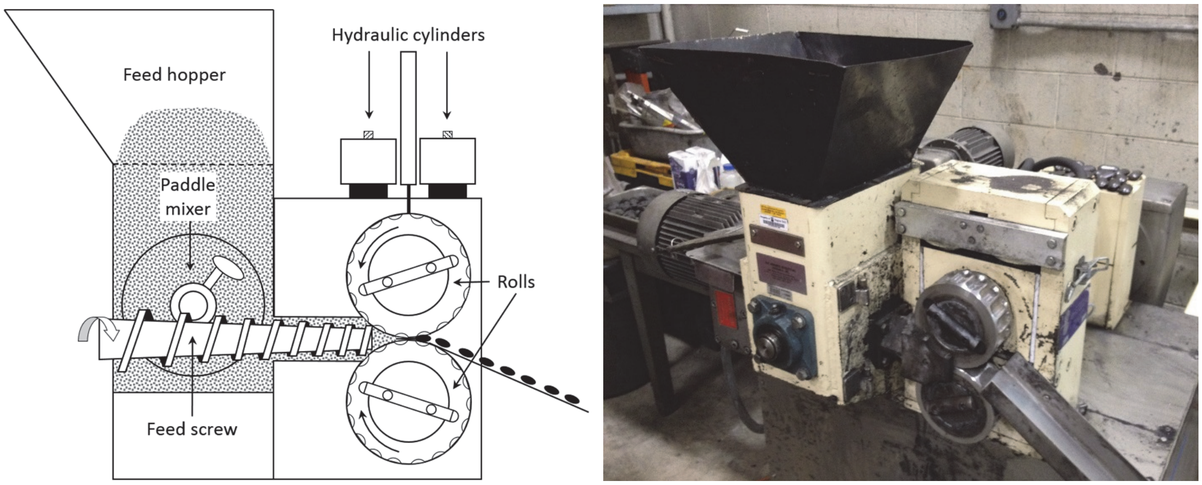


Figure 4-4. Komarek B-100R roll press (left) schematic diagram (modified from Guigon & Simon, 2003) and (right) laboratory installation

For roll press production, briquettes were produced in two kilogram batches with 80 percent coal and 20 percent sawdust on a dry mass basis. A calculated mass of water was added to each batch to reach a targeted water content. The water content of the blend was varied over a range of 0.007 to 0.082 for each of the three sets of bituminous coal-sawdust briquettes and over a range of 0.025 to 0.225 for the sub-bituminous coal-sawdust mixture. Next, the coal, biomass and water were homogenized for five minutes in a Hobart A200 20-quart commercial mixer. After mixing, a five-gram sub-sample of the homogenized feed was tested for water content, and the rest of the material was briquetted in the Komarek B-100R. Immediately after formation, the briquettes were screened across a Sweco vibrating separator equipped with a 0.5-inch screen to remove excess fines. The briquettes were then placed in an aluminum dish and immediately evaluated for water content, dry density, mechanical durability and crushing strength.

4.3.3 Briquette Characterization

4.3.3.1 Water Content

The water content of briquettes was determined by drying for 24 hours at 105 degrees Celsius in a drying oven. The mass of water in the briquettes was calculated by subtracting the dry mass of the briquettes from the initial mass before drying. The water content was then calculated by dividing the mass of water by the dry mass of the sample, as outlined in Equation 4-2. The water content of the briquettes produced with the roll press was measured immediately after briquette production and again roughly three hours later, after durability and strength measurements were conducted, to monitor the change in water content over time. In both instances, measurements were conducted on 10 individual briquettes and the average of the 10 values was reported as the water content. Water content of the feed material was measured prior to briquette production using an AND MF-50 moisture analyzer set at 105 degrees Celsius. Feed samples were dried until the change in mass was reduced to 0.05 percent per minute, at which point the displayed value was reported as the water content of the feed.

4.3.3.2 Dry Density

The dry density (i.e. dry particle density) of briquettes was calculated by first measuring the initial (wet) density and then calculating the dry density (ρ_d) based on the measured water content as outlined in Equation 4-4. To accomplish this, a density determination rig was used to measure the apparent mass of briquettes in a solution of water and detergent. The wet density (ρ_{wet}) was then calculated by:

$$\rho_{wet} = (m_a/(m_a - m_b))\rho_w \qquad \text{(Eq. 4-5)}$$

where m_a is the mass of the briquette in air, m_b is the apparent mass of the briquette in water and ρ_w is the density of the liquid. The dry density of the briquettes produced with the roll press was calculated immediately after briquette production and again roughly three hours later, after durability and strength measurements were conducted, to monitor the change in dry density over time. In both instances, the procedure was repeated for 10 briquettes produced with the roll press and the average of the 10 values was reported as the dry density. For both cases, the procedure was repeated for 10 briquettes and the average of the 10 values was reported as the dry density.

4.3.3.3 Mechanical Durability

The mechanical durability of briquettes was measured by tumbling 20 briquettes for five minutes at 40 rotations per minute in a 12-inch PVC cylinder equipped with three 2-inch lifters. The briquettes were then removed from the cylinder and screened in a Ro-tap sieve shaker for 30 seconds over a 4.75-millimeter sieve. The mechanical durability (MD) of the briquettes was then calculated by:

$$MD = 100 \times \left(m_{final}/m_{initial}\right) \qquad \text{(Eq. 4-6)}$$

where m_{final} is the mass of briquettes retained on the 4.75-millimeter sieve and $m_{initial}$ is the initial mass of the briquettes prior to durability testing. This procedure was repeated two times to ensure that the results were within two percent agreement.

4.3.3.4 Crushing Strength

The crushing strength of briquettes was determined using a Mark-10 M5-500 digital force gauge fitted with a four-inch diameter aluminum plate. The force gauge was mounted to a Mark-10 TSA750 manual test stand equipped with a one-inch diameter aluminum plunger that was used to apply force to the briquettes until failure. The force gauge was configured with a break detect feature which stops data acquisition once the applied force drops to 95 percent of the maximum force attained during each test. The crushing strength of each briquette was then reported as the maximum force attained during each test. To improve the accuracy of readings, an aluminum bar (51 x 8 x 8 millimeters) was placed upon the aluminum plate with each briquette then placed atop and parallel to the bar for testing. Evaluations were performed on 50 briquettes and the crushing strength was reported as the average of the 50 values.

4.4 Results and Discussion

4.4.1 Hydraulic Press Moisture Optimization

The results obtained using the Briquette Proctor Test are presented in Table 4-3 through Table 4-6 for each of the four coal types. These tables list the calculated water contents and dry densities of the coal-sawdust briquettes that were produced with the hydraulic press. The water contents of the produced briquettes typically varied by 10 to 20 percent from the target values due to the inherent variability of the coal and biomass feedstocks. The dry density of the Toms Creek-sawdust (TC-SD) briquettes ranged from 1.045 g/cm^3 at a water content of 0.010 to 0.923 g/cm^3 at a water content of 0.133, with a maximum value of 1.103 g/cm^3 at a water content of 0.037 (Table 4-3). Similarly, the dry density of the McClure River-sawdust (MR-SD) briquettes ranged from 0.997 g/cm^3 at a water content of 0.011 to 0.914 g/cm^3 at a water content of 0.125, with a maximum value of 1.066 g/cm^3 at a water content of 0.033 (Table 4-4). Moreover, the dry density of the Emerald-sawdust (EM-SD) briquettes ranged from 0.997 g/cm^3 at a water content of 0.011 to 0.901 g/cm^3 at a water content of 0.129, with a maximum value of 1.060 g/cm^3 at a water content of 0.025 (Table 4-5). The dry density of the TC-SD briquettes was clearly the highest of the three bituminous coal briquettes. This is most likely a direct result of the higher true density of the TC coal (i.e. 1.33 g/cm^3) as compared to the MR and EM coals (i.e. 1.27 g/cm^3). In contrast to results obtained for the three bituminous coals, the dry density of the Eagle Butte-sawdust (EB-SD) briquettes ranged from 0.862 g/cm^3 at a water content of 0.019 to 0.818 g/cm^3 at a water content of 0.238, with a maximum value of 0.922 g/cm^3 at a water content of 0.111 (Table 4-6).

Table 4-3. Summary of water content optimization results for TC-SD hydraulic press briquettes

Test ID	Water Content		Dry Density (g/cm^3)
	Target	Actual	
TC-SD-1H	0.01	0.010	1.045
TC-SD-2H	0.02	0.022	1.069
TC-SD-3H	0.03	0.026	1.096
TC-SD-4H	0.04	0.037	1.103
TC-SD-5H	0.05	0.042	1.091
TC-SD-6H	0.06	0.055	1.087
TC-SD-8H	0.08	0.072	1.044
TC-SD-10H	0.10	0.089	1.001
TC-SD-15H	0.15	0.133	0.923

Table 4-4. Summary of water content optimization results for MR-SD hydraulic press briquettes

Test ID	Water Content		Dry Density (g/cm^3)
	Target	Actual	
MR-SD-1H	0.01	0.011	0.997
MR-SD-2H	0.02	0.018	1.043
MR-SD-3H	0.03	0.025	1.049
MR-SD-4H	0.04	0.033	1.066
MR-SD-5H	0.05	0.039	1.065
MR-SD-6H	0.06	0.050	1.051
MR-SD-8H	0.08	0.063	1.022
MR-SD-10H	0.10	0.082	0.982
MR-SD-15H	0.15	0.125	0.914

Table 4-5. Summary of water content optimization results for EM-SD hydraulic press briquettes

Test ID	Water Content		Dry Density (g/cm^3)
	Target	Actual	
EM-SD-1H	0.01	0.011	0.997
EM-SD-2H	0.02	0.018	1.033
EM-SD-3H	0.03	0.025	1.060
EM-SD-4H	0.04	0.033	1.059
EM-SD-5H	0.05	0.043	1.047
EM-SD-6H	0.06	0.049	1.041
EM-SD-8H	0.08	0.068	1.021
EM-SD-10H	0.10	0.083	0.962
EM-SD-15H	0.15	0.129	0.901

Table 4-6. Summary of water content optimization results for EB-SD hydraulic press briquettes

Test ID	Water Content		Dry Density (g/cm^3)
	Target	Actual	
EB-SD-2H	0.02	0.019	0.862
EB-SD-4H	0.04	0.037	0.906
EB-SD-6H	0.06	0.057	0.920
EB-SD-8H	0.08	0.080	0.919
EB-SD-10H	0.10	0.095	0.914
EB-SD-12H	0.12	0.111	0.922
EB-SD-15H	0.15	0.146	0.921
EB-SD-20H	0.20	0.189	0.883
EB-SD-25H	0.25	0.238	0.818

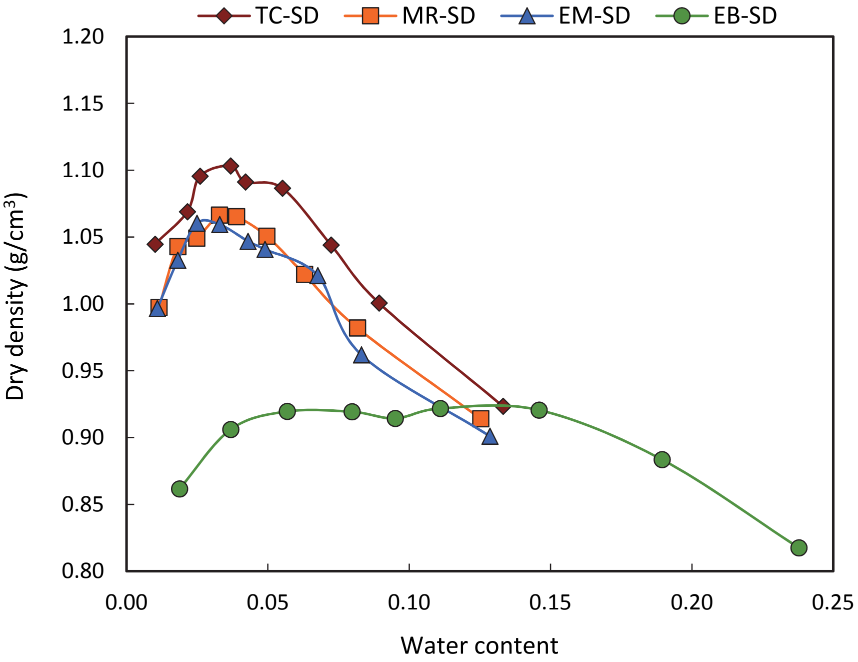


Figure 4-5. Correlation between water content and dry density for all hydraulic press briquettes

The calculated water content and dry density values for each of the four coals are displayed graphically in Figure 4-5. In this figure and throughout the remainder of this analysis, maroon diamonds represent TC-SD data, orange squares represent MR-SD data, blue triangles represent EM-SD data and green circles represent EB-SD, unless otherwise specified. It is evident from this figure that the water content of the feed greatly influenced the dry density of the briquettes. As predicted, the Briquette Proctor Test results depicted in Figure 4-5 for the three bituminous coal briquettes (i.e. TC-SD, MR-SD and EM-SD) are very similar to the standard Proctor curve for clay soils. Conversely, the correlation between water content and dry density of the sub-bituminous coal briquettes (i.e. EB-SD) is more obscure and appears to have a wide range of optimum water content values.

Although maximum dry density values were easily determined using the Briquette Proctor Test, there was actually a range of water content values that produced briquettes within a narrow band of near-optimum dry density values. For example, the dry density of the TC-SD briquettes varied between 1.087 g/cm^3 and 1.10^3 g/cm3 for water contents of 0.026, 0.037, 0.042 0.055. This suggests that a range of water contents can be targeted to approach the maximum dry density for briquettes produced with the hydraulic press. As a result, the selection of the optimum water content for a particular application could be chosen based on other considerations, such as the economic tradeoff between an incremental increase in dry density (i.e. quality) and the incremental cost of drying materials to a particular water content. It is also evident from Figure 4-5 that water contents outside of the optimum range produce briquettes with much lower dry densities. For example, the minimum dry density of the TC-SD briquettes was found to be 0.923 g/cm^3 at a water content of 0.133, which represents a decrease of 16.3 percent from the maximum achieved dry density. Similarly, the dry density of the MR-SD briquetted decreased by 14.3 percent from the maximum to the minimum value, while the dry density of the EM-SD briquettes decreased by 15.0 percent and the dry density of the EB-SD briquettes decreased by 11.3 percent.

To further investigate the similarity of the three bituminous coals with respect to the water content and dry density of briquettes produced with a hydraulic press, normalized dry density values were calculated and compared. Normalizing the dry density results enables the direct comparison of the compaction behavior of the three coals without regarding the differences in true density, size modulus and bulk modulus. Each of these properties influence the measured dry density values, but are not believed to have any effect on the relationship between water content and dry density in compaction processes. Measured dry density values were normalized by dividing the individual dry density values by the maximum achieved dry density for each coal type. The result is displayed in Figure 4-6, which clearly shows the high degree of similarity in the compaction behavior of the three coals. This indicates that the fundamental compaction mechanisms are the same for bituminous coals, even though individual properties can impact dry density values.

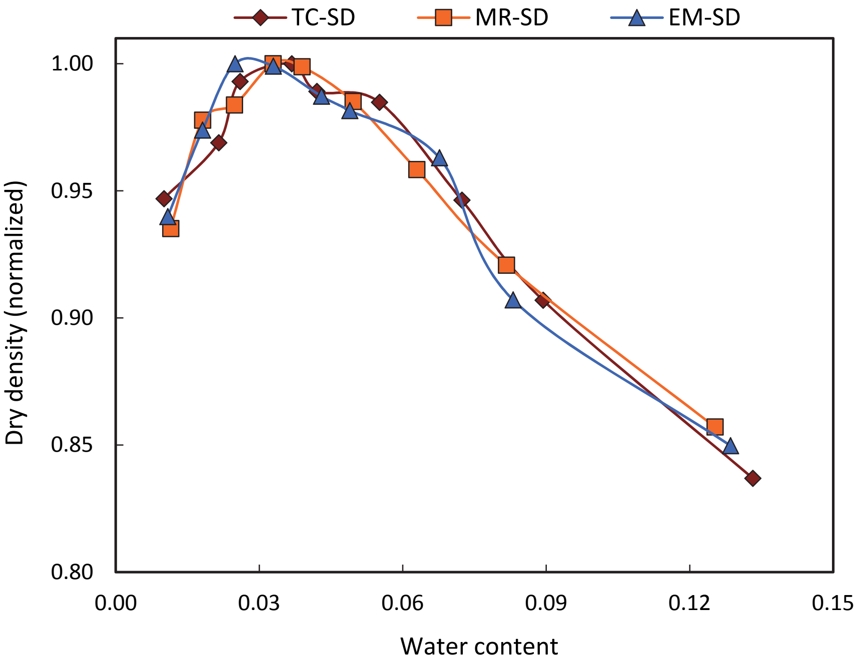


Figure 4-6. Correlation between water content and normalized dry density for the bituminous coal briquettes produced with the hydraulic press

4.4.2 Roll Press Moisture Optimization

The results of the continuous roll press briquetting tests are presented in Table 4-7 through Table 4-10 for each of the four coal types. These tables list the calculated water content, dry density, mechanical durability and crushing strength values of the coal-sawdust briquettes as determined by the procedures outlined in 4.3.3. The briquette water content and dry density values listed in each table represent the average dry density and water content values for the initial tests and those conducted roughly three hours after briquette production. The water content of the homogenized feed material typically varied by 10 to 20 percent from the target feed moisture, which is thought to be a result of imperfect mixing and sampling, as well as the inherent variability of the coal and biomass feedstocks. Another interesting observation was that the water content of the briquettes was consistently lower than the water content of the feed material. The source of this discrepancy is most likely a combination of water evaporation from heat produced during roll press briquette production and water loss due to air-drying prior to briquette evaluations.

Table 4-7. Summary of water content optimization results for TC-SD roll press briquettes

Test ID	**Feed Water Content**		**Briquette Water Content**	**Dry Density (g/cm$^{3)}$**	**Mechanical Durability (%)**	**Crushing Strength (lb$_f$)**
	Target	**Actual**				
TC-SD-0.7R	0.007	0.008	0.006	1.10	85.4	145.2
TC-SD-1.5R	0.015	0.016	0.014	1.14	91.9	180.6
TC-SD-2.2R	0.022	0.023	0.018	1.16	92.9	219.2
TC-SD-3.7R	0.037	0.039	0.029	1.14	92.5	210.9
TC-SD-5.2R	0.052	0.049	0.038	1.12	88.2	179.5
TC-SD-6.7R	0.067	0.068	0.050	1.10	76.9	108.8
TC-SD-8.2R	0.082	0.083	0.063	1.06	63.1	60.4

Table 4-8. Summary of water content optimization results for MR-SD roll press briquettes

Test ID	**Feed Water Content**		**Briquette Water Content**	**Dry Density (g/cm$^{3)}$**	**Mechanical Durability (%)**	**Crushing Strength (lb$_f$)**
	Target	**Actual**				
MR-SD-0.7R	0.007	0.011	0.011	1.12	93.3	189.9
MR-SD-1.5R	0.015	0.016	0.014	1.13	94.4	192.1
MR-SD-2.2R	0.022	0.022	0.017	1.15	95.1	269.4
MR-SD-3.7R	0.037	0.038	0.028	1.12	94.3	252.0
MR-SD-5.2R	0.052	0.045	0.037	1.10	89.8	200.7
MR-SD-6.7R	0.067	0.060	0.051	1.04	81.0	109.2
MR-SD-8.2R	0.082	0.075	0.065	1.01	69.4	59.6

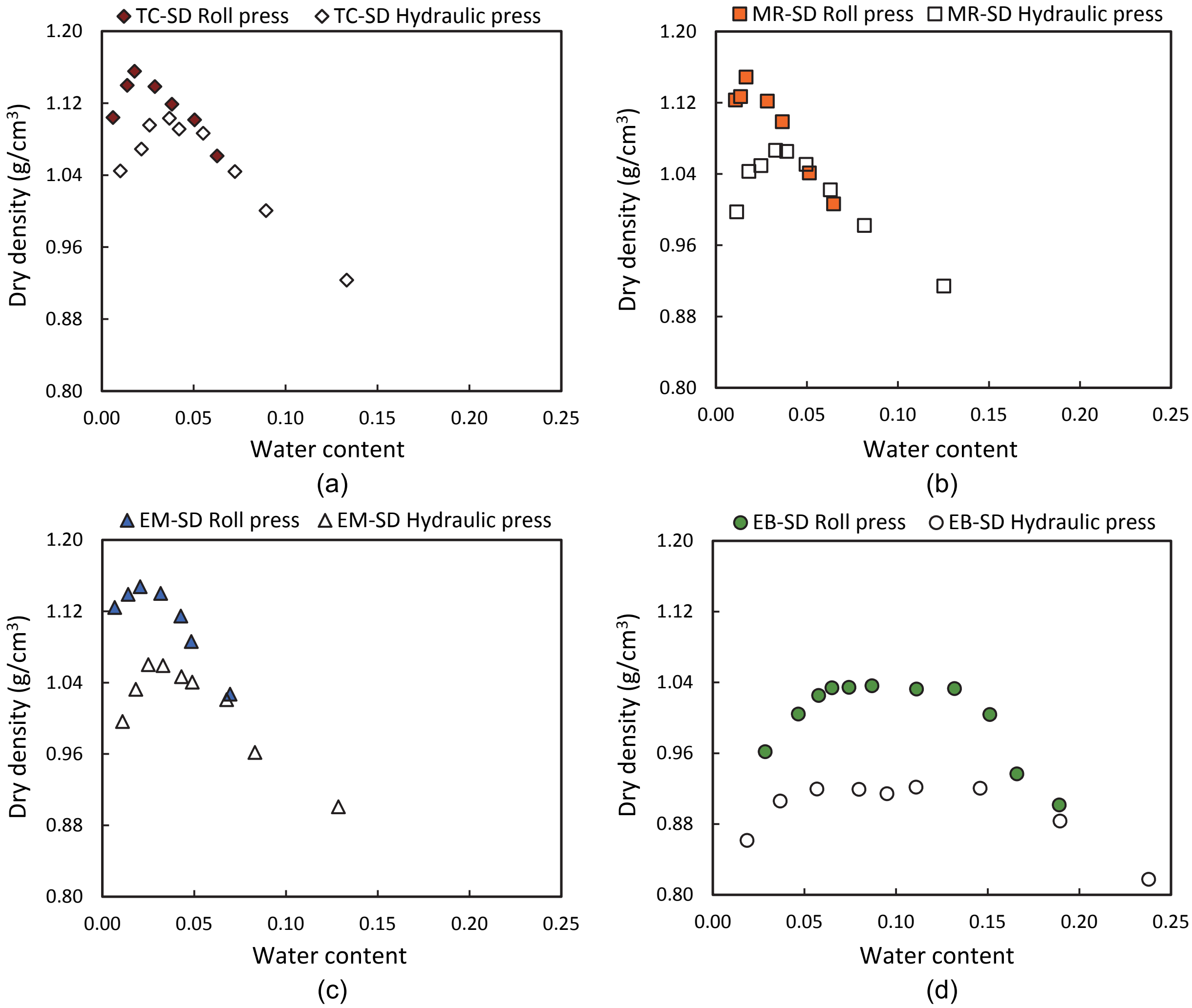
Table 4-9. Summary of water content optimization results for EM-SD roll press briquettes

Test ID	**Feed Water Content**		**Briquette Water Content**	**Dry Density (g/cm$^{3)}$**	**Mechanical Durability (%)**	**Crushing Strength (lb$_f$)**
	Target	**Actual**				
EM-SD-0.7R	0.007	0.007	0.007	1.12	94.0	240.7
EM-SD-1.5R	0.015	0.018	0.014	1.14	94.7	267.5
EM-SD-2.2R	0.022	0.025	0.021	1.15	95.2	279.2
EM-SD-3.7R	0.037	0.044	0.032	1.14	95.0	299.4
EM-SD-5.2R	0.052	0.052	0.043	1.11	92.2	236.6
EM-SD-6.7R	0.067	0.069	0.048	1.09	85.1	141.9
EM-SD-8.2R	0.082	0.082	0.070	1.03	73.0	81.3

Table 4-10. Summary of water content optimization results for EB-SD roll press briquettes

Test ID	Feed Water Content		Briquette Water Content	Dry Density (g/cm^3)	Mechanical Durability (%)	Crushing Strength (lb$_f$)
	Target	Actual				
EB-SD-2.5R	0.025	0.040	0.029	0.96	54.2	85.7
EB-SD-4.0R	0.040	0.049	0.047	1.00	65.7	106.9
EB-SD-5.5R	0.055	0.053	0.058	1.03	71.0	118.5
EB-SD-7.0R	0.070	0.072	0.065	1.03	75.2	133.7
EB-SD-8.5R	0.085	0.084	0.074	1.03	77.7	147.1
EB-SD-10.0R	0.100	0.100	0.087	1.04	81.1	166.6
EB-SD-12.5R	0.125	0.127	0.111	1.03	85.7	220.7
EB-SD-15.0R	0.150	0.143	0.132	1.03	86.8	234.8
EB-SD-17.5R	0.175	0.169	0.151	1.00	87.3	206.6
EB-SD-20.0R	0.200	0.170	0.166	0.94	84.0	131.3
EB-SD-22.5R	0.225	0.188	0.189	0.90	71.3	100.5

The calculated water content and dry density values of the roll press briquettes and the hydraulic press briquettes for each of the four coals are displayed graphically in Figure 4-7. A visible shift in the location of the optimum dry density and water content of the roll press briquettes is apparent. For example, the maximum dry density of the TC-SD briquettes (Figure 4-7a) was 1.16 g/cm^3, which occurred at a water content of 0.018. Although this shift to higher dry density and lower water content was found, the data points for briquettes produced with the roll press appear to fall on the same zero air voids curve as the data from briquettes produced with the hydraulic press. This suggests that the maximum value of the zero air voids density is very similar for briquettes produced with both types of presses. It is believed that the shift in optimum values occurred due to differences in the mechanisms of compression present in the roll press and hydraulic press. Specifically, the only force applied by the hydraulic press is a uniaxial compression force. In contrast, briquettes produced with the roll press are fed by a variable speed screw into rotating rolls held together by a uniaxial compression force, which creates torque. During this dynamic process, friction forces produce heat that also aids in the compaction and densification process. Nonetheless, these finding suggest that the Briquette Proctor Test can be used to determine a range of water content values for coal-biomass blends in which the optimum water content for roll press briquette production likely exists.



(a) (b) (c) (d)

Figure 4-7. Correlation between water content and dry density for (a) TC-SD briquettes, (b) MR-SD briquettes, (c) EM-SD briquettes and (d) EB-SD briquettes

The results of the roll press briquetting tests further validate the similarity in the compaction behavior of the three bituminous coals investigated. As with the results presented in the previous section, the TC-SD roll press briquettes (Figure 4-7a), MR-SD roll press briquettes (Figure 4-7b) and EM-SD roll press briquettes (Figure 4-7c) all exhibit the same relationship between water content and dry density, wherein the maximum dry density occurs at a slightly higher dry density and lower water content than the results from the hydraulic press tests indicated. Specifically, the maximum dry densities of the three bituminous coal briquettes ranged from 1.15 g/cm^3 to 1.16 g/cm^3 over a water content range of 0.017 to 0.021. Another similarity of these results and the hydraulic press results is that the dry density of the TC-SD briquettes was again the highest of the three bituminous coal samples. In contrast to the bituminous coal results, the maximum dry density of the EB-SD roll press briquettes was 1.04 g/cm^3, which occurred at a water content of 0.087 (Figure 4-7d). This result further exemplifies the difference in the compaction behavior of sub-bituminous coal as compared to bituminous coal.

Normalized dry density values were calculated and compared to further investigate the similarity of the three bituminous coals with respect to briquette water content and dry density. As shown in Figure 4-8, the normalized dry density values for the three bituminous coals are very comparable over the range of water contents evaluated. However, the visual similarity of these results is not as pronounced as the results presented for the hydraulic press briquettes (i.e. Figure 4-6), even though the location of the maximum dry density is very similar. The most probable reason for the decreased similarity in the relationship between briquette water content and dry density is the greater forces present in roll press systems, which leads to a greater discernment between samples.

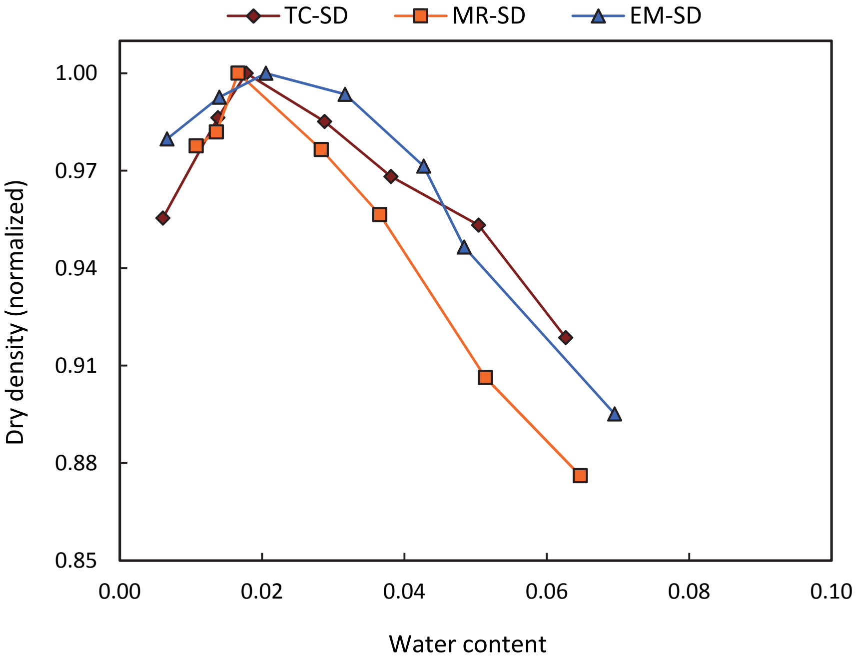


Figure 4-8. Correlation between water content and normalized dry density for the bituminous coal briquettes produced with the roll press

4.4.3 Correlations between Briquette Properties

Crushing strength and mechanical durability were measured for each batch of briquettes produced with the roll press to determine the influence of water content and dry density on these quality indicators. The water content of each type of briquettes is plotted versus mechanical durability in Figure 4-9. The highest mechanical durability value for the TC-SD briquettes was 92.9%, which occurred at a water content of 0.018. Similarly, the highest mechanical durability values for the MR-SD (95.1%) and EM-SD briquettes (95.2%) occurred at water contents of 0.017 and 0.021, respectively. In contrast, the maximum mechanical durability of the EB-SD briquettes was 87.3%, which occurred at a water content of 0.151. It is evident from Figure 4-9 that mechanical durability values decrease significantly when water content is varied outside of a small range of near-optimum values. For example, an increase in the water content of TC-SD briquettes from 0.018 to 0.063 resulted in a 32.1 percent decrease in mechanical durability and a decrease in the water content of EB-SD briquettes from 0.151 to 0.029 led to a 37.9 percent decrease in mechanical durability. Moreover, an increase in the water content of MR-SD briquettes from 0.017 to 0.065 resulted in a 27.0 percent decrease in mechanical durability and an increase in the water content of EM-SD briquettes from 0.021 to 0.070 led to a 23.3 percent decrease in mechanical durability.

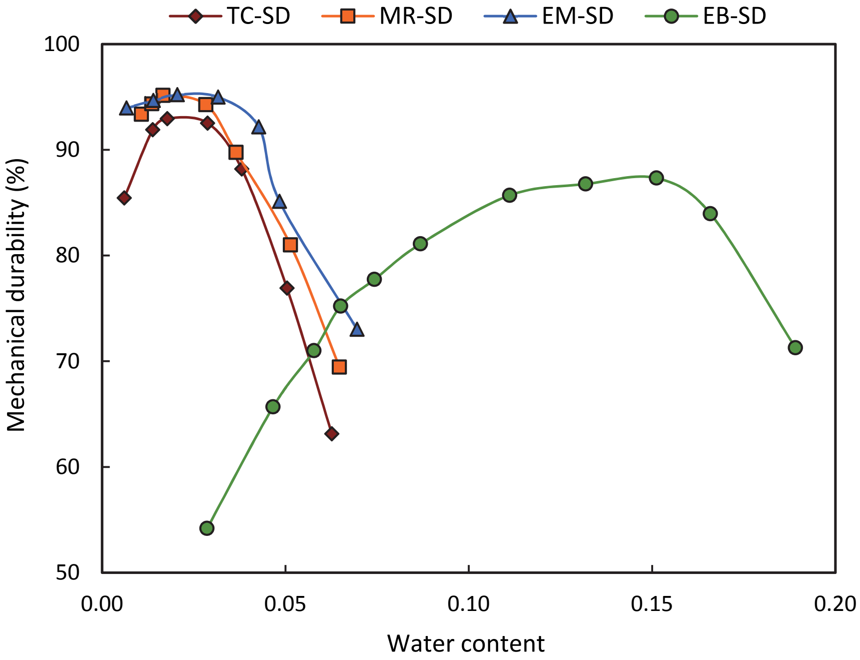


Figure 4-9. Correlation between water content and mechanical durability for all roll press briquettes

The water content of each type of briquettes is plotted versus crushing strength in Figure 4-10. The highest crushing strength value for the TC-SD briquettes was 219.2 lb_f, which occurred at a water content of 0.018. Similarly, the highest crushing strength values for the MR-SD (269.4 lb_f) and EM-SD briquettes (299.4 lb_f) occurred at water contents of 0.017 and 0.032, respectively.

The maximum crushing strength of the EB-SD briquettes (234.8 lb_f) was similar in magnitude to the bituminous coal briquettes, but it occurred at a water content of 0.132. It is evident from Figure 4-10 that a dramatic decrease in crushing strength occurs when water content is varied outside of a small range of near-optimum values. For example, an increase in the water content of TC-SD briquettes from 0.018 to 0.063 resulted in a 72.4 percent decrease in crushing strength and a decrease in the water content of EB-SD briquettes from 0.132 to 0.029 led to a 63.5 percent decrease in crushing strength. Moreover, an increase in the water content of MR-SD briquettes from 0.017 to 0.065 resulted in a 77.9 percent decrease in crushing strength and an increase in the water content of EM-SD briquettes from 0.032 to 0.070 led to a 72.8 percent decrease in crushing strength.

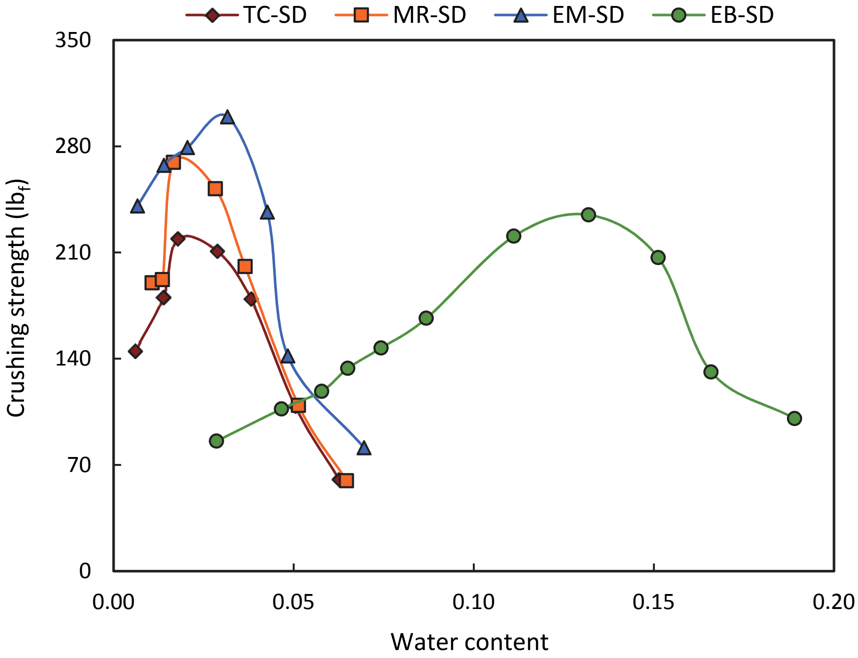
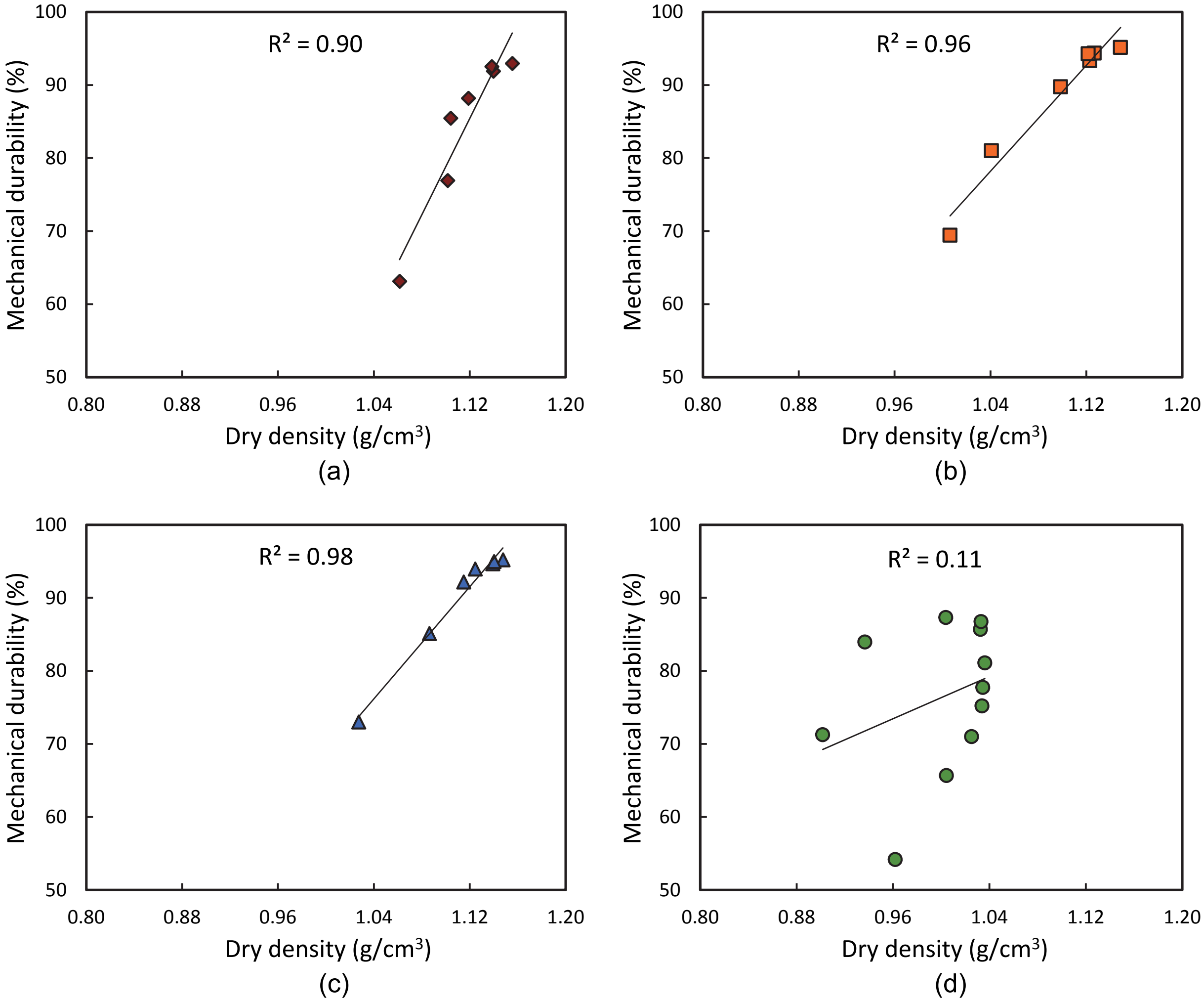


Figure 4-10. Correlation between water content and crushing strength for all roll press briquettes

The reason for significant variances in the mechanical durability and crushing strength of the different types of bituminous coal briquettes cannot be definitively determined. However, it appears that the distribution modulus, which is the measure of the spread of particle size distribution as calculated by the Rosin-Rammler equation, and ash content are the major sources of these variations. Specifically, the distribution modulus appears to have the largest impact on strength and durability, with higher distribution moduli corresponding to greater strength and durability of briquettes. For example, the distribution modulus of the Emerald coal was the highest of the three coal samples (1.02), and the EM-SD briquettes had the greatest crushing strength (299.4 lb$_f$) and mechanical durability (95.2%). In contrast, the distribution modulus of the McClure River coal was 0.91, and the MR-SD briquettes exhibited lower crushing strength (269.4 lb$_f$) and mechanical durability (95.1%). Similarly, the distribution modulus of the Toms Creek coal was the lowest of the three bituminous coal samples (0.88), and the TC-SD briquettes were found to have the lowest strength (219.2 lb$_f$) and durability (92.9%).

Further examination revealed that the difference in maximum strength and maximum durability of MR-SD briquettes and TC-SD briquettes (i.e. 50.2 lb$_f$ and 2.2%) is much greater than the difference observed between MR-SD briquettes and EM-SD briquettes (i.e. 30 lb$_f$ and 0.01%). However, the difference in the distribution modulus of McClure River coal and Toms Creek coal (i.e. 0.03) is significantly less than the difference in the distribution modulus of McClure River coal and Emerald coal (i.e. 0.11). Therefore, the distribution modulus is not the only significant factor that influences briquette strength and durability. The other significant variable appears to be ash content, which would account for the significant difference in strength and durability of MR-SD briquettes (MR ash = 6.22%) and TC-SD briquettes (TC ash = 11.30%), despite a very small difference in the calculated distribution moduli. Thus, it appears that ash content is inversely related to briquette strength and durability. Still, the data does not indicate that ash content has as large of an influence on briquette strength and durability as distribution modulus. This is supported by the fact that the EM-SD briquettes are superior to the MR-SD briquettes in both strength and durability, yet the ash content of the Emerald coal (i.e. 9.37%) is higher than that of the McClure River coal (i.e. 6.22%).

An interesting correlation is that between dry density and the mechanical durability of the coal-biomass briquettes. To visualize this correlation, the measured mechanical durability values were plotted versus the calculated dry density values, as shown in Figure 4-11. A least squares linear regression was performed to model the relationship between these two variables. The results of the regression analysis are provided in Figure 4-11 for each type of coal. The coefficient of determination (R^2) was calculated for each trend line to quantify the fit of the data to the linear regression model. These results are provided in Figure 4-11a for the TC-SD briquettes, Figure 4-11b for the MR-SD briquettes, Figure 4-11c for the EM-SD briquettes and Figure 4-11d for the EB-SD briquettes.

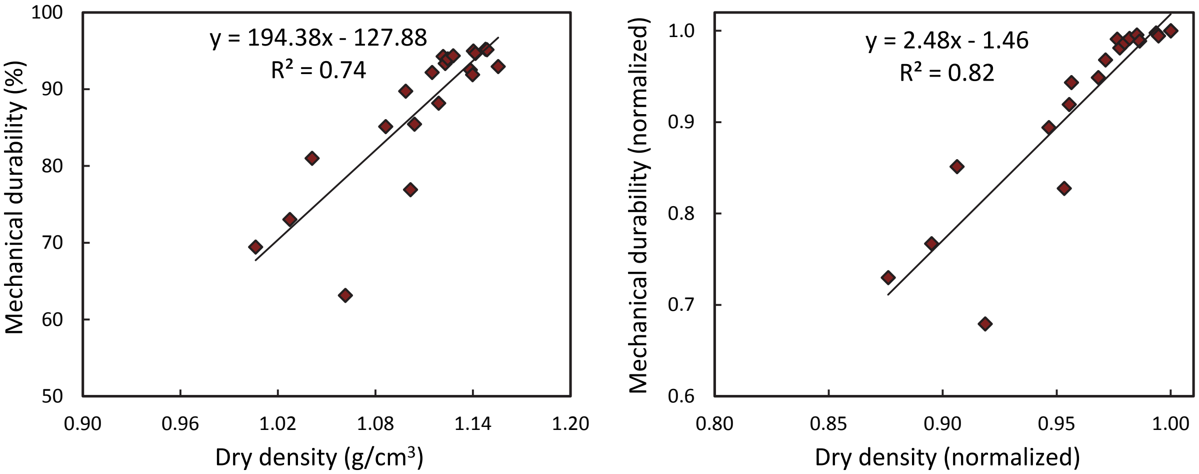


(a) (b) (c) (d)

Figure 4-11. Linear correlation between mechanical durability and dry density for (a) TC-SD briquettes, (b) MR-SD briquettes, (c) EM-SD briquettes and (d) EB-SD briquettes

The individual R-squared values for each bituminous coal type were very high, which indicates that a strong linear correlation exists between the dry density and mechanical durability of each set of briquettes. Specifically, the EM-SD briquettes were found to have the highest R-squared value (0.98) followed closely by the MR-SD briquettes (0.96) and the TC-SD briquettes (0.90). To determine if a correlation exists between all of the bituminous coal briquette data, the 21 pairs of dry density and mechanical durability data displayed in Figure 4-11a through Figure 4-11c were combined into a single data set (Figure 4-12a) and a linear regression was again performed. The coefficient of determination of the data fit to this model was 0.74, which indicates that the dry density and mechanical durability of bituminous coal-biomass briquettes fits a generalized linear model fairly well, regardless of the physical and chemical properties of the coal.

For reference, the derived empirical equation is included in Figure 4-12a. To provide additional insight to this relationship, the dry density and mechanical durability values of the 21 bituminous coal data pairs were normalized and a linear regression was again performed (Figure 4-12b). The calculated R^2 value for this model was 0.82, which represents a 10.8 percent improvement in the fit of the model to the data. Again, the derived empirical formula is included in Figure 4-12b for reference.



(a) (b)

Figure 4-12. (a) Linear correlation between mechanical durability and dry density for the combined data from the three bituminous coals and (b) linear correlation between normalized mechanical durability and normalized dry density for the combined data from the three bituminous coals

In contrast to the findings for the bituminous coals, the EB-SD briquettes were found to have a very low R-squared value (0.11), which suggests that little or no correlation exists between dry density and mechanical durability of sub-bituminous coal-biomass briquettes. However, further investigation of the trend displayed in Figure 4-11d reveals that a correlation does exist between the dry density and mechanical durability of the EB-SD briquettes. To visualize this correlation, the dry density and mechanical durability data was divided into two sets: (1) increasing dry density values, which include the first six test results in Table 4-10 (i.e. water contents of 0.029 to 0.087), and (2) decreasing dry density values, which include the last six test results in Table 4-10 (i.e. water contents of 0.087 to 0.189). A linear regression was then performed independently on each data set to determine if an independent linear correlation exists between briquettes of increasing and decreasing dry densities. As displayed in Figure 4-13, the two sets of data fit the independent linear models much better than the single model presented in Figure 4-11d, as evidenced by an R^2 value of 0.94 for the increasing dry density data and an R-squared value of 0.51 for the decreasing dry density data. This clearly demonstrates that linear correlations do exist between dry density and mechanical durability values for sub-bituminous coal-biomass briquettes.

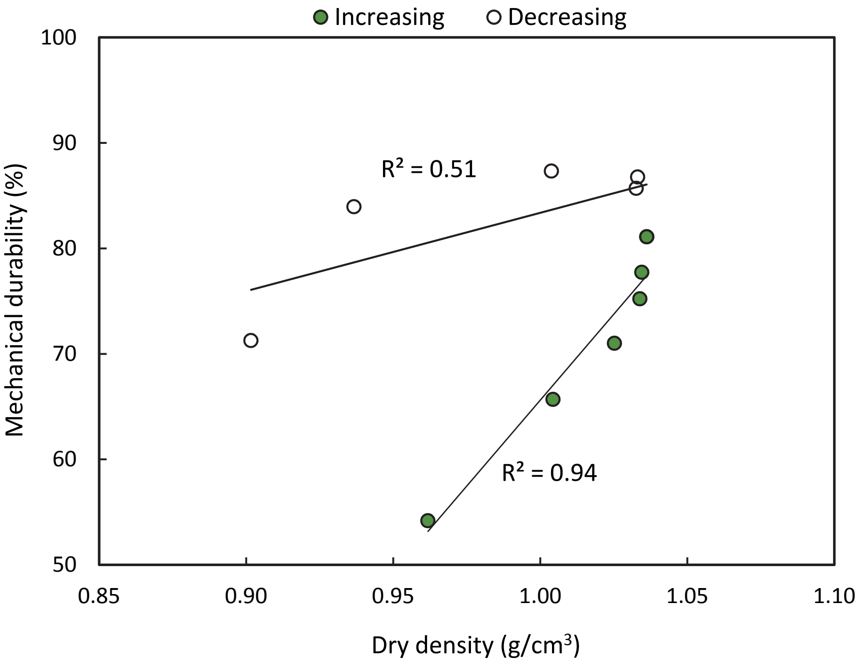


Figure 4-13. Linear correlations between mechanical durability and dry density of EB-SD briquettes for increasing and decreasing dry density values

Another interesting observation is the correlation between dry density and the crushing strength of the coal-biomass briquettes. To visualize this correlation, the measured crushing strength values were plotted versus the calculated dry density values, as shown in Figure 4-14. A least squares linear regression was performed to model the relationship between these two variables. The results of the regression analysis are provided in Figure 4-14 for each type of coal. The coefficient of determination was calculated for each trend line to quantify the fit of the data to the linear regression model. These results are provided in Figure 4-14a for the TC-SD briquettes, Figure 4-14b for the MR-SD briquettes, Figure 4-14c for the EM-SD briquettes and Figure 4-14d for the EB-SD briquettes. The R-squared values for each bituminous coal type were very high, which indicates that a strong linear correlation exists between the dry density and crushing strength for each coal type. Specifically, the EM-SD briquettes were found to have the highest R-squared value (0.94) followed closely by the TC-SD briquettes (0.92) and the MR-SD briquettes (0.89).

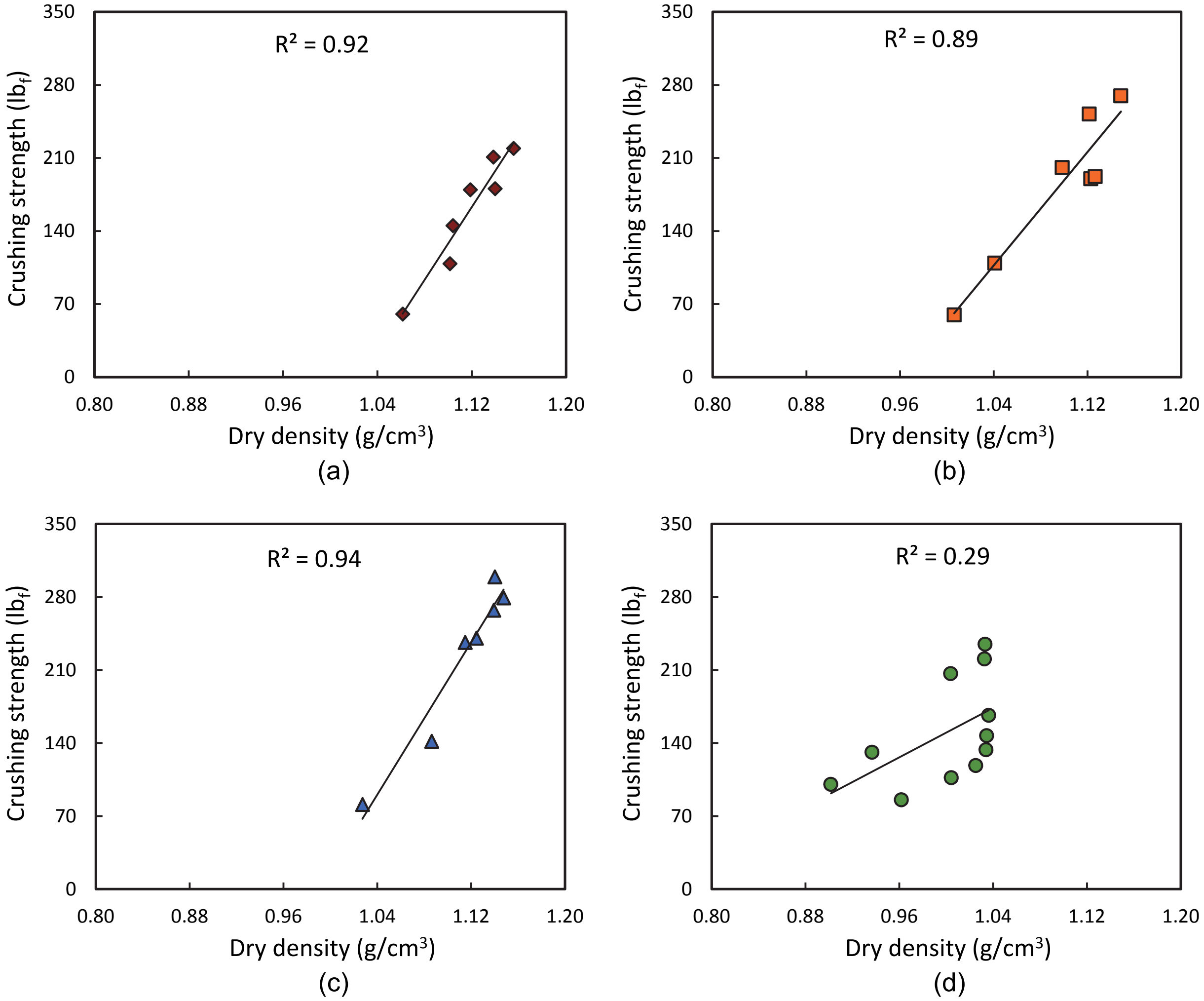


Figure 4-14. Linear correlation between crushing strength and dry density for (a) TC-SD briquettes, (b) MR-SD briquettes, (c) EM-SD briquettes and (d) EB-SD briquettes

To determine if a correlation exists between all of the bituminous coal briquette data, the 21 pairs of dry density and crushing strength data displayed in Figure 4-14a through Figure 4-14c were combined into a single data set (Figure 4-15a) and a linear regression was again performed. The coefficient of determination of the data fit to this model was 0.73, which indicates that the dry density and crushing strength of bituminous coal-biomass briquettes fits a generalized linear model fairly well, regardless of the physical and chemical properties of the coal. For reference, the derived empirical equation is included in Figure 4-15a. To provide additional insight to this relationship, the dry density and crushing strength values of the 21 bituminous coal data pairs were normalized and a linear regression was again performed (Figure 4-15b). The calculated R-squared value for this model was 0.88, which represents a 20.5 percent improvement in the fit of the model to the data. Again, the derived empirical formula is included in Figure 4-15b for reference.

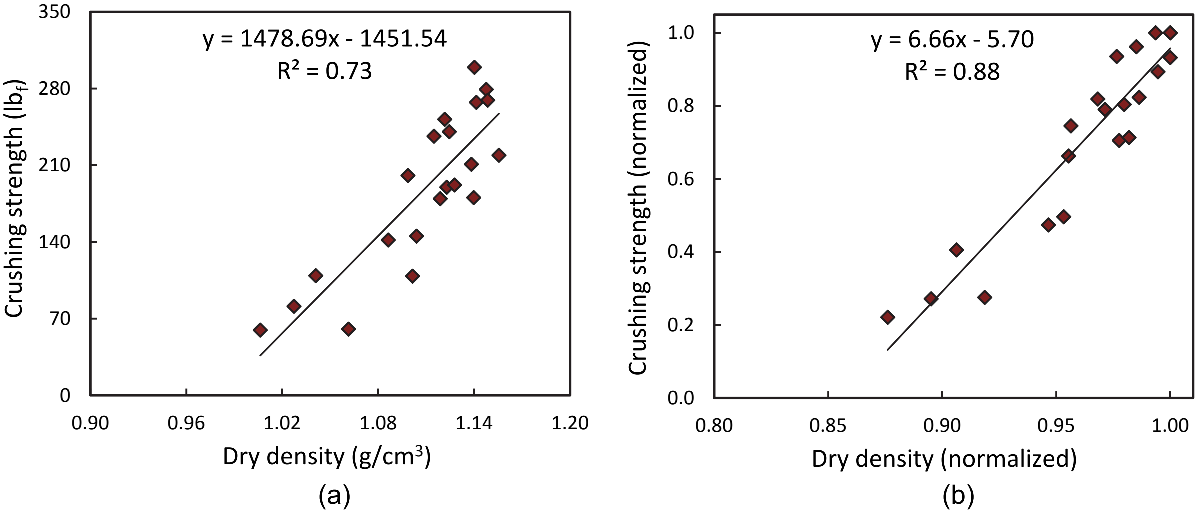


Figure 4-15. (a) Linear correlation between crushing strength and dry density for the combined data from the three bituminous coals and (b) linear correlation between normalized crushing strength and normalized dry density for the combined data from the three bituminous coals

In contrast to the findings for the bituminous coals, the EB-SD briquettes were found to have a very low R-squared value (0.29), which suggests that little or no correlation exists between dry density and mechanical durability of sub-bituminous coal-biomass briquettes. However, further investigation of the trend displayed in Figure 4-14d reveals that a correlation does exist between the dry density and mechanical durability of the EB-SD briquettes. To visualize this correlation, the dry density and mechanical durability data was divided into two sets: (1) increasing dry density values, which include the first six test results in Table 4-10 (i.e. water contents of 0.029 to 0.087), and (2) decreasing dry density values, which include the last six test results in Table 4-10 (i.e. water contents of 0.087 to 0.189). A linear regression was then performed independently on each data set to determine if an independent linear correlation exists between briquettes of increasing and decreasing dry densities. As displayed in Figure 4-16, the two sets of data fit the independent linear models much better than the single model presented in Figure 4-14d, as evidenced by an R-squared value of 0.77 for both the increasing and decreasing dry density data. This clearly demonstrates that linear correlations do exist between dry density and mechanical durability values for sub-bituminous coal-biomass briquettes.

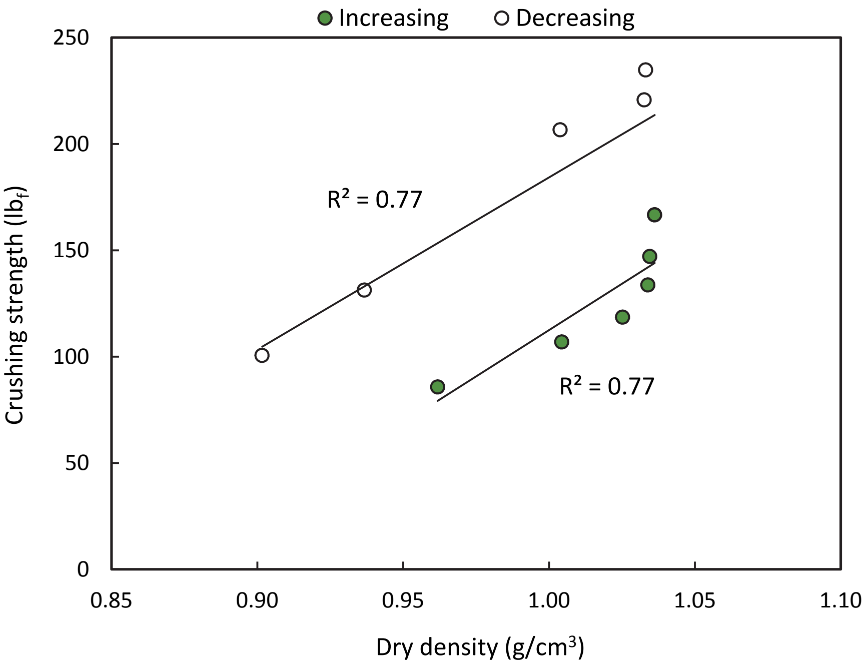


Figure 4-16. Linear correlations between crushing strength and dry density of EB-SD briquettes for increasing and decreasing dry density values

To analyze the relationship between mechanical durability and crushing strength, the two quality indicators were plotted against one another for each coal type, as shown in Figure 4-17. An exponential regression was performed to model the relationship between these two quality indicators. The results of the regression analysis are provided in Figure 4-11 for each type of coal. The coefficient of determination was calculated for each trend line to quantify the fit of the data to the exponential regression model. These results are provided in Figure 4-17a for the TC-SD briquettes, Figure 4-17b for the MR-SD briquettes, Figure 4-17c for the EM-SD briquettes and Figure 4-17d for the EB-SD briquettes. The individual R^2 values for each coal type were very high, which indicates that a strong exponential correlation exists between the mechanical durability and crushing strength of the briquettes. Specifically, the TC-SD briquettes were found to have the highest R-squared value (0.99) followed closely by the EM-SD briquettes (0.98) and the MR-SD briquettes (0.95). For the EB-SD briquettes, the fit of the data to the exponential model was not as precise, as evidenced by an R-squared value of 0.80. Nonetheless, the strong correlation between mechanical durability and crushing strength indicates that as the mechanical durability of coal-biomass briquettes increases in a moisture optimization process, the crushing strength typically increases at an exponential rate. This suggests that measurement of both crushing strength and mechanical durability is not needed to locate optimum moisture with respect to briquette quality.

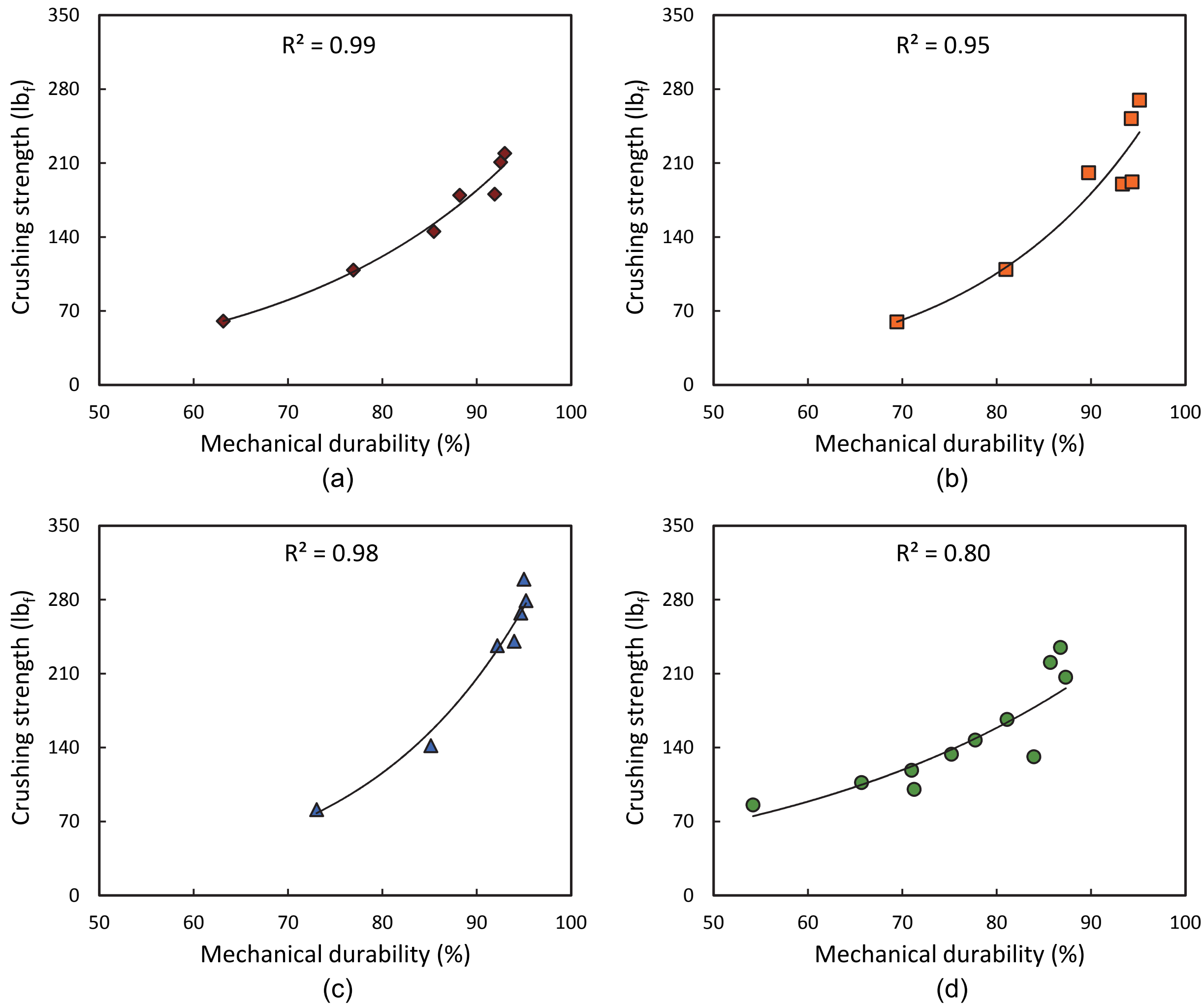


Figure 4-17. Exponential correlation between mechanical durability and crushing strength for (a) TC-SD briquettes, (b) MR-SD briquettes, (c) EM-SD briquettes and (d) EB-SD briquettes

4.5 Summary and Conclusions

The primary objective of this study was to develop a methodology that minimizes time and materials required to identify the optimum water content of coal-biomass blends prior to briquette production. In support of this effort, the Briquette Proctor Test was developed based on the theoretical compaction concepts employed by the Proctor Test for clay soils. Accordingly, three hypotheses were formulated and evaluated to determine the applicability of this novel test method. The secondary objective of this study was to compare and contrast the briquetting performance of three bituminous coals and one sub-bituminous coal. This was accomplished by evaluating the three hypotheses for each of the coals studied, comparing the results of the evaluations and determining the sources of any inconsistencies.

The first hypothesis stated that the water content of coal-biomass blends directly influences the dry density, crushing strength and mechanical durability of briquettes. A peak in dry density was easily identified for each coal type at a particular water content for the roll press and hydraulic press briquettes. The water content that corresponded to the maximum dry density of the bituminous coal-sawdust briquettes was in the range of 0.017 to 0.021. In contrast, the water content that corresponded to the maximum dry density of the sub-bituminous coal-sawdust briquettes was in the range of 0.058 to 0.132. The results obtained by the Briquette Proctor Test proved that water content does indeed influence the dry density of coal-biomass briquettes very similarly to the influence of water content on the dry density of compacted clay soils as determined by the Proctor Test. Additionally, a peak in mechanical durability and crushing strength values was easily observed for each coal type. The major sources of inconsistencies in the dry density, mechanical durability and crushing strength of the bituminous coal-sawdust briquettes was determined to be the distribution modulus and ash content. Specifically, it was determined that a positive correlation exists between distribution modulus and each briquette quality and a negative correlation exists between ash content and each briquette quality.

The second hypothesis stated that batch briquette production using a hydraulic press with a pellet mold is representative of continuous roll press briquette production. From the dry density versus water content results for briquettes produced with both types of presses, it is clear that the hydraulic press gives a good indication of the results that would be expected with the roll press. However, the peak value of dry density calculated for briquettes produced with the roll press occurred at a lower water content and was greater in magnitude than the values recorded for briquettes produced with the hydraulic press. Although this shift was observed, both sets of data appear to fall on the same zero air voids curve, which suggests that the maximum value of the zero air voids density is very similar for both data sets. This shift is thought to be a result of a temperature increase and the presence of other forces that occurs with roll press briquette production.

The final hypothesis stated that dry density is directly related to the crushing strength and mechanical durability of coal-biomass briquettes. To test this theory, the calculated values of dry density were plotted versus the measured crushing strength and mechanical durability values for each coal type and a linear regression model was fitted to each data set. For each of the bituminous coals studied, a very high coefficient of determination was calculated for both crushing strength and mechanical durability. To determine the similarity of the compaction behavior of the three bituminous coals, the data sets were combined and fitted with a linear regression model, which found fairly decent correlations between dry density and mechanical durability ($R^2 = 0.74$), and between dry density and crushing strength ($R^2 = 0.73$). Although these values could have been higher, they are deemed acceptable due to the inherent variability of coal-biomass briquettes.

These findings suggest that an exhaustive experimental moisture optimization study for roll press briquetting coal-biomass mixtures could be streamlined by simply determining the water content that results in the highest dry density. It is likely that the maximum crushing strength and mechanical durability of the briquettes exist at or near this value as well. In addition to reducing the time required to perform evaluations, the Briquette Proctor Test also reduces material requirements as significantly fewer briquettes are required to locate optimum conditions. Another major implication of these findings is the realization that bituminous coals with similar water contents exhibit very similar compaction behavior regardless of the physical and chemical properties of the coals. However, sub-bituminous coals exhibit very different compaction behavior than bituminous coals, and thus require independent investigation. Ultimately, moisture optimization will improve the quality of briquettes and promote the co-utilization of coal-biomass feedstocks.

4.6 References

Basu, P., Butler, J., & Leon, M. (2011). Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. *Renewable energy, 36*(1), 282-288.

EN 15150 (2011). *Solid biofuels − Determination of particle density*. Brussels, Belgium: European Committee for Standardization.

Fernando, R. (2009). *Co-gasification and indirect cofiring of coal and biomass*. London, England: IEA Clean Coal Centre.

Honaker, R., Parekh, B., Taulbee, D., & Tao, D. (2005). *Premium fuel production from mining and timber waste using advanced separation and pelletizing technologies*. Washington, DC: U.S. Department of Energy.

Kaliyan, N. & Morey, R. (2009). Factors affecting strength and durability of densified biomass products. *Biomass and bioenergy, 33*(3), 337-359.

Lindeburg, M. (1989). *Civil engineering reference manual* (5th ed.). Belmont, CA: Professional Publications, Inc.

Mangena, S. & Cann, V. (2007). Binderless briquetting of some selected South African prime coking, blend coking and weathered bituminous coals and the effect of coal properties on binderless briquetting. *International journal of coal geology, 71*(2-3), 303-312.

Mani, S., Tabil, L., & Sokhansanj, S. (2003). An overview of compaction of biomass grinds. *Powder handling and processing, 15*(3), 160-168.

Patil, D., Taulbee, D., Parekh, B., & Honaker, R. (2009). Briquetting of coal fines and sawdust - Effect of particle size distribution. *International journal of coal preparation and utilization*, *29*(1), 251-264.

Pietsch, W. (2002). *Agglomeration processes: Phenomena, technologies, equipment*. Weinheim, Germany: Wiley-VCH.

Sami, M., Annamalai, K., & Wooldridge, M. (2001). Co-firing of coal and biomass fuel blends. *Progress in energy and combustion science, 27*(2), 171-214.

Taulbee, D., Neathery, J., Patil, D., Sowder, N., O'Daniel, B., & Montross, M. (2010). Combustion of Briquettes and Fuels Pellets Prepared from Blends of Biomass and Fine Coal. In R. Honaker (Ed.), *International coal preparation congress 2010 conference proceedings*. Littleton, CO: Society for Mining, Metallurgy, and Exploration.

Taulbee, D., Patil, D., Honaker, R., & Parekh, B. (2009). Briquetting of coal fines and sawdust Part I: Binder and briquetting-parameters evaluations. *International journal of coal preparation and utilization, 29*(1), 1-22.

Tumuluru, J., Wright, C., Hess, J., & Kenney, K. (2011). A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. *Biofuels, bioproducts and biorefining, 5*(6), 683-707.

Chapter 5

Evaluation of Briquette Production Variables

5.1 Abstract

Experimental optimization of coal-biomass briquette production is an essential task to improve the strength and durability of briquettes. In support of this challenge, an exhaustive bench-scale study was conducted to examine the most significant feedstock, additive and roll press variables in coal-biomass briquette production. Additional work was performed to identify optimum process conditions for each variable, which were defined for this study as the conditions that contribute to production of coal-biomass briquettes with the greatest crushing strength and mechanical durability. In addition, work was conducted to compare and contrast the quality of briquettes composed of four coal types and five biomass types. Lastly, a comprehensive series of tests were conducted to characterize the physical properties, flow properties and gasification behavior of selected coal-biomass briquettes to verify the enhanced quality of co-briquetted feedstocks. The results of this study show that biomass content and water content are the most statistically significant mixture variables with regard to the crushing strength and mechanical durability of coal-biomass briquettes. The results also confirm that starch content is a very statistically significant mixture variable with regard to the crushing strength and mechanical durability of coal-biomass briquettes. Another important finding is that roll torque is the most statistically significant roll press operating variable with regard to the particle density, crushing strength and mechanical durability of coal-biomass briquettes. Finally, it is shown that binderless coal-biomass briquettes produced at optimized conditions exhibit very high crushing strength and mechanical durability values, which indicate that the briquettes would remain competent in the presence of forces encountered in handling, storage and transportation. Binderless coal-biomass briquettes produced at optimized conditions also exhibit excellent gasification behavior. This confirms that coal-biomass briquettes are exceptional gasification feedstocks for the co-production of power and synthetic fuels.

5.2 Introduction

5.2.1 Problem Statement

Co-utilization of biomass with coal in existing coal-fired facilities presents a unique opportunity to reduce greenhouse gas emissions and increase energy production from renewable resources. Significant interest in this opportunity has led to more than 150 coal-fired power stations across the world co-firing coal and biomass on a commercial or trial basis as of 2009 (Fernando, 2009). These co-firing experiences have revealed a number of technical challenges including upstream issues, such as biomass availability, transportation, storage, and handling, as well as problems encountered during energy conversion, such as fouling, corrosion, inconsistent feeding and segregation (Basu et al., 2011; Sami et al., 2001). Recent studies suggest that many of these challenges can be mitigated by reconstituting coal-biomass mixtures into larger particles. Specifically, roll press briquetting has been investigated to produce homogeneous, free-flowing feedstocks that minimize handling and segregation problems often encountered with combustion and gasification systems (Taulbee et al., 2010; Honaker et al., 2005).

One of the major challenges surrounding this technology is the degradation of coal-biomass briquettes during handling, transportation and storage. Fortunately, the strength and durability of briquettes can be greatly improved by optimizing the briquette production process. Despite its perceived simplicity, roll press briquetting is a complex process that is characterized by a number of design variables, which makes theoretical prediction of briquette quality extremely difficult. As a result, optimization of roll press briquetting is best accomplished by a series of laboratory tests, from which empirical models can be developed for particular feedstocks (Dec & Komarek, 1997). Therefore, experimental optimization of the briquetting process is essential to enhance the quality and marketability of coal-biomass briquettes.

5.2.2 Roll Press Briquette Production

5.2.2.1 Compaction Theory

The potential binding mechanisms employed in briquette production processes are generally classified into five major groups by the nature of particle-particle interactions: (1) solid bridges, (2) adhesion and cohesion forces, (3) surface tension and capillary pressure, (4) attraction forces between solids and (5) interlocking bonds (Rumpf, 1962). These groups of forces can be further divided into several subgroups, and in practice, a combination of forces act simultaneously within briquettes to bond individual particles to one another. Figure 2-8 depicts the potential particle binding mechanisms in briquette production processes.

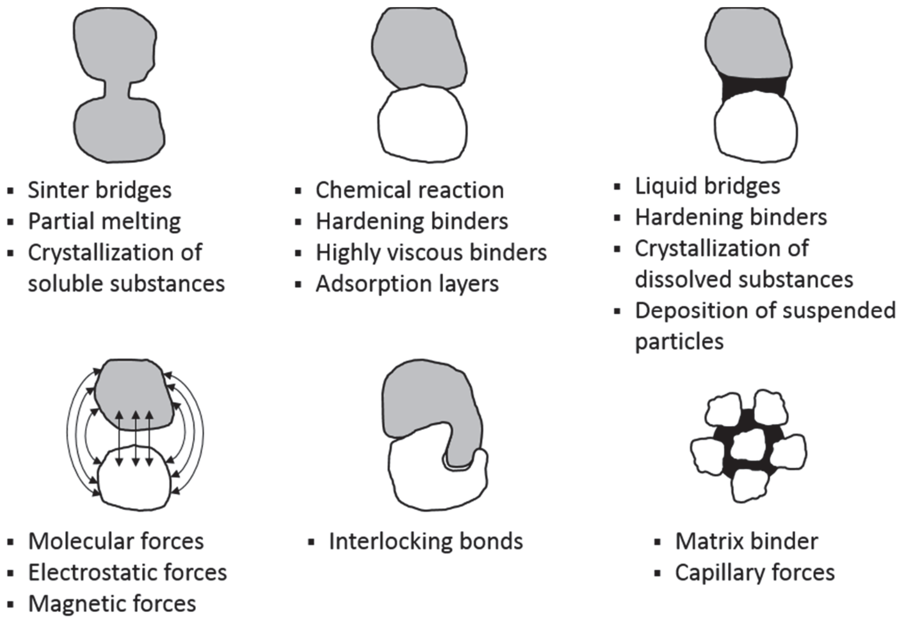


Figure 5-1. Particle binding mechanisms in briquette production (modified from Pietsch, 2002)

The mechanisms of compaction in briquette production can be divided into two stages. In the initial stage, low pressures cause bulk particles to settle and rearrange, which results in a reduction of porosity and an increase in bulk density. The total surface area of contact between particles also increases during this stage and bonds are formed through liquid bridges and capillary pressure (Drzymala, 1993). At this point, briquettes are relatively weak and require additional compaction pressure to improve strength and durability. In the second stage, much higher pressures are exerted on the densified mass, which results in the fracture of brittle particles and/or plastic deformation of malleable materials (Pietsch, 2002). Additional bonds are formed during this stage by activation of interparticle adhesive forces, which occurs when the surface area of contact between particles is further increased and the distance between particles becomes extremely small. Figure 2-13 provides a schematic representation of these processes.

The top half of this figure shows the structural change of particulate solids with the progression of compaction, densification, fragmentation and plastic deformation that occurs with increasing pressure. The bottom half of the figure depicts the increase in pressing force at a constant compression rate over a period of time until the maximum pressure (P_{max}) is reached.

Beyond this point, the pressure drops and expansion of compressed air and/or elastic spring-back can crack and weaken briquettes, which can lead to partial or complete degradation if not adequately addressed. One method to reduce the effects of elastic spring-back and expansion of compressed air is to reduce the speed of compaction, which in turn increases the amount of time material remains confined under the influence of the load. This parameter is referred to as dwell time (Pietsch, 2002). Another method to reduce the effects of these mechanisms is deaeration of the feed material prior to briquette formation. This is typically accomplished by selection of the proper feeding mechanism (e.g. paddle feeder and tapered screw) for a particular application.

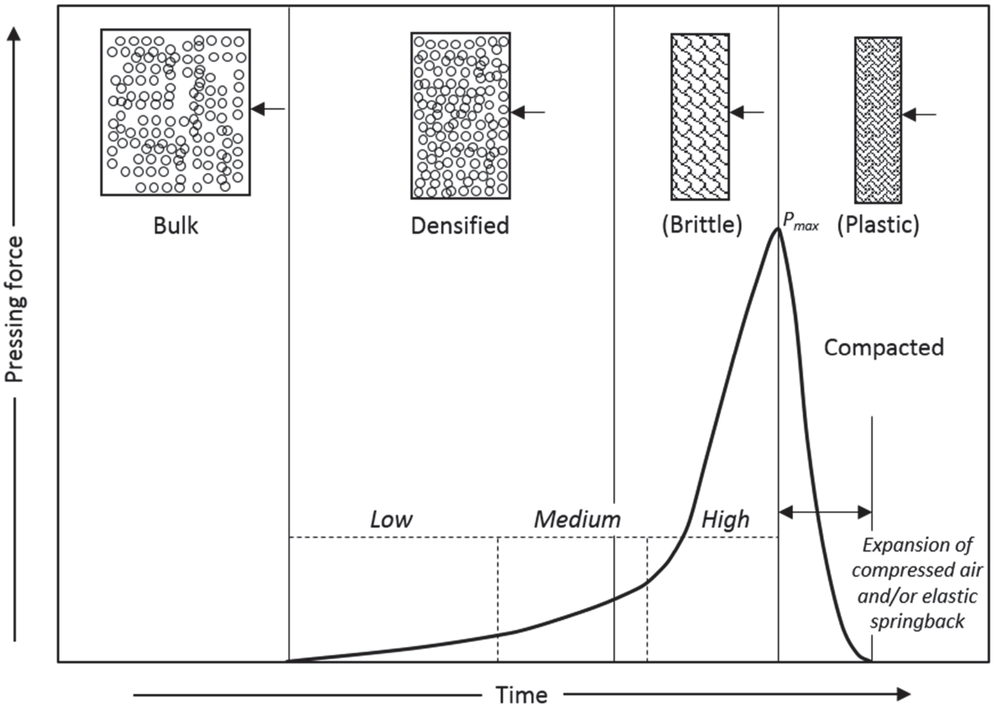
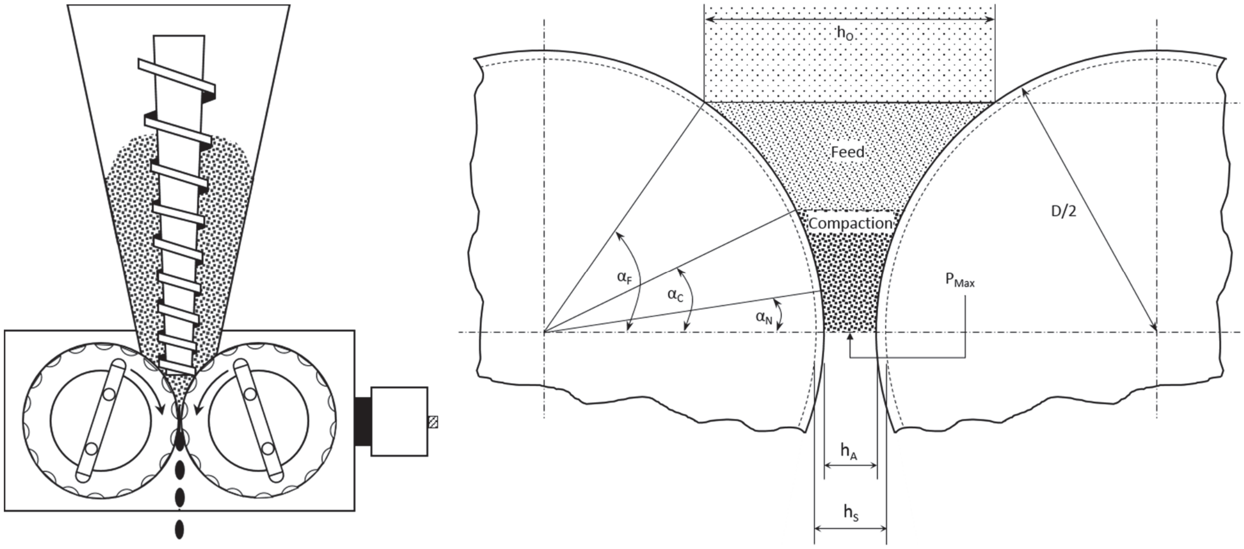


Figure 5-2. Mechanisms of compaction in briquette production (modified from Pietsch, 2002)

5.2.2.2 Roll Press Machines

Roll pressing is the most widely used pressure agglomeration technology for size enlargement of particulate solids in the mineral processing industry. Originally developed to agglomerate coal fines, roll presses are characterized by two identical counter-rotating rolls held together by an applied force that compact particulate material as it is drawn between the rolls. In roll press briquetting machines, particulate solids are force or gravity fed through pocket rollers to produce briquettes of uniform size and shape (Figure 5-3a). This process produces a 'web' or 'flash' material on the edges of the briquettes due to the flat area around each pocket. The majority of the web material is typically removed by screening the briquettes after formation and recycled back into the feed to minimize the production of fines during handling.



(a) (b)

Figure 5-3. Schematic diagram of (a) force fed roll press with pocket rollers (modified from Pietsch, 2002) and (b) nip region between two smooth counter-rotating rollers (modified from Pietsch, 2002 and Capes, 1980)

As particulate solids enter the nip region between the rollers and compaction begins, three distinct zones can be defined: the feed zone, the compaction zone and the release zone (Pietsch, 2002). Figure 5-3b depicts the movement of material through these zones for a gravity fed system with two smooth counter-rotating rollers. In the feed zone, material is drawn into the nip region by the combination of gravity and friction between the rollers and the particulate solids. This zone is defined by the width of the rectangular feed opening (h_O), the angle of delivery (α_F) and the angle of nip (α_C). During the compaction process, low pressure forces are developed in the feed zone, which leads to preliminary densification by particle rearrangement. From here material continues into the compaction zone, defined by the area between the angle of nip (α_C) and the neutral angle (α_N), where a sharp increase in pressure leads to the fragmentation and plastic deformation of particles. Beyond the neutral angle (α_N), the densified product enters the release zone, in which particles are subjected to the maximum pressure (P_{Max}) within the system and the maximum particle density is attained with a thickness (h_A) equal to the width between the rollers. Finally, the frictional force is reversed and the briquette is ejected from the rollers. Immediately following ejection, the final particle thickness (h_S) slightly increases due to the expansion of compressed air and elastic spring-back. The complexity of material flow through the nip region is greatly enhanced in the case of roll press briquetting with pocket rollers (Pietsch, 2002).

5.2.2.3 Briquette Production Variables

Roll press briquette production is a complex process that is characterized by a number of important design variables. These variables can be divided into three groups: (1) operating parameters, (2) feedstock variables and (3) additive variables. The most important roll press operating parameters are compaction pressure, roll torque and roll rotational speed (Dec & Komarek, 1997). Each of these parameters influences the degree of compaction of a material and the quality of briquettes produced. Specifically, compaction pressure and roll torque affect the shear and hydrostatic stresses developed within individual briquettes, which greatly influence briquette strength and durability (Dec & Komarek, 1997). The roll torque applied to a material in a roll press system can be adjusted by varying the feed rate of material to the rolls, which rotate at a fixed speed. Although it is difficult to maintain a constant value for this parameter, measurement of roll torque is easily accomplished in most roll press machines using an integrated torque transducer.

The compaction pressure applied to a material during briquette production in a roll press is typically adjusted by varying the roll separating force applied by an integrated hydraulic system. In contrast to roll torque measurement, interpretation and measurement of compaction pressure is a much greater challenge. The pressure applied by the rolls on a material during briquette production depends on material properties (i.e. stress-strain relationship), friction conditions and the design of the pressing system (Dec & Komarek, 1997). Compaction pressure could be measured with a pressure transducer at the roll surface, but this component is generally not incorporated in roll press systems because of the cost and technical complexity of such systems. As a result, true compaction pressure is not typically measured. However, compaction pressure can be estimated and reported as two different variables: (1) force factor, wherein roll separating force is divided by the width of the rolls and (2) briquette calculated (or mean) pressure, wherein roll separating force is divided by the surface determined by the circumferential length of the briquette and the roll width (Dec & Komarek, 1997).

The other important roll press operating parameter is roll rotational speed. This parameter affects both the quality of briquettes and the production rate of the machine. As roll speed is decreased, the negative effects of elastic spring-back and expansion of compressed air are reduced as permanent material bonds form with an increase in dwell time. However, due to desired production rates in industrial processes, roll speed must be optimized to balance production rate with briquette quality. For example, roll speed is often limited in fine powder applications by deaeration and precompaction requirements to maintain briquette quality. Since roll speed is an adjustable parameter on modern roll press machines, measurement is very straightforward.

Feedstock variables also have a large influence on the strength and durability of briquettes produced by roll pressing. For any given material, the most important of these variables are moisture content and particle-size distribution (Komarek, 2001). Both properties can greatly influence the packing density, and thus the quality, of coal-biomass briquettes. In experimental optimization of coal-biomass briquetting, the impact of these variables should be considered for every specific combination of coal and biomass investigated. This includes every combination of different types of coal and biomass, as well as every ratio of coal to biomass in the blended feed. Although these parameters are not true material variables, they are classified as such for the purpose of this study.

The impact of moisture content on the particle density, strength and durability of coal-biomass briquettes was discussed in detail in Chapter 4. Specifically, several sets of laboratory tests were conducted for different coal types, the results of which proved that water content has a very significant influence on the quality of coal-biomass briquettes. A clear optimum water content was experimentally determined for each bituminous coal type, and a range of optimum values was identified for the sub-bituminous coal studied. Additionally, a strong positive correlation was found between the dry density, mechanical durability and crushing strength of coal-biomass briquettes. However, the one aspect this study did not address is the combined influence of water content and other material variables.

The importance of particle-size distribution in briquette production is largely a function of the achievable packing density of particles and the number of contact points for the formation of particle bonds. For instance, the maximum theoretical packing density of perfect spheres is 74 percent (i.e. $\sqrt{2}\pi/6$ = 0.7405). This value increases to 86 percent if a smaller size fraction of spheres is added to the material that occupy the void spaces between the larger particles (Scott & Kilgour, 1969). Similarly, if third and fourth size fraction is added that fills the new void spaces between the larger particles then the theoretical packing density approaches 90 to 92 percent and

95 to 97 percent, respectively (Drzymala, 1993). In an investigation on the effect of particle-size distribution on the production of briquettes composed of fine coal and sawdust, Patil et al. (2009) determined that packing density can be maximized by combining 70 to 80 percent coarse coal recovered from a spiral separator (1.18 x 0.15 mm) with 20 to 30 percent fine coal recovered from a flotation cell (< 0.15 mm). However, the maximum compressive strength of the briquettes occurred with 100 percent fine coal, and thus no strong correlation between density and strength were noted.

When binders or lubricants are combined with coal and biomass to improve briquette properties, additional variables concerning these additives must also be considered. Specifically, the influence of the amount of additive used and briquette cure time are particularly important to consider in these applications. For example, Taulbee et al. (2009) determined that binder content and cure time have a significant impact on the quality of briquettes produced from blends of fine coal and sawdust. This study determined that increased binder content and cure time generally improved the quality of the coal-biomass briquettes.

5.2.3 Research Objectives

Experimental optimization of coal-biomass briquette production is an essential task to improve the strength and durability of briquettes. In support of this challenge, an exhaustive bench-scale study was conducted to examine the most significant process variables and to identify optimum process conditions. The specific objectives of this study were to:

1. Evaluate and analyze the influence of material variables (i.e. water content, biomass content and biomass top size) on the density, strength and durability of briquettes composed of different types of coal and biomass feedstocks;
2. Evaluate and analyze the influence of additive variables (i.e. binder content and curing time) on the density, strength and durability of coal-biomass briquettes;
3. Evaluate and analyze the influence of roll press operating parameters (i.e. roll force, roll torque and roll rotational speed) on the density, strength and durability of coal-biomass briquettes;
4. Determine the optimum combination of feedstock variables, additive variables and roll press variables for industrial production of coal-biomass briquette feedstocks; and

5. Conduct an extensive characterization study on important physical properties, flow properties and gasification behavior of selected coal-biomass briquettes to verify the enhanced quality of co-briquetted feedstocks.

5.3 Experimental

5.3.1 Materials

Several different coal and biomass feedstocks were collected to address the objectives of this research. Processing was required to prepare each bulk feedstock for briquetting experiments. Specifically, size reduction and screening operations were conducted to obtain a desired top size for each of the feedstocks. A top size of one millimeter was selected for the coal feedstocks because coal particles less than this size are typically difficult to handle and transport. Large quantities of this size fraction are produced during the mechanical excavation of coal in modern coal mines. Thus, coal particles less than one millimeter in diameter present a significant opportunity for agglomeration into larger particles by briquetting. Several different biomass top sizes (i.e. 1.20, 2.38 and 4.75 mm) were selected to evaluate the impact of biomass size reduction on the quality of coal-biomass briquettes. Additional preparation was conducted to dry the coal and biomass feedstocks so that briquettes could be produced at target moisture levels for further investigation of this material property. The only additive evaluated in this study was pregelatinized wheat starch, which did not require any preparation prior to briquette production.

5.3.1.1 Coal Feedstocks

The coal feedstocks investigated in this study included three high-rank bituminous coals and one low-rank sub-bituminous coal. These coals were chosen because they represent the vast majority of proven coal resources in the United States and because they dominate the country's current coal production portfolio. The bituminous coals were obtained from preparations plants operated by Alpha Natural Resources throughout the Appalachian coal basin of the eastern United States. In contrast, the sub-bituminous coal was obtained from a mine operated by Alpha Natural Resources in the Powder River Basin in the western United States. Specifically, the coal samples obtained for briquetting evaluations were:

1. Emerald: a high-volatile, high-sulfur bituminous coal obtained from the Emerald mine preparation plant in Waynesburg, Pennsylvania;

2. McClure River: a medium-volatile bituminous coal obtained from the McClure River preparation plant in McClure, Virginia;
3. Toms Creek: a high-volatile bituminous coal obtained from the Toms Creek preparation plant in Coeburn, Virginia; and
4. Eagle Butte: a sub-bituminous coal obtained from the Eagle Butte mine in Gillette, Wyoming.

The Emerald coal sample was obtained from the clean coal stockpile at the preparation plant and was subjected to further processing to prepare the coal for briquette production. Size reduction of the sample was accomplished by successive crushing in a jaw crusher, roll crusher and grinder. The coal was then screened to a top size of one millimeter using a Uniflex two-deck screen, air-dried for one week, split into two-kilogram lots and stored in sealed plastic bags. Several evaluations were performed to determine important physical properties of coal, the results of which are included in Table 4-1. The moisture content of the coal prior to briquette production was 1.60% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The true density of the Emerald coal was 1.27 g/cm^3, which was determined by water displacement in a 250 milliliter volumetric flask. The size distribution of the crushed coal was measured by wet screening and analyzed using the Rosin-Rammler equation (Figure 4-2). Based on this analysis, the Emerald coal was found to have a mass median diameter of 301 microns, a size modulus of 0.43 and a distribution modulus of 1.02. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the Emerald coal (Table 4-2). Notable results of the analyses include a moisture and ash free heating value of 15,268 Btu/lb, an ash content of 9.37% (dry basis) and a sulfur content of 3.04% (dry basis).

Table 5-1. Physical properties of coal feedstocks

Physical Property	Emerald	McClure River	Toms Creek	Eagle Butte
Moisture Content (%)	1.60	0.93	1.03	1.80
True Density (g/cm^3)	1.27	1.27	1.33	1.27
Mass Median Diameter (µm)	301	266	239	295
Size Modulus	0.43	0.40	0.36	0.41
Distribution Modulus	1.02	0.91	0.88	1.16

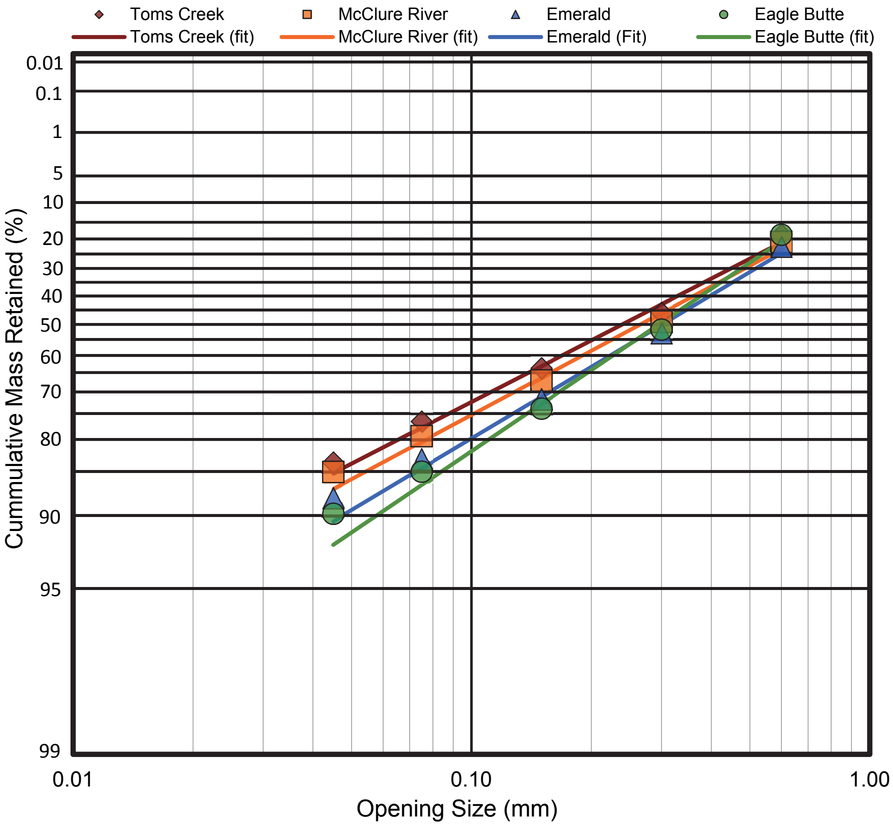


Figure 5-4. Particle-size distribution of coal feedstocks

Table 5-2. Chemical properties of coal feedstocks

Chemical Property	Emerald		McClure River		Toms Creek		Eagle Butte	
	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis
Moisture (%)	4.28	--	7.89	--	13.73	--	29.08	--
Ash (%)	8.97	9.37	5.73	6.22	9.75	11.30	5.60	7.89
Sulfur (%)	3.04	3.18	0.81	0.88	0.80	0.93	0.64	0.90
Volatiles (%)	37.59	39.27	26.17	28.41	27.24	31.57	40.89	57.66
Fixed Carbon (%)	49.16	51.36	59.80	64.92	49.29	57.13	24.43	34.45
Carbon (%)	74.26	77.58	75.77	82.26	66.19	76.72	47.08	66.38
Hydrogen (%)	4.91	5.13	4.38	4.75	3.85	4.46	4.00	5.64
Nitrogen (%)	1.39	1.45	1.44	1.56	1.36	1.58	0.70	0.99
Oxygen (%)	3.15	3.29	0.05	0.05	4.32	5.01	12.91	18.20
HHV (Btu/lb)	13,245	13,837	12,963	14,073	11,670	13,527	8,149	11,490
MAF HHV (Btu/lb)	--	15,268	--	15,724	--	15,250	--	12,474

The McClure River coal sample was also obtained from the clean coal stockpile at the preparation plant and subjected to further processing to prepare the coal for briquette production. Size reduction of the coal was accomplished by successive crushing in a jaw crusher, roll crusher and grinder. The coal was then screened to a top size of one millimeter using a Uniflex two-deck screen, air-dried for one week, split into two-kilogram lots and stored in sealed plastic bags. Again, several evaluations were performed to determine important physical properties of coal, the results of which are included in Table 4-1. The moisture content of the coal prior to briquette production was 0.93% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The true density of the McClure River coal was 1.27 g/cm^3, which was determined by water displacement in a 250 milliliter volumetric flask. The size distribution of this coal was also measured by wet screening and analyzed using the Rosin-Rammler equation (Figure 4-2). Based on this analysis, the McClure River coal was found to have a mass median diameter of 266 microns, a size modulus of 0.40 and a distribution modulus of 0.91. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the McClure River coal (Table 4-2). Notable results of the analyses include a moisture and ash free heating value of 15,724 Btu/lb, an ash content of 6.22% (dry basis) and a sulfur content of 0.88% (dry basis).

The Toms Creek coal sample was a combined spiral and flotation clean product sampled from a screen bowl centrifuge in the preparation plant. In preparation for briquette production, the coal was screened to a top size of one millimeter using a Uniflex two-deck screen, air dried for one week, split into two-kilogram lots and stored in sealed plastic bags. Again, several evaluations were performed to determine important physical properties of coal, the results of which are included in Table 4-1. The moisture content of the coal prior to briquette production was 1.03% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The true density of the Toms Creek coal was 1.33 g/cm^3, which was determined by water displacement in a 250 milliliter volumetric flask. The size distribution of the crushed coal was measured by wet screening and analyzed using the Rosin-Rammler equation (Figure 4-2). Based on this analysis, the Toms Creek coal was found to have a mass median diameter of 239 microns, a size modulus of 0.36 and a distribution modulus of 0.88. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the coal (Table 4-2). Notable results of the analyses include a moisture and ash free heating value of 15,250 Btu/lb, an ash content of 11.30% (dry basis) and a sulfur content of 0.93% (dry basis).

The Eagle Butte coal sample was obtained from the raw coal stockpile of the Eagle Butte mine. In preparation for briquette production, the coal was successively crushed in a jaw crusher, roll crusher and grinder. The coal was then screened to a top size of one millimeter using a Uniflex two-deck screen, air dried for one week, oven dried at 105 degrees Celsius for 48 hours, split into two-kilogram lots and stored in sealed plastic bags. Again, several evaluations were performed to determine important physical properties of coal, the results of which are included in Table 4-1. The moisture content of the Eagle Butte coal prior to briquette production was 1.80% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The true density of the Eagle Butte coal was 1.27 g/cm^3, which was determined by water displacement in a 250 milliliter volumetric flask. The size distribution was again analyzed using the Rosin-Rammler equation (Figure 4-2), which indicated that the coal had a mass median diameter of 295 microns, a size modulus of 0.41 and a distribution modulus of 1.16. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the Eagle Butte coal (Table 4-2). Notable results of the analyses include a moisture and ash free heating value of 12,474 Btu/lb and an ash content of 7.89% (dry basis).

5.3.1.2 Biomass Feedstocks

The biomass feedstocks investigated in this study included five total samples of corn stover, grasses and wood that represent the wide spectrum of renewable biomass resources available in the United States. A particular focus was placed on agricultural residues, forestry residues and perennial grasses that are viable energy crops. Specifically, the biomass samples obtained for briquetting evaluations were:

1. Corn stover: an agricultural by-product of corn production (i.e. stalk, leaf, husk and cob) obtained from a farm in Blacksburg, Virginia operated by Virginia Tech;
2. Switchgrass: a perennial warm season bunchgrass native to North America, obtained from Piedmont Bioproducts in Gretna, Virginia;
3. Miscanthus: a large perennial warm season bunchgrass, obtained from Piedmont Bioproducts in Gretna, Virginia;
4. Wheat straw: an agricultural by-product of wheat production (i.e. dry stalks after grain is removed), obtained from a farm in Riner, Virginia; and
5. Sawdust: a forestry by-product produced by cutting, drilling or sanding wood, obtained from Turman Sawmill in Hillsville, Virginia.

The corn stover sample evaluated in this study was obtained as large round bales, which were processed in a Jordan Reduction Solutions knife mill (Figure 3-4a) equipped with a 6.35-

millimeter screen. The corn stover was then screened to three different top sizes (i.e. 1.20, 2.38, 4.75 mm) using a Sweco vibrating separator and stored in sealed five-gallon buckets. A portion of each size class was oven dried at 105 degrees Celsius for 48 hours to facilitate low moisture content evaluations. An additional bale of the corn stover was processed in the Jordan Reduction Solutions knife mill with a 4.7625-millimeter screen to produce a large quantity of material that did not require any screening, for use in evaluations were biomass top size was not varied. Particle-size distribution was not determined for the processed biomass materials because previous attempts to collect this information has indicated that the results are skewed due to the elongated shape of the milled particles (i.e. elongated particles tend to screen differently than round particles). Prior to briquette production, the moisture content of the oven dried and as-received corn stover was 1.40% (dry basis) and 11.35% (dry basis) respectively, as determined by oven drying at 105 degrees Celsius for 24 hours. Ultimate and proximate analyses were conducted on the corn stover sample, the results of which are presented in Table 5-3. Notable results of the analyses include a moisture and ash free heating value of 8,499 Btu/lb, an ash content of 5.01% (dry basis) and a sulfur content of 0.10% (dry basis).


(a) (b) (c)

Figure 5-5. Equipment used for biomass size reduction: (a) knife mill, (b) tub grinder and (c) hammer mill

The switchgrass sample examined in this study was obtained as large round bales, which were successively processed through a Sperry New Holland tub grinder (Figure 3-4b) and a Bliss Industries hammer mill (Figure 3-4c) equipped with a 6.35-millimeter screen. The switchgrass was then screened to three different top sizes (i.e. 1.20, 2.38, 4.75 mm) using a Sweco vibrating separator and stored in sealed five-gallon buckets. A portion of each size class was oven dried at

105 degrees Celsius for 48 hours to facilitate low moisture content evaluations. Prior to briquette production, the moisture content of the oven dried and as-received switchgrass was 1.00% (dry basis) and 17.50% (dry basis) respectively, as determined by oven drying at 105 degrees Celsius for 24 hours. Ultimate and proximate analyses were conducted on the switchgrass sample with the results presented in Table 5-3. Notable results of the analyses include a moisture and ash free heating value of 8,353 Btu/lb, an ash content of 2.86% (dry basis) and a sulfur content of 0.08% (dry basis).

Table 5-3. Chemical properties of biomass feedstocks

Chemical Property	**Corn Stover**		**Switchgrass**		**Miscanthus**		**Wheat Straw**		**Sawdust**	
	As Received	**Dry Basis**	**As Received**	**Dry Basis**	**As Received**	**Dry Basis**	**As Received**	**Dry Basis**	**As Received**	**Dry Basis**
Moisture (%)	12.95	--	14.79	--	11.65	--	12.14	--	14.08	--
Ash (%)	4.36	5.01	2.44	2.86	2.38	2.69	3.07	3.49	0.22	0.26
Sulfur (%)	0.09	0.10	0.07	0.08	0.05	0.06	0.06	0.07	0.03	0.03
Volatiles (%)	71.49	82.13	70.37	82.58	74.07	83.84	70.24	79.95	78.64	81.53
Fixed Carbon (%)	11.19	12.86	12.41	14.56	11.90	13.47	14.55	16.56	7.05	8.21
Carbon (%)	46.37	53.27	41.59	48.81	42.44	48.04	41.81	47.59	51.66	60.12
Hydrogen (%)	4.94	5.67	6.32	7.04	5.43	6.15	5.38	6.12	5.40	6.28
Nitrogen (%)	0.54	0.62	0.35	0.30	0.14	0.16	0.40	0.46	0.02	0.02
Oxygen (%)	30.75	35.33	41.58	48.57	37.90	42.90	37.14	42.27	28.60	33.29
HHV (Btu/lb)	7,028	8,073	6,914	8,114	7,272	8,231	7,299	8,307	8,110	9,439
MAF HHV (Btu/lb)	--	8,499	--	8,353	--	8,459	--	8,607	--	9,464

The miscanthus sample evaluated in this study was obtained as large round bales, which were successively processed through a Sperry New Holland tub grinder and a Bliss Industries hammer mill equipped with a 6.35-millimeter screen. The miscanthus was then screened to three different top sizes (i.e. 1.20, 2.38, 4.75 mm) using a Sweco vibrating separator and stored in sealed five-gallon buckets. A portion of each size class was oven dried at 105 degrees Celsius for 48 hours to facilitate low moisture content evaluations. Prior to briquette production, the moisture content of the oven dried and as-received miscanthus was 1.25% (dry basis) and 16.30% (dry basis) respectively, as determined by oven drying at 105 degrees Celsius for 24 hours. Ultimate and proximate analyses were conducted on the switchgrass sample with the results presented in Table 5-3. Notable results of the analyses include a moisture and ash free heating value of 8,459 Btu/lb, an ash content of 2.69% (dry basis) and a sulfur content of 0.06% (dry basis).

The wheat straw sample examined in this study was obtained as small rectangular bales, which processed in a Jordan Reduction Solutions knife mill equipped with a 6.35-millimeter screen. The corn stover was then screened to three different top sizes (i.e. 1.20, 2.38, 4.75 mm) using a Sweco vibrating separator and stored in sealed five-gallon buckets. A portion of each size class was oven dried at 105 degrees Celsius for 48 hours to facilitate low moisture content evaluations. Prior to briquette production, the moisture content of the oven dried and as-received wheat straw was 1.65% and 12.25% (dry basis) respectively, as determined by oven drying at 105 degrees Celsius for 24 hours. Ultimate and proximate analyses were conducted on the switchgrass sample with the results presented in Table 5-3. Notable results of the analyses include a moisture and ash free heating value of 8,607 Btu/lb, an ash content of 3.49% (dry basis) and a sulfur content of 0.07% (dry basis).

The sawdust sample evaluated in this study was kiln-dried eastern white pine dust and shavings. To prepare the sawdust for briquette production, the bulk sample was screened to three different top sizes (i.e. 1.20, 2.38, 4.75 mm) using a Sweco vibrating separator and stored in sealed five-gallon buckets. A portion of each size class was oven dried at 105 degrees Celsius for 48 hours to facilitate low moisture content evaluations. Prior to briquette production, the moisture content of the oven dried and as-received sawdust was 1.35% (dry basis) and 10.60% (dry basis) respectively, as determined by oven drying at 105 degrees Celsius for 24 hours. The ultimate and proximate analyses results for the sawdust sample are displayed in Table 5-3. Notable results of the analyses include a moisture and ash free heating value of 9,464 Btu/lb, an ash content of 0.26% (dry basis) and a sulfur content of 0.03% (dry basis).

5.3.1.3 Additives

The only additive used to improve the quality of briquettes throughout this study was wheat starch. A pretreated form of the carbohydrate was obtained from Archer Daniels Midland Company in a 50-pound bag. This starch was cooked in the presence of water and heat to break down intermolecular bonds in a process known as starch gelatinization. The gelatinized starch was then dried, which rendered it cold water soluble. This type of commercially available starch is commonly known as pregelatinized wheat starch. This organic, water soluble matrix binder was chosen for this study because it has been proven to improve the quality of coal-biomass briquettes and is readily available throughout the United States (Taulbee et al., 2009; Shimasaki et al., 2003).

5.3.2 Briquette Production

Throughout this study, pill-shaped briquettes (approximately 43 x 19 x 14 mm) were produced with a Komarek B-100R laboratory roll press equipped with 13-centimeter diameter pocketed rolls. The machine is comprised of two counter-rotating rolls, two hydraulic cylinders, a horizontal tapered screw and a paddle feeder. A schematic diagram of the roll press and the laboratory installation are depicted in Figure 5-6. The hydraulic cylinders control the position of the upper roll and thus control the gap between the rolls. The paddle feeder is driven by a fixed speed motor and distributes the material to the horizontal screw that in turn feeds material to the rolls. The counter-rotating rolls and the horizontal screw are driven by variable speed motors, which enable adjustment of the torque applied to the material from the rolls and screw.

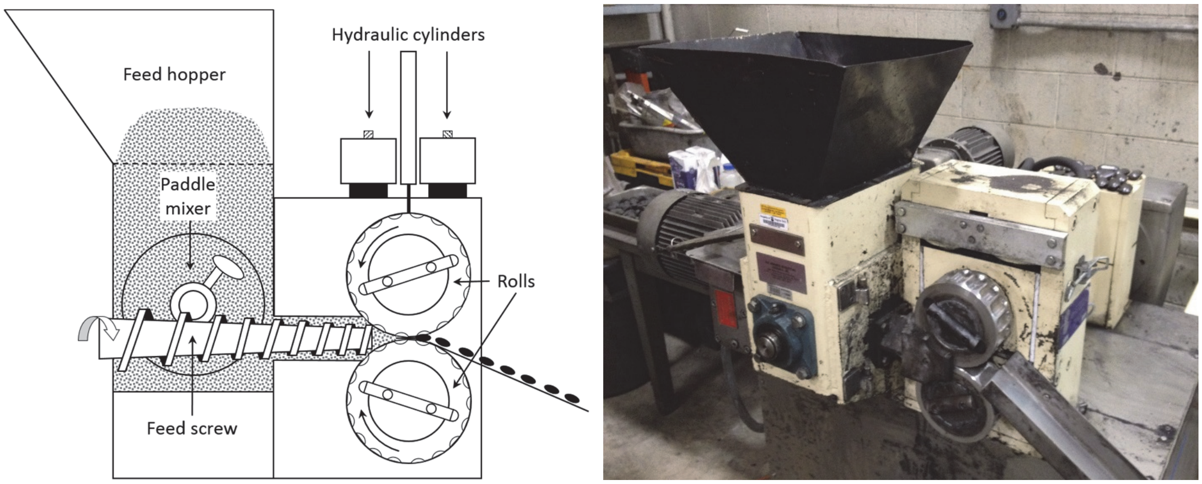
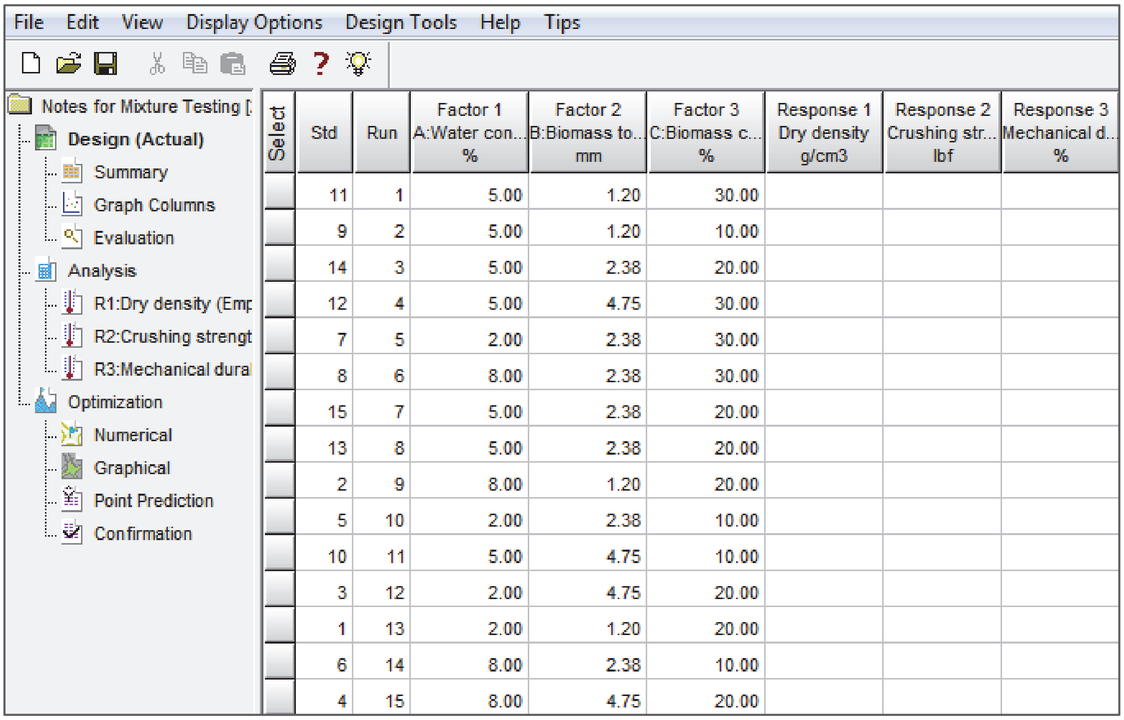


Figure 5-6. Komarek B-100R roll press (left) schematic diagram (modified from Guigon & Simon, 2003) and (right) laboratory installation

5.3.2.1 Evaluations of Feedstock and Additive Variables

Several series of tests were designed to evaluate the influence of feedstock variables, additive variables and machine parameters on the quality of coal-biomass briquettes. The specifications for each series of tests were developed in Design-Expert® 8 using a Box-Behnken experimental design. This approach facilitated the creation of response surfaces and empirical models that relate variables of interest to measured responses, while minimizing the number of required tests. The first series of evaluations were designed to determine the influence of feedstock variables (i.e. water content, biomass content and biomass top size) on the dry density, crushing strength and mechanical durability of binderless bituminous coal-biomass briquettes. Due to the similar compaction behavior of bituminous coals during roll press briquetting, as discussed in Chapter 4, it was determined that the most efficient course of action was to initially evaluate the influence of material variables for a single bituminous coal blended with each of the five types of biomass. The data obtained from these tests was used to compare the relative briquetting performance of each biomass type. Next, a series of verification tests were designed using the other two bituminous coals to verify that the optimum material variables from the initial exhaustive study are indeed similar for each coal. This experimental design reduced the amount of time and materials required to determine the influence of feedstock variables on quality indicators for each coal-biomass combination.



Select	Std	Run	Factor 1 A:Water con... %	Factor 2 B:Biomass to... mm	Factor 3 C:Biomass c... %	Response 1 Dry density g/cm3	Response 2 Crushing str... lbf	Response 3 Mechanical d... %
	11	1	5.00	1.20	30.00			
	9	2	5.00	1.20	10.00			
	14	3	5.00	2.38	20.00			
	12	4	5.00	4.75	30.00			
	7	5	2.00	2.38	30.00			
	8	6	8.00	2.38	30.00			
	15	7	5.00	2.38	20.00			
	13	8	5.00	2.38	20.00			
	2	9	8.00	1.20	20.00			
	5	10	2.00	2.38	10.00			
	10	11	5.00	4.75	10.00			
	3	12	2.00	4.75	20.00			
	1	13	2.00	1.20	20.00			
	6	14	8.00	2.38	10.00			
	4	15	8.00	4.75	20.00			

Figure 5-7. Example of an experimental design constructed in Design-Expert® 8

The Emerald coal was selected for the initial series of tests because it produced briquettes with the greatest compressive strength and mechanical durability in the moisture optimization study presented in Chapter 4. Using the Box-Behnken experimental design with three center points, a series of 15 briquetting tests were designed for the Emerald coal and each type of biomass. An example of the experimental design layout produced in Design-Expert® 8 is displayed in Figure 5-7. For every individual test, briquettes were produced in 1.5 kilogram (dry mass) batches with a target water content (i.e. 0.02, 0.05, or 0.08), biomass content (i.e. 10, 20 or 30%) and biomass top size (i.e. 1.20, 2.38 or 4.75 mm). To accomplish this, a calculated mass of coal, biomass and water were homogenized for five minutes in a Hobart A200 20-quart commercial mixer. The mixture was then fed to the Komarek B-100R, which was operated at a roll motor speed of 450 rotations per minute, a roll force of 100 kilonewtons and a roll torque of approximately 1500 newton-meters. Immediately after formation, the briquettes were screened across a Sweco vibrating separator equipped with a 0.5-inch screen to remove excess fines and subsequently evaluated for water content, dry density, mechanical durability and crushing strength.

Next, a series of verification tests were designed to evaluate the McClure River and Toms Creek coals. The objective of these tests was to verify that the optimum combinations of feedstock variables identified for each Emerald coal-biomass mixture can also produce strong and durable briquettes with the other bituminous coals, and to validate that an exhaustive optimization study is not required for each bituminous coal type. A secondary objective of these tests was to give a clear indication to the effect of coal and biomass type on the quality of coal-biomass briquettes. To accomplish this, a single set of feedstock variables (e.g. 0.02 water content, 1.20 mm biomass top size, 20% biomass content) was selected for each of the five biomass types that corresponded with the best combination of measured crushing strength and mechanical durability in the Emerald coal tests. For each of the five tests, briquettes were produced in 1.5 kilogram (dry mass) batches with a calculated mass of coal, biomass and water. These materials were homogenized for five minutes in a Hobart A200 20-quart commercial mixer and fed to the Komarek B-100R, which was operated at a roll motor speed of 450 rotations per minute, a roll force of 100 kilonewtons and a roll torque of approximately 1500 newton-meters. Immediately after formation, the briquettes were screened across a Sweco vibrating separator equipped with a 0.5-inch screen to remove excess fines and subsequently evaluated for water content, dry density, mechanical durability and crushing strength.

The third series of tests that were designed to determine the combined impacts of additive variables (i.e. starch content and cure time) on the dry density, crushing strength and mechanical durability of bituminous coal-biomass briquettes produced with different biomass contents. Using the Box-Behnken experimental design with three center points, a series of 15 briquetting tests were specified. For each test, briquettes were produced in 1.5 kilogram (dry mass) batches at a target water content of 0.05, a biomass top size of 4.75 millimeters, a specified biomass content (i.e. 10, 20 or 30%) and a specified pregelatinized wheat starch content (i.e. 0.0, 2.5 or 5.0%). To accomplish this, a calculated mass of Emerald coal, corn stover, pregelatinized wheat starch and water were homogenized for five minutes in a Hobart A200 20-quart commercial mixer. The mixture was then fed to the Komarek B-100R, which was operated at a roll motor speed of 450 rotations per minute, a roll force of 100 kilonewtons and a roll torque of approximately 1500 newton-meters. Immediately after formation, the briquettes were screened across a Sweco vibrating separator equipped with a 0.5-inch screen to remove excess fines. Finally, the briquettes were cured for a specified period of time (i.e. 0, 1 or 7 days) prior to evaluations for water content, dry density, mechanical durability and crushing strength.

The fourth series of tests were designed to determine the combined influence of feedstock and additive variables (i.e. water content, biomass content and binder content) on the dry density, crushing strength and mechanical durability of sub-bituminous coal-biomass briquettes. Based on the insignificant influence of biomass top size on the quality of Emerald coal-biomass briquettes as discussed in Section 5.4.1, the biomass top size variable was excluded from these evaluations. Using the Box-Behnken experimental design with three center points, a series of 15 briquetting tests were planned to evaluate the quality of briquettes produced from mixtures of Eagle Butte coal and corn stover. For each test, briquettes were produced in 1.5 kilogram (dry mass) batches with a specified water content (i.e. 0.10, 0.15, or 0.20), corn stover content (i.e. 10, 20 or 30%) and pregelatinized wheat starch content (i.e. 0.0, 2.5 or 5.0%). To accomplish this, a calculated mass of Emerald coal, corn stover (minus 4.7625 mm), pregelatinized wheat starch and water were homogenized for five minutes in a Hobart A200 20-quart commercial mixer. The mixture was then fed to the Komarek B-100R, which was operated at a roll motor speed of 450 rotations per minute, a roll force of 100 kilonewtons and a roll torque of approximately 1500 newton-meters. Immediately after formation, the briquettes were screened across a Sweco vibrating separator equipped with a 0.5-inch screen to remove excess fines. Finally, the briquettes were cured for 24 hours prior to evaluations for water content, dry density, mechanical durability and crushing strength.

A final series of evaluations of feedstock variables were designed to evaluate the quality of binderless briquettes produced with sub-bituminous coal and all five biomass types. The objective of these tests was to verify the binderless briquetting potential of sub-bituminous coal-biomass mixtures at the optimum binderless conditions (i.e. 0.0% binder content) determined from the previous series of tests. For each test, briquettes were produced in 1.5 kilogram (dry mass) batches at a target water content of 0.15, a biomass content of 30 percent, and a biomass top size of 4.75 millimeters. To accomplish this, a calculated mass of Eagle Butte coal, biomass (minus 4.75 mm) and water were homogenized for five minutes in a Hobart A200 20-quart commercial mixer. The mixture was then fed to the Komarek B-100R, which was operated at a roll motor speed of 450 rotations per minute, a roll force of 100 kilonewtons and a roll torque of approximately 1500 newton-meters. Immediately after formation, the briquettes were screened across a Sweco vibrating separator equipped with a 0.5-inch screen to remove excess fines and subsequently evaluated for water content, dry density, mechanical durability and crushing strength.

5.3.2.2 Evaluations of Roll Press Operating Parameters

A separate series of tests were designed to determine the combined impacts of the Komarek B-100R roll press operating parameters (i.e. roll speed, roll force and roll torque) on the dry density, crushing strength and mechanical durability of coal-biomass briquettes. Using the Box-Behnken experimental design with three center points, a series of 15 tests were planned to evaluate the quality of briquettes produced from mixtures of bituminous coal and corn stover. For each test, briquettes were produced in 1.5 kilogram (dry mass) batches at a target water content of 0.03, a biomass content of 20 percent and a biomass top size of 4.75 millimeters. To accomplish this, a calculated mass of McClure River coal, corn stover (minus 4.7625 mm) and water were homogenized for five minutes in a Hobart A200 20-quart commercial mixer. The mixture was then fed directly to the Komarek B-100R, which was operated at a specified roll motor speed (i.e. 300, 600 or 900 rpm), a specified roll force (i.e. 50, 75 or 100 kN) and a specified roll torque (i.e. 600, 1200 or 1800 N-m). Immediately after formation, the briquettes were screened across a Sweco vibrating separator equipped with a 0.5-inch screen to remove excess fines and subsequently evaluated for water content, dry density, mechanical durability and crushing strength.

5.3.2.3 Detailed Characterization Study

A final series of briquettes were produced for a detailed characterization study of the physical properties, flow properties and gasification behavior of selected types of optimum coal-biomass briquettes. The purpose of this study was to verify the enhanced quality of the co-briquetted feedstocks and to provide additional information that may be useful to industrial consumers of coal-biomass briquettes. Two types of briquettes were produced for the detailed characterization study. The first type of briquettes were composed of the Emerald coal and sawdust, while the second type of briquettes were composed of Eagle Butte coal and corn stover.

These combinations were chosen because of the geographical proximity of bituminous coal to forestry operations in the eastern United States and the geographical proximity of the nation's largest sub-bituminous coal producing region (i.e. Powder River basin) to the nation's largest corn producing states in the Midwest.

The bituminous coal-sawdust briquettes were produced in a single 20-kilogram batch with 70 percent Emerald coal and 30 percent sawdust (minus 1.20 mm) at a target water content of 0.0022. Similarly, the sub-bituminous coal-corn stover briquettes were produced in a single eight-kilogram batch with 70 percent Eagle Butte coal and 30 percent corn stover (minus 4.75 mm) at a target water content of 0.1850. These feedstock parameters (i.e. water content, biomass content and biomass top size) were selected using an optimization tool in Design-Expert® 8, which used the mathematical models developed for each coal-biomass combination to maximize the predicted values of mechanical durability and crushing strength. For briquette production, a calculated mass of coal, biomass and water (total mixture mass of 2 kg) were homogenized for five minutes in a Hobart A200 20-quart commercial mixer. This process was repeated ten times for each coal-biomass combination to produce 20 kilograms of mixed feed material. The mixture was then fed directly to the Komarek B-100R, which was operated at a roll motor speed of 900 rotations per minute, a roll force of 100 kilonewtons and a roll torque of approximately 1800 newton-meters. These roll press operating parameters were also selected using an optimization tool in Design-Expert® 8, which used the empirical model developed for the roll press to maximize the predicted values of mechanical durability and crushing strength. Immediately after formation, the briquettes were screened across a Sweco vibrating separator equipped with a 0.5-inch screen and subsequently evaluated for tensile strength, crushing strength, elasticity, mechanical durability, attritability, friability, water content, particle density, water resistance and chemical dosage. All additional briquettes were sent to specialized external laboratories for analysis of flow properties and gasification behavior.

5.3.3 Briquette Characterization

5.3.3.1 Water Content

The water content of briquettes was determined by drying five briquettes for 24 hours at 105 degrees Celsius in a drying oven. The mass of water in the briquettes was calculated by subtracting the dry mass of the briquettes from the initial mass before drying. The water content was then calculated by:

$$w = m_w/m_s \tag{Eq. 5-1}$$

where w is the water content, m_w is the mass of water and m_s is the dry mass of the briquettes. Water content of the feed material was measured prior to briquette production using an AND MF-50 moisture analyzer set at 105 degrees Celsius. Feed samples were dried until the change in mass was reduced to 0.05 percent per minute, at which point the displayed value was reported as the water content of the feed.

5.3.3.2 Particle Density

The particle density of briquettes was calculated by first measuring the initial (wet) density and then calculating the dry density (ρ_d) based on the measured water content by:

$$\rho_d = \rho_{wet}/(1 + w) \tag{Eq. 5-2}$$

where ρ_{wet} is the calculated wet density and w is the calculated water content. A density determination rig was used to measure the apparent mass of briquettes in a solution of water and detergent. Wet density (ρ_{wet}) was then calculated by:

$$\rho_{wet} = (m_a/(m_a - m_b))\rho_w \tag{Eq. 5-3}$$

where m_a is the mass of the briquette in air, m_b is the apparent mass of the briquette in water and ρ_w is the density of the liquid. Wet density was measured after the 24-hour curing period for the conventional binder tests and after the one hour cooling period for the coating tests. For both cases, the procedure was repeated for 10 briquettes and the average of the 10 values was reported as the dry particle density.

5.3.3.3 Mechanical Durability

The mechanical durability of briquettes was measured by tumbling 20 briquettes for five minutes at 40 rotations per minute in a 12-inch PVC cylinder equipped with three 2-inch lifters. The briquettes were then removed from the cylinder and screened in a Ro-tap sieve shaker for 30 seconds over a 4.75-millimeter sieve. The mechanical durability (MD) of the briquettes was then calculated by:

$$MD = 100 \times \left(m_{final}/m_{initial}\right) \tag{Eq. 5-4}$$

where m_{final} is the mass of briquettes retained on the 4.75-millimeter sieve and $m_{initial}$ is the initial mass of the briquettes prior to durability testing. Weathered mechanical durability values were also measured for selected briquettes by performing a series of mechanical durability and water uptake tests. This series of tests included an initial mechanical durability test followed by water uptake evaluation of the plus 4.75-millimeter material, followed by another mechanical durability test, followed by another water uptake evaluation of the plus 4.75-millimeter material, followed by a final mechanical durability test. The weathered mechanical durability was then calculated by the product of each mechanical durability test result.

5.3.3.4 Crushing Strength

The crushing strength of briquettes was determined using a Mark-10 M5-500 digital force gauge fitted with a four-inch diameter aluminum plate. The force gauge was mounted to a Mark-10 TSA750 manual test stand equipped with a one-inch diameter aluminum plunger that was used to apply force to the briquettes until failure. The force gauge was configured with a break detect feature which stops data acquisition once the applied force drops to 95 percent of the maximum force attained during each test. The crushing strength of each briquette was then reported as the maximum force attained during each test. To improve the accuracy of readings, an aluminum bar (51 x 8 x 8 millimeters) was placed upon the aluminum plate with each briquette then placed atop and parallel to the bar for testing. Evaluations were performed on 25 briquettes and the crushing strength was reported as the average of the 25 values.

5.3.3.5 Water Resistance

The water resistance of briquettes was determined using an apparatus designed to simulate precipitation that briquettes may encounter during storage and transportation. To calculate water resistance, five briquettes were subjected to a 15-second water spray at a flow rate of three gallons per minute from a height of 18 inches above the briquettes. Water resistance was reported as the water uptake of the briquettes that resulted from this spray test, with water uptake (u) calculated by:

$$u = (m_f - m_i)/m_i \tag{Eq. 5-5}$$

where m_i is the initial mass of briquettes and m_f is the mass of briquettes after the water spray. Weathered water uptake values were also determined in conjunction with the weathered mechanical durability tests as the product of the two water uptake test results.

5.3.3.6 Friability

The friability of briquettes was measured by dropping 20 briquettes twice from a height of six feet onto a steel plate using a modified shatter test device. The briquettes were then screened for 30 seconds in a Ro-tap sieve shaker over a 4.75-millimeter sieve. The friability (F) of the briquettes was then calculated by:

$$F = 100 \times \left(m_{final}/m_{initial}\right) \tag{Eq. 5-6}$$

where m_{final} is the mass of briquettes retained on the 4.75-millimeter sieve and $m_{initial}$ is the initial mass of the briquettes prior to friability testing.

5.3.3.7 Attritability

The attritability of briquettes was measured by screening 20 briquettes for five minutes in a Ro-tap sieve shaker over a 4.75-millimeter sieve. The attritability (A) of the briquettes was then calculated by:

$$A = 100 \times \left(m_{final}/m_{initial}\right) \tag{Eq. 5-7}$$

where m_{final} is the mass of briquettes retained on the 4.75-millimeter sieve and $m_{initial}$ is the initial mass of the briquettes prior to attritability testing.

5.3.3.8 Tensile Strength

To measure tensile strength, individual briquettes were crushed between two flat compression plates with the briquette standing tall (i.e. with the long axis of the briquette parallel to the axis of force application). This was accomplished using a Mark-10 M5-500 digital force gauge fitted with a four-inch diameter aluminum plate. The force gauge was mounted to a Mark-10 TSA750 manual test stand equipped with a one-inch diameter aluminum plunger that was used to apply force to the briquettes until failure. The force gauge was configured with a break detect feature which stops data acquisition once the applied force drops to 95 percent of the maximum force attained during each test. Tensile strength of each briquette was then designated as this maximum force. Evaluations were performed on 25 briquettes and the tensile strength was reported as the average of the 25 values.

5.3.3.9 Elasticity

To measure the elasticity of briquettes, the same equipment and procedure that was described for crushing strength evaluations was utilized. However, in this instance the test stand was fitted with a Mark-10 ESM001 digital travel display to record the displacement of briquettes while the load was applied by the plunger. This installation was required to determine the spring constant (SC) of the briquettes, which is calculated by:

$$SC = (F_2 - F_1)/(x_2 - x_1) \tag{Eq. 5-8}$$

where F_2 is the maximum force applied during elastic deformation, F_1 is the minimum force applied during elastic deformation, x_2 is the displacement that corresponds with F_2, and x_1 is the displacement that corresponds with F_1. These values are obtained from the force versus displacement curve that is produced during data acquisition. The force gauge was configured to record two force and displacement data points per second with the break detect feature activated. Evaluations were performed on 25 briquettes and the elasticity was reported as the average calculated spring constant value for all 25 measurements.

5.3.3.10 Flow Properties

To measure briquette flow properties and determine the hopper dimensions needed to ensure reliable material flow, two 5-gallon buckets of each briquette type were sent to Solids Handling Technologies in Rock Hill, South Carolina for a series of extensive evaluations. Although flow properties of bulk solids are typically determined using a Jenike Shear Tester, this device is not recommended for particles larger than 6.35 millimeters because they cannot be properly sheared, which leads to significant error and inaccurate results. Therefore, a modified approach was used for coal-biomass briquette evaluations due to the size of the pill-shaped briquettes (i.e. 43 x 19 x 14 mm). In this modified approach, the cohesive properties of briquettes were determined using a hopper with variable sized openings (i.e. gates), which is specially designed for large particles. This was accomplished by filling the hopper in stages and applying consolidation weights for a short period of time to ensure even consolidation of the briquettes. After filling and consolidating, the gates were successively removed to determine the opening size required for material flow, which is referred to as the arching dimension for a particular consolidation pressure. Additional tests were conducted at varying consolidation pressure to generate a flow function for the briquettes. In addition to these cohesive properties, wall friction values were determined for each type of coal-biomass briquettes to determine the hopper slopes required for mass flow. Finally, the bulk density of the briquettes was measured as a function of consolidation pressure (i.e. compressibility), which is useful for calculating bin loads and required hopper angles and opening sizes.

5.3.3.11 Gasification Behavior

The gasification behavior of selected coal-biomass briquettes was examined to verify the quality of these feedstocks in co-gasification processes. Gasification experiments were conducted at the University of Kentucky using a laboratory-scale updraft moving bed gasification system (Figure 5-8). The gasifier is a stainless steel cylinder with a height of 36 inches and an internal diameter of 1.37 inches. Crushed briquettes were fed at a variable rate to the top of the gasifier onto a stainless steel grate at the bottom of the cylinder. The oxidant and steam were introduced at the bottom of the system and moved up through the bed of particles. The syngas was then removed through a port located at the top of the vessel and transported to a condenser to clean the gas of impurities. Finally, the syngas was analyzed in a GOW-MAC Series 600 gas chromatograph to measure the composition of hydrogen, carbon monoxide, methane and carbon dioxide.

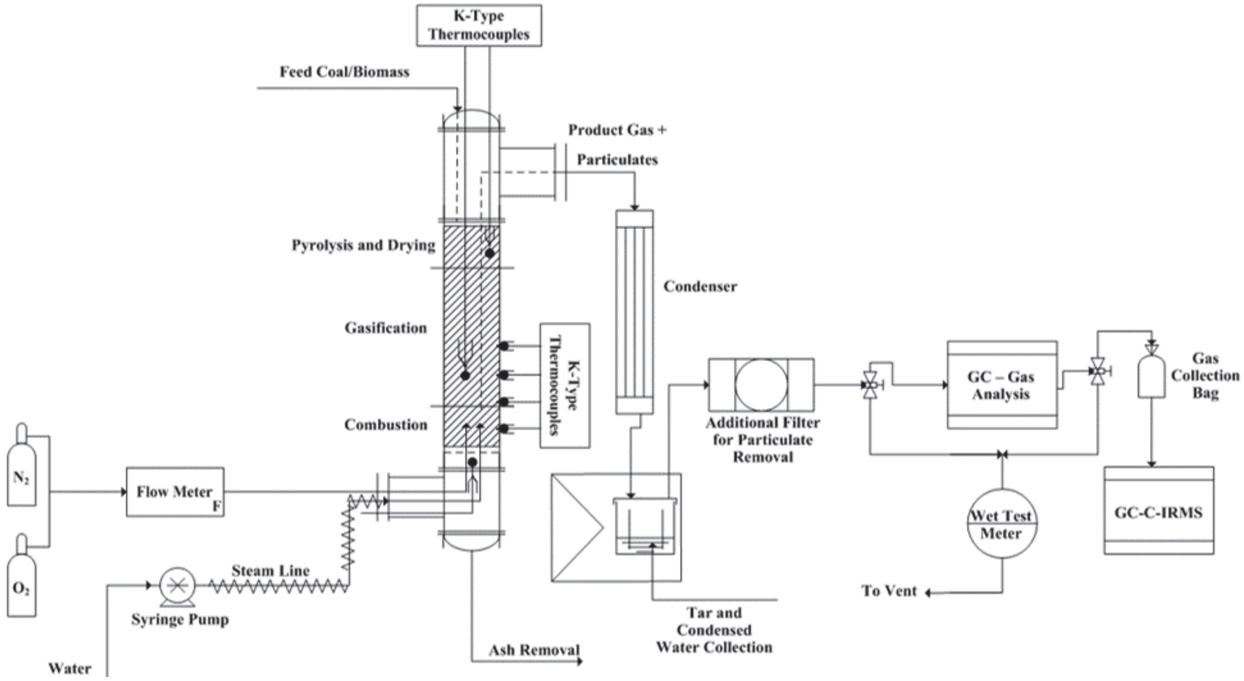


Figure 5-8. Schematic drawing of bench-scale moving bed gasifier used to characterize the gasification behavior of coal-biomass briquettes (Bhagavatula, 2013)

All gasification experiments were performed at atmospheric pressure with a fixed steam to oxygen ratio of 2 to 1. This configuration was selected to minimize the production of carbon dioxide and to maximize the production of hydrogen and carbon monoxide. Experiments were conducted separately with pure oxygen air as the oxidant to determine the resultant concentrations of the product gasses. In addition, the energy content of the product gas was measured to calculate the cold gas efficiency of each gasification process.

5.4 Results and Discussion

5.4.1 Evaluation of Feedstock Variables – Bituminous Coal

5.4.1.1 Summary of Results

The results of the Emerald coal-biomass briquette evaluations are summarized in Table 5-4 for corn stover, Table 5-5 for switchgrass, Table 5-6 for miscanthus, Table 5-7 for wheat straw, and Table 5-8 for sawdust. Each test is identified in these tables by coal type (i.e. EM = Emerald coal), biomass type (i.e. CS = corn stover, SG = switchgrass, MC = miscanthus, WS = wheat straw and SD = sawdust) and the standard test number assigned in Design-Expert® 8 according to the target water content, biomass top size and biomass content (i.e. 01 = target water content of 0.02, biomass content of 20% and biomass top size of 1.20 mm). In the following sections, correlations between each feedstock variable and each response (i.e. briquette property) are presented and discussed. The results were then analyzed using the Design-Expert® 8 statistical analysis tools to fit mathematical models to each response, which can be used to predict briquette quality. In addition, contour graphs of the models are presented to visually interpret and evaluate the results. Finally, numerical optimization of the model was conducted to determine the combination of feedstock conditions that produce the highest quality briquettes.

Table 5-4. Summary of characterization results for briquettes composed of Emerald coal and corn stover

Test ID	Feed Water Content	Biomass Content (%)	Biomass Top Size (mm)	Briquette Water Content	Particle Density (g/cm^3)	Crushing Strength (lb$_f$)	Mechanical Durability (%)
EM-CS-01	0.0180	20	1.20	0.013	1.12	284.9	88.0
EM-CS-02	0.0810	20	1.20	0.061	1.04	122.0	64.9
EM-CS-03	0.0165	20	4.75	0.012	1.11	278.3	88.6
EM-CS-04	0.0865	20	4.75	0.057	1.06	127.9	46.6
EM-CS-05	0.0210	10	2.38	0.015	1.16	236.0	91.9
EM-CS-06	0.0840	10	2.38	0.065	1.10	32.9	19.1
EM-CS-07	0.0165	30	2.38	0.012	1.04	330.4	77.0
EM-CS-08	0.0870	30	2.38	0.068	1.00	304.5	75.2
EM-CS-09	0.0465	10	1.20	0.036	1.11	147.1	80.4
EM-CS-10	0.0585	10	4.75	0.029	1.12	159.1	79.7
EM-CS-11	0.0455	30	1.20	0.041	1.06	414.8	89.4
EM-CS-12	0.0600	30	4.75	0.033	1.08	449.7	90.2
EM-CS-13	0.0405	20	2.38	0.034	1.13	288.9	87.0
EM-CS-14	0.0605	20	2.38	0.038	1.10	280.2	86.7
EM-CS-15	0.0500	20	2.38	0.039	1.10	278.0	85.8

Table 5-5. Summary of characterization results for briquettes composed of Emerald coal and switchgrass

Test ID	Feed Water Content	Biomass Content (%)	Biomass Top Size (mm)	Briquette Water Content	Particle Density (g/cm^3)	Crushing Strength (lb$_f$)	Mechanical Durability (%)
EM-SG-01	0.020	20	1.20	0.014	1.12	310.3	89.7
EM-SG-02	0.077	20	1.20	0.065	1.00	25.2	17.0
EM-SG-03	0.019	20	4.75	0.013	1.11	281.2	86.0
EM-SG-04	0.084	20	4.75	0.066	1.05	18.0	12.8
EM-SG-05	0.020	10	2.38	0.012	1.15	211.3	90.1
EM-SG-06	0.082	10	2.38	0.065	1.08	14.0	5.9
EM-SG-07	0.020	30	2.38	0.015	1.03	408.2	83.2
EM-SG-08	0.071	30	2.38	0.066	0.98	134.1	38.3
EM-SG-09	0.046	10	1.20	0.036	1.07	80.1	48.6
EM-SG-10	0.052	10	4.75	0.036	1.09	84.5	40.2
EM-SG-11	0.042	30	1.20	0.037	1.04	402.9	84.0
EM-SG-12	0.046	30	4.75	0.032	1.04	404.6	82.6
EM-SG-13	0.040	20	2.38	0.040	1.05	202.8	68.6
EM-SG-14	0.056	20	2.38	0.042	1.03	216.5	71.3
EM-SG-15	0.039	20	2.38	0.035	1.05	199.3	67.3

Table 5-6. Summary of characterization results for briquettes composed of Emerald coal and miscanthus

Test ID	Feed Water Content	Biomass Content %	Biomass Top Size mm	Briquette Water Content	Particle Density (g/cm^3)	Crushing Strength (lb$_f$)	Mechanical Durability (%)
EM-MC-01	0.023	20	1.20	0.015	1.13	312.2	89.0
EM-MC-02	0.076	20	1.20	0.062	1.09	25.8	15.6
EM-MC-03	0.024	20	4.75	0.015	1.13	272.3	89.2
EM-MC-04	0.080	20	4.75	0.066	1.09	40.0	13.6
EM-MC-05	0.021	10	2.38	0.015	1.18	202.2	91.0
EM-MC-06	0.076	10	2.38	0.066	1.12	16.1	5.1
EM-MC-07	0.024	30	2.38	0.014	1.07	437.5	86.1
EM-MC-08	0.077	30	2.38	0.067	1.01	190.1	46.5
EM-MC-09	0.048	10	1.20	0.039	1.13	67.1	36.7
EM-MC-10	0.047	10	4.75	0.037	1.13	69.4	32.4
EM-MC-11	0.050	30	1.20	0.039	1.06	402.3	85.0
EM-MC-12	0.036	30	4.75	0.036	1.07	455.5	83.2
EM-MC-13	0.051	20	2.38	0.039	1.09	194.3	66.3
EM-MC-14	0.045	20	2.38	0.039	1.09	227.3	72.5
EM-MC-15	0.053	20	2.38	0.040	1.07	207.7	65.3

Table 5-7. Summary of characterization results for briquettes composed of Emerald coal and wheat straw

Test ID	Feed Water Content	Biomass Content (%)	Biomass Top Size (mm)	Briquette Water Content	Particle Density (g/cm^3)	Crushing Strength (lb$_f$)	Mechanical Durability (%)
EM-WS-01	0.021	20	1.20	0.016	1.15	256.5	90.5
EM-WS-02	0.084	20	1.20	0.066	1.04	72.4	42.8
EM-WS-03	0.026	20	4.75	0.015	1.14	287.3	87.2
EM-WS-04	0.077	20	4.75	0.065	1.06	121.5	41.3
EM-WS-05	0.022	10	2.38	0.014	1.18	212.0	91.7
EM-WS-06	0.079	10	2.38	0.065	1.11	33.5	21.0
EM-WS-07	0.024	30	2.38	0.016	1.06	362.7	77.0
EM-WS-08	0.080	30	2.38	0.071	0.98	188.3	74.1
EM-WS-09	0.049	10	1.20	0.042	1.13	94.1	63.5
EM-WS-10	0.055	10	4.75	0.039	1.12	118.3	52.9
EM-WS-11	0.059	30	1.20	0.047	1.09	317.8	86.1
EM-WS-12	0.056	30	4.75	0.045	1.09	472.0	88.1
EM-WS-13	0.050	20	2.38	0.041	1.09	249.0	81.0
EM-WS-14	0.057	20	2.38	0.046	1.10	239.0	79.9
EM-WS-15	0.051	20	2.38	0.041	1.10	232.9	84.9

Table 5-8. Summary of characterization results for briquettes composed of Emerald coal and sawdust

Test ID	Feed Water Content	Biomass Content (%)	Biomass Top Size (mm)	Briquette Water Content	Particle Density (g/cm^3)	Crushing Strength (lb$_f$)	Mechanical Durability (%)
EM-SD-01	0.022	20	1.20	0.016	1.14	305.0	92.7
EM-SD-02	0.084	20	1.20	0.066	0.97	15.0	16.0
EM-SD-03	0.021	20	4.75	0.014	1.14	287.2	92.0
EM-SD-04	0.089	20	4.75	0.065	1.04	19.4	16.5
EM-SD-05	0.023	10	2.38	0.015	1.15	222.6	92.5
EM-SD-06	0.081	10	2.38	0.064	1.08	24.1	20.0
EM-SD-07	0.022	30	2.38	0.017	1.10	375.8	91.3
EM-SD-08	0.088	30	2.38	0.064	0.97	38.5	30.7
EM-SD-09	0.052	10	1.20	0.038	1.05	53.7	46.8
EM-SD-10	0.058	10	4.75	0.039	1.09	59.4	44.4
EM-SD-11	0.055	30	1.20	0.041	1.04	207.9	80.5
EM-SD-12	0.057	30	4.75	0.042	1.04	250.7	78.8
EM-SD-13	0.055	20	2.38	0.041	1.03	126.0	65.9
EM-SD-14	0.052	20	2.38	0.040	1.05	137.3	68.4
EM-SD-15	0.056	20	2.38	0.039	1.03	134.3	68.0

5.4.1.1.1 Feed Water Content Correlations

The correlation between feed water content and each measured briquette property were evaluated for all five types of biomass by linear regression analysis. To investigate these correlations, feed water content was plotted versus each measured briquette property with the data points grouped by biomass content (i.e. 10, 20 and 30%). This approach was used because little or no correlation existed for the entire data sets due to the influence of the other two feedstock variables (i.e. biomass content and biomass top size). The feed water content correlations were initially investigated with the data grouped separately by biomass content and biomass top size. From these investigations, it was found that water content correlations were greatest with the data grouped by biomass content.

Figure 5-9 displays the correlations between feed water content and particle density for each of the five types of biomass. Specifically, the water content correlations are shown in Figure 5-9a for corn stover, Figure 5-9b for switchgrass, Figure 5-9c for miscanthus, Figure 5-9d for wheat straw and Figure 5-9e for sawdust. It is clear from these charts that feed water content has a negative correlation with the particle density of briquettes. For each of the five biomass types, an increase in water content led to a general reduction in particle density at each biomass content. For briquettes produced with 10 percent biomass, the maximum particle density occurred at the minimum water content for all five types of biomass. However, this was not always the case for briquettes produced with 30 percent biomass. The particle density of briquettes produced with corn stover, switchgrass and wheat straw initially increased with an increase in water content. The particle density reached a maximum value in the water content range of 0.04 to 0.06, and then dropped off when the water content approached or exceeded 0.08. In contrast, the briquettes composed of sawdust exhibited a strong negative correlation (i.e. $R^2 = 0.99$) at 30 percent biomass. These findings suggest that the ideal feed water content with respect to dry density is lowest for briquettes composed of 10 percent biomass. However, the optimum water content increases as biomass content is increased for each biomass type except sawdust.

Figure 5-10 illustrates the correlations between feed water content and crushing strength for each of the five types of biomass. Specifically, the water content correlations are shown in Figure 5-10a for corn stover, Figure 5-10b for switchgrass, Figure 5-10c for miscanthus, Figure 5-10d for wheat straw and Figure 5-10e for sawdust. It is clear from these charts that feed water content generally exhibits a negative correlation with briquette crushing strength. At 10 and 20 percent biomass, an increase in feed water content led to a reduction in crushing strength for all five biomass types (i.e. maximum crushing strength occurred at minimum water content). In contrast, the crushing strength of briquettes composed of 30 percent biomass initially increased with an increase in water content, and reached a maximum value in the water content range of 0.03 to 0.06. However, this correlation at 30 percent biomass was not observed for the briquettes composed of sawdust. These results further confirm the findings of the particle density correlations, in which the ideal feed water content was determined to be lowest for briquettes composed of 10 percent biomass and highest for briquettes composed of 30 percent biomass, with the lone exception occurring with sawdust briquettes. The low crushing strength values recorded at a water content of 0.08 suggest that binderless briquetting of coal-biomass mixtures is not feasible at or above this water content.

Figure 5-11 shows the correlations between feed water content and mechanical durability for each of the five biomass types. Specifically, the water content correlations are shown in Figure 5-11a for corn stover, Figure 5-11b for switchgrass, Figure 5-11c for miscanthus, Figure 5-11d for wheat straw and Figure 5-11e for sawdust. As expected, the feed water content generally exhibits a negative correlation with the mechanical durability of briquettes. At 10 and 20 percent biomass, an increase in feed water content led to a reduction in mechanical durability for all five biomass types (i.e. maximum mechanical durability occurred at minimum water content). In contrast, the mechanical durability of briquettes composed of 30 percent biomass initially increased with an increase in water content, and reached a maximum value in the water content range of 0.03 to 0.06. However, this correlation at 30 percent biomass was not observed for the briquettes composed of sawdust. These results further confirm the findings of the particle density and crushing strength correlations, in which the ideal feed water content was determined to be lowest for briquettes composed of 10 percent biomass and highest for briquettes composed of 30 percent biomass, with the lone exception occurring with sawdust briquettes. The low mechanical durability values recorded at a water content of 0.08 suggest that binderless briquetting of coal-biomass mixtures is not feasible at or above this water content.

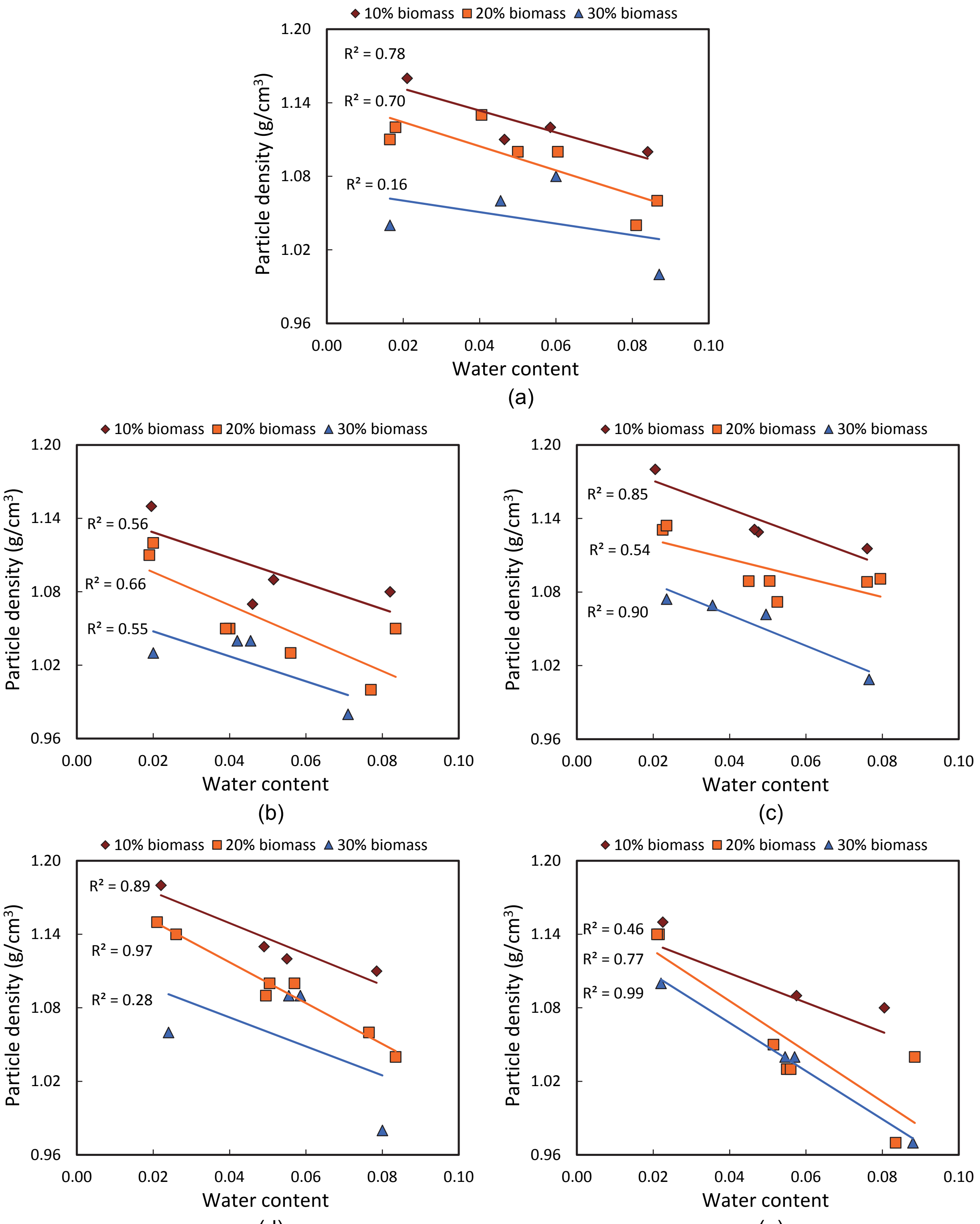
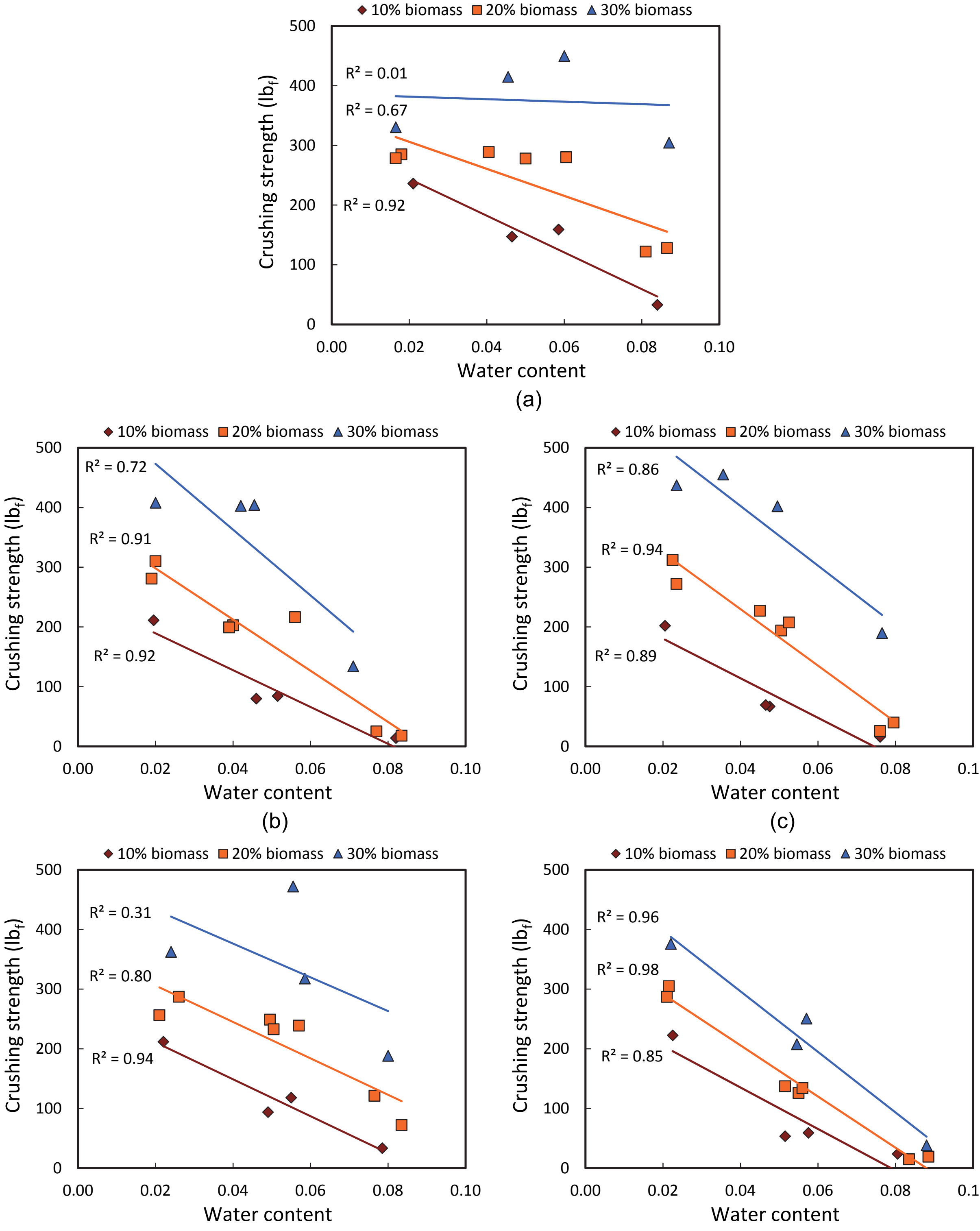


Figure 5-9. Effect of feed water content on particle density of briquettes composed of Emerald (bituminous) coal and (a) corn stover, (b) switchgrass, (c) miscanthus, (d) wheat straw and (e) sawdust



(a)

(b)

(c)

(d)

(e)

Figure 5-10. Effect of feed water content on crushing strength of briquettes composed of Emerald (bituminous) coal and (a) corn stover, (b) switchgrass, (c) miscanthus, (d) wheat straw and (e) sawdust

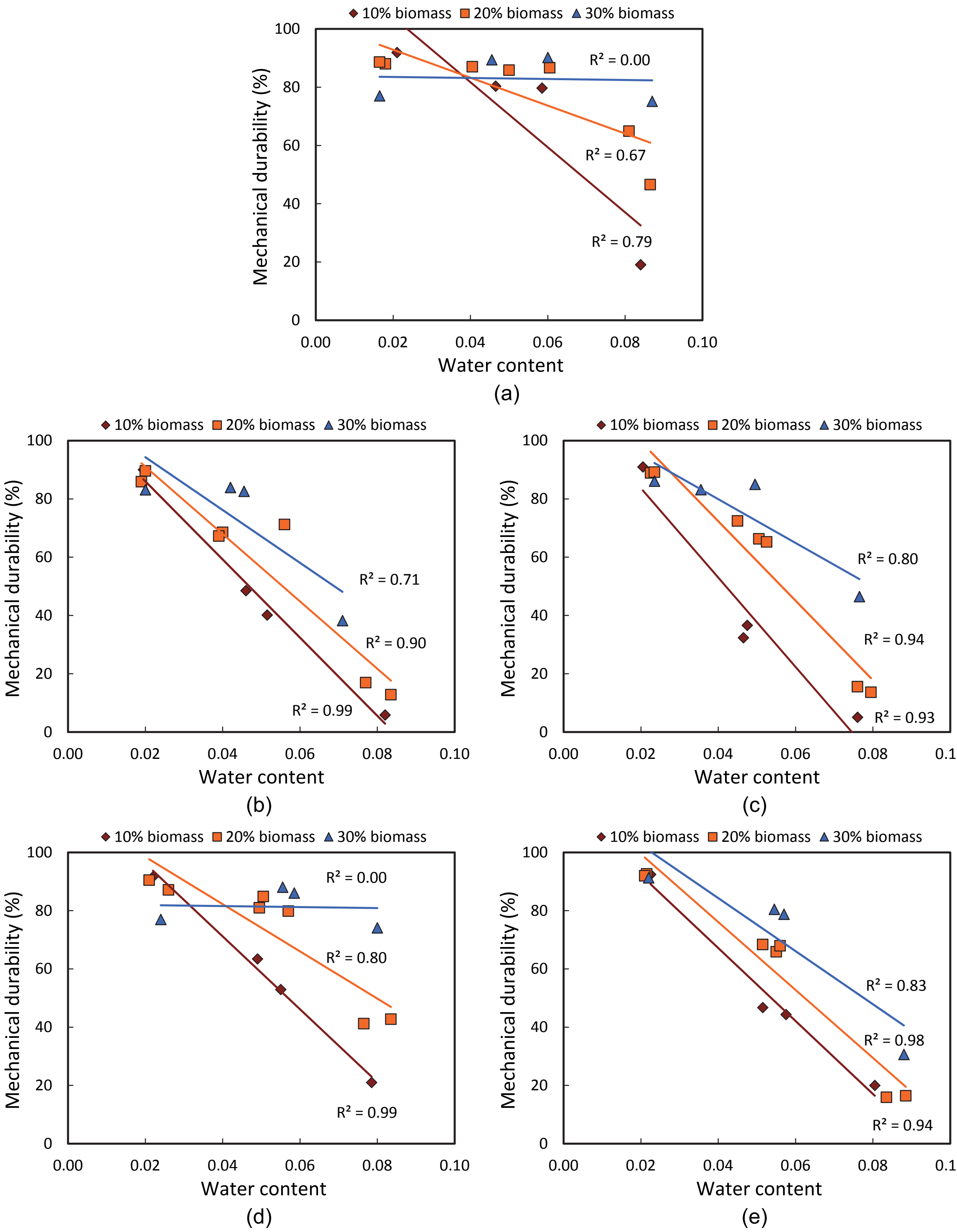


Figure 5-11. Effect of feed water content on mechanical durability of briquettes composed of Emerald (bituminous) coal and (a) corn stover, (b) switchgrass, (c) miscanthus, (d) wheat straw and (e) sawdust

5.4.1.1.2 Biomass Content Correlations

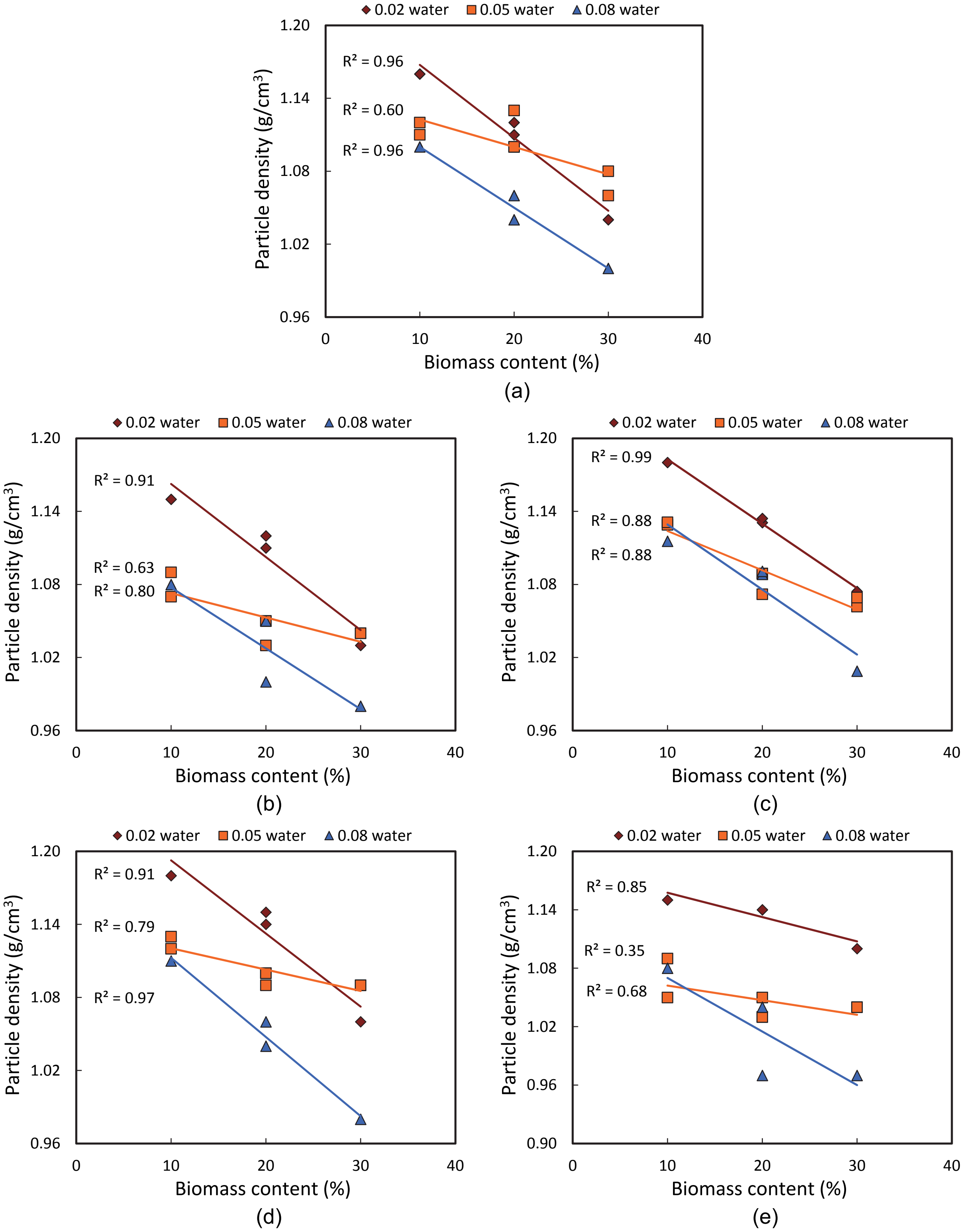
The correlation between biomass content and each measured briquette property were also evaluated for all five biomass types by linear regression analysis. To investigate these correlations, biomass content was plotted versus each measured briquette property with the data points grouped by the target feed water content (i.e. 0.02, 0.05 and 0.08). This approach was used because little or no correlation existed for the entire data sets due to the influence of the other two feedstock variables (i.e. water content and biomass top size). The biomass content correlations were initially investigated with the data grouped separately by water content and biomass top size. From these investigations, it was found that biomass content correlations were greatest with the data grouped by water content.

Figure 5-12 displays the correlations between biomass content and particle density for each of the five types of biomass. Specifically, the biomass content correlations are shown in Figure 5-12a for corn stover, Figure 5-12b for switchgrass, Figure 5-12c for miscanthus, Figure 5-12d for wheat straw and Figure 5-12e for sawdust. It is clear from these charts that biomass content has a negative correlation with the particle density of briquettes. For each of the five biomass types, an increase in biomass content directly reduced the particle density at each water content. This finding was expected since the addition of additional biomass with a true density much lower than coal will reduce the composite density of the mixture prior to briquette production. This correlation was very strong for briquettes produced with a water content of 0.02, which is evident by an average coefficient of determination (R^2) of 0.92. In contrast, the weakest average correlation ($R^2 = 0.65$) was found at a water content of 0.05. Another interesting observation is that the correlations for the briquettes composed of sawdust were weaker than those for the other four types of biomass. Nonetheless, these findings prove that an increase in biomass content directly reduces the particle density of coal-biomass briquettes.

Figure 5-13 illustrates the correlations between biomass content and crushing strength for each of the five types of biomass. Specifically, the biomass content correlations are shown in Figure 5-13a for corn stover, Figure 5-13b for switchgrass, Figure 5-13c for miscanthus, Figure 5-13d for wheat straw and Figure 5-13e for sawdust. It is clear from these charts that biomass content has a positive correlation with the crushing strength of briquettes. For each of the five biomass types, an increase in biomass content directly increased the crushing strength at each water content. The average correlations were very strong for water contents of 0.02 ($R^2 = 0.97$) and 0.05

($R^2 = 0.95$), but were not as apparent at a water content of 0.08 ($R^2 = 0.73$). These findings suggest that addition of biomass to coal briquettes improves the crushing strength of feedstocks and that low biomass content briquettes are typically lower in strength. This phenomena is thought to be a result of mechanical interlocking bonds that form between elongated biomass particles during briquette production.

Figure 5-14 shows the correlations between biomass content and mechanical durability for each of the five biomass types. Specifically, the biomass content correlations are shown in Figure 5-14a for corn stover, Figure 5-14b for switchgrass, Figure 5-14c for miscanthus, Figure 5-14d for wheat straw and Figure 5-14e for sawdust. These charts show that an increase in biomass content reduces the mechanical durability of briquettes produced at a water content of 0.02. In contrast, an increase in biomass content improves the mechanical durability of briquettes produced at a water content of 0.05 and 0.08. Another interesting observation is that the mechanical durability at 30 percent biomass is highest for briquettes produced with a water content of 0.05. However, this correlation was not observed for the briquettes produced with sawdust, which further exemplifies the difference between sawdust and the other types of biomass with regard to briquetting optimization.



(a)

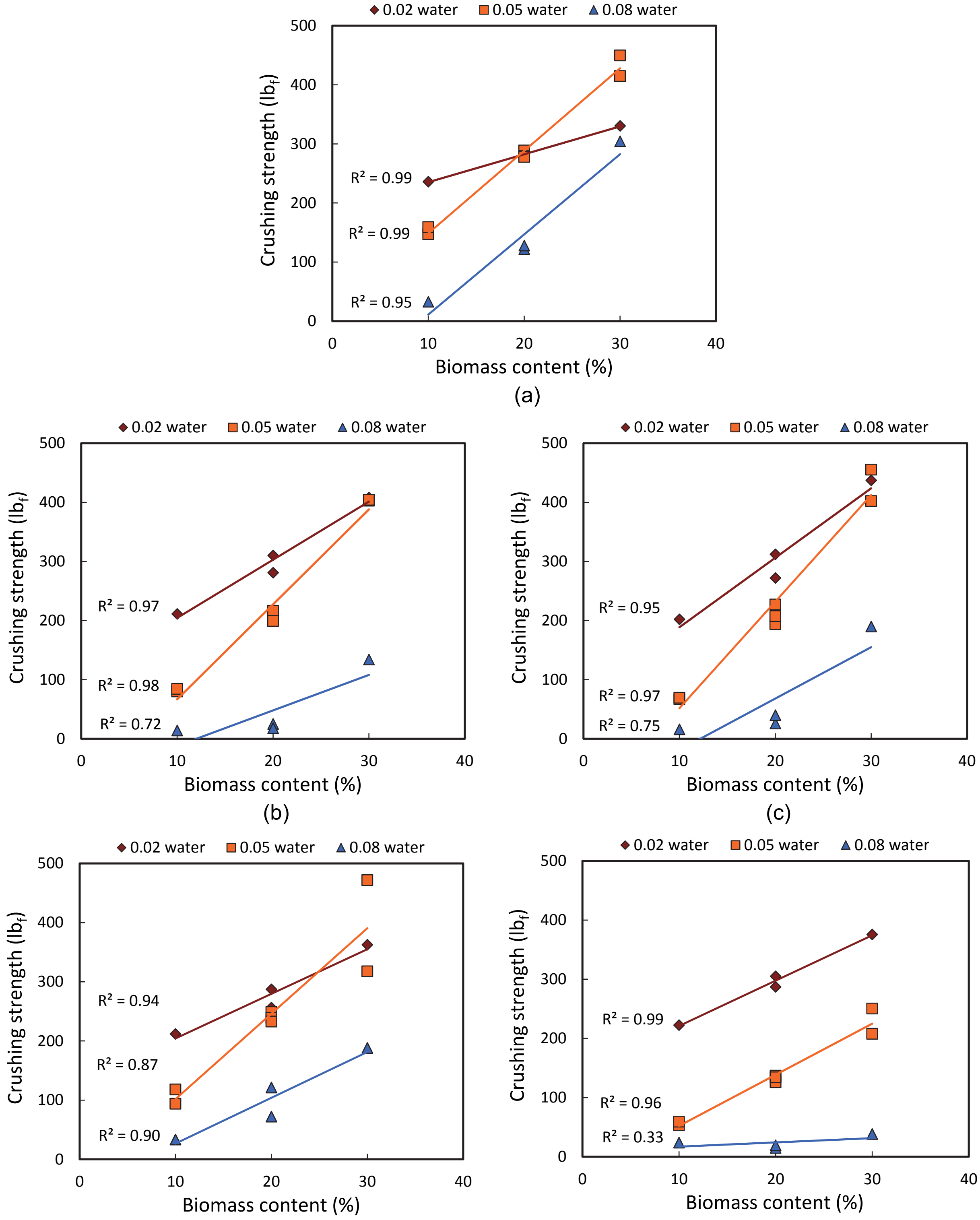
(b)

(c)

(d)

(e)

Figure 5-12. Effect of biomass content on particle density of briquettes composed of Emerald (bituminous) coal and (a) corn stover, (b) switchgrass, (c) miscanthus, (d) wheat straw and (e) sawdust



(a)

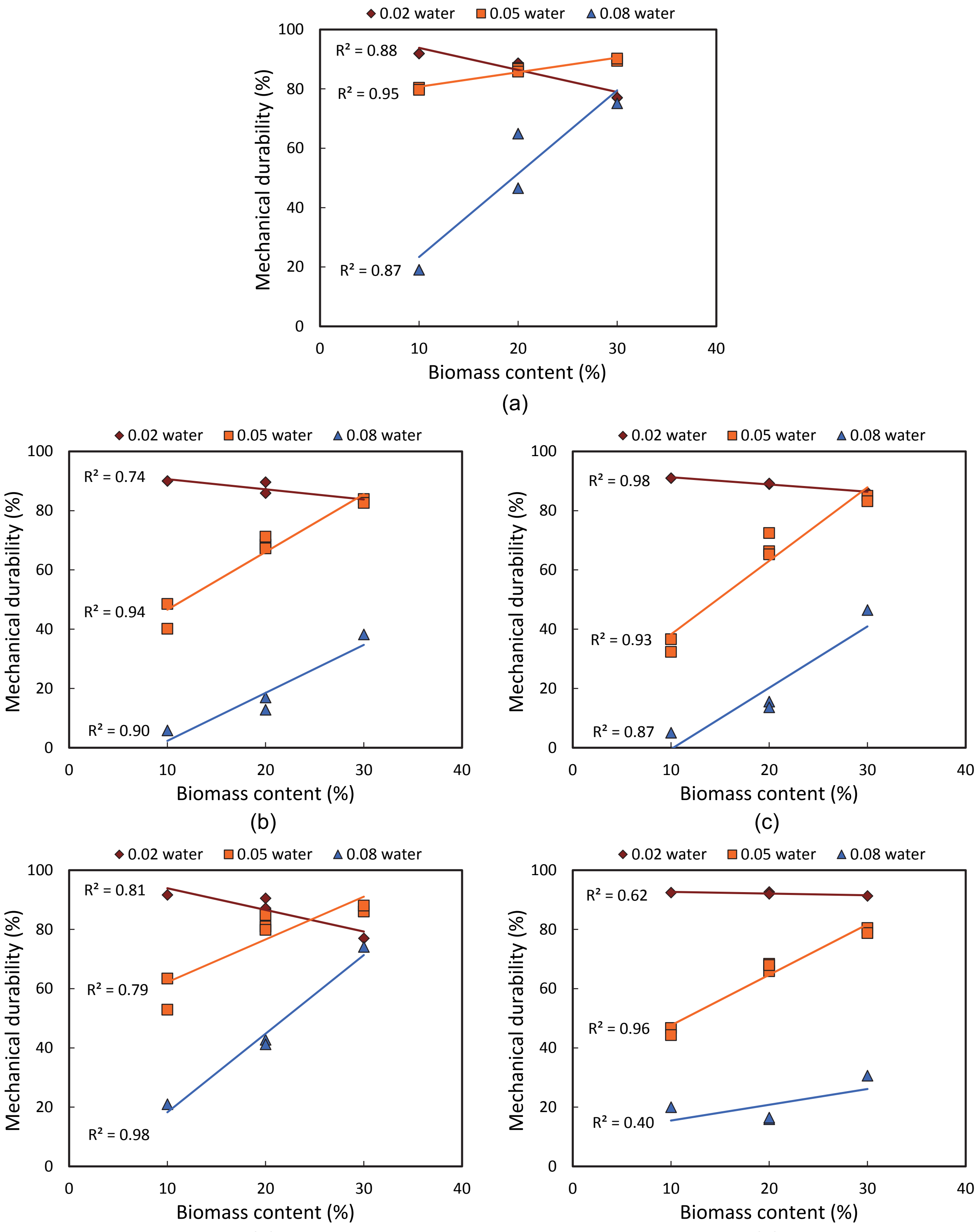
(b)

(c)

(d)

(e)

Figure 5-13. Effect of biomass content on crushing strength of briquettes composed of Emerald (bituminous) coal and (a) corn stover, (b) switchgrass, (c) miscanthus, (d) wheat straw and (e) sawdust



(a)

(b)

(c)

(d)

(e)

Figure 5-14. Effect of biomass content on mechanical durability of briquettes composed of Emerald (bituminous) coal and (a) corn stover, (b) switchgrass, (c) miscanthus, (d) wheat straw and (e) sawdust

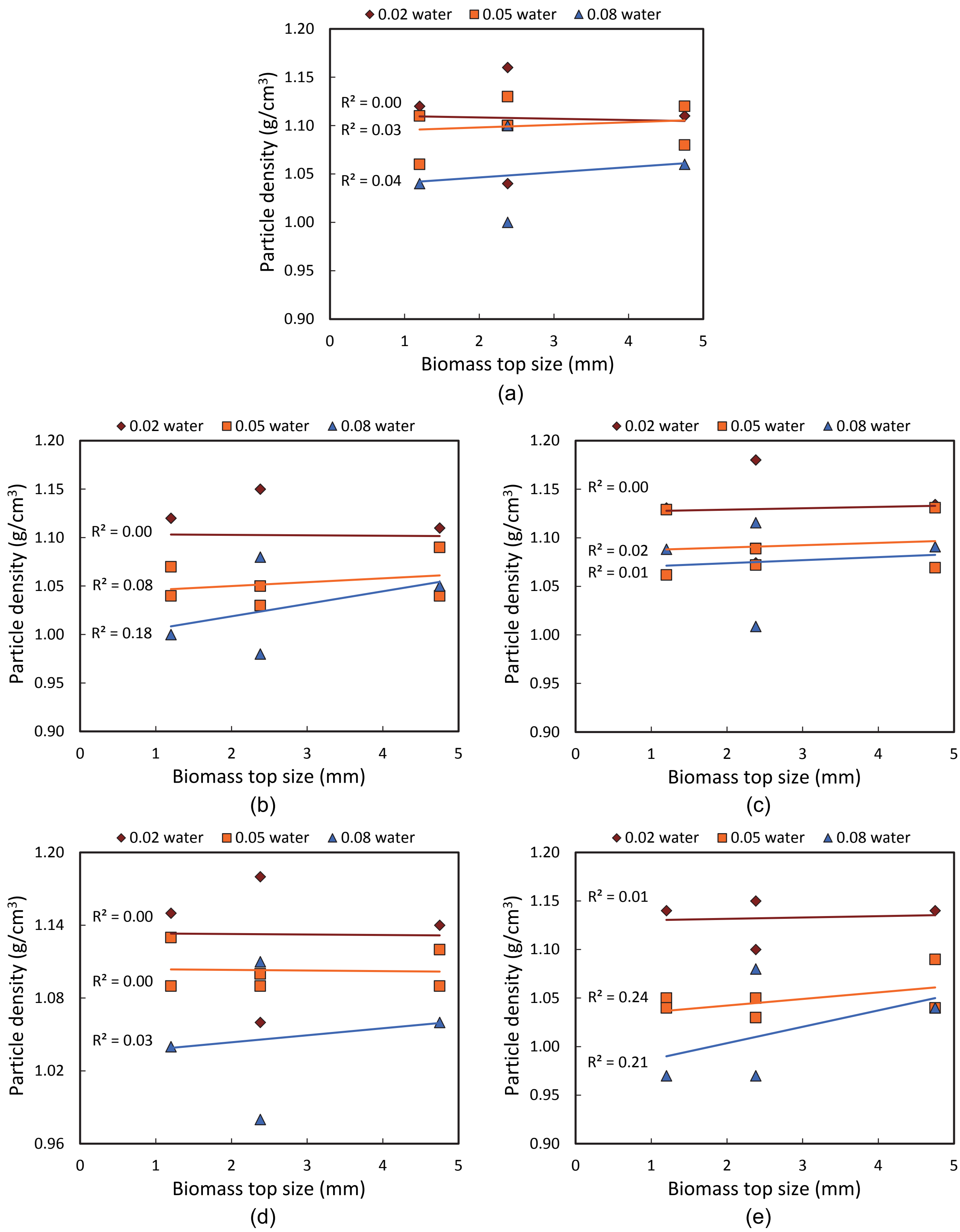
5.4.1.1.3 Biomass Top Size Correlations

The correlation between biomass top size and each measured briquette property were also evaluated for all five biomass types by linear regression analysis. To investigate these correlations, biomass top size was plotted versus each measured briquette property with the data points grouped by the target feed water content (i.e. 0.02, 0.05 and 0.08). This approach was used because little or no correlation existed for the entire data sets due to the influence of the other two feedstock variables (i.e. water content and biomass content). The biomass top size correlations were initially investigated with the data grouped separately by water content and biomass content. From these investigations, it was found that biomass top size correlations were greatest with the data grouped by water content, although neither resulted in any significant correlations.

Figure 5-15 displays the correlations between biomass top size and particle density for each of the five types of biomass. Specifically, the biomass top size correlations are shown in Figure 5-15a for corn stover, Figure 5-15b for switchgrass, Figure 5-15c for miscanthus, Figure 5-15d for wheat straw and Figure 5-15e for sawdust. It is clear from these charts that there is very little correlation between biomass top size and particle density. This is supported by average coefficient of determination values of 0.00, 0.07 and 0.09 for water contents of 0.02, 0.05 and 0.08, respectively. However, these findings do suggest that the slight influence of biomass top size on particle density increases with a corresponding increase in water content.

Figure 5-16 illustrates the correlations between biomass top size and crushing strength for each of the five types of biomass. Specifically, the biomass top size correlations are shown in Figure 5-16a for corn stover, Figure 5-16b for switchgrass, Figure 5-16c for miscanthus, Figure 5-16d for wheat straw and Figure 5-16e for sawdust. It is clear from these charts that there is very little correlation between biomass top size and crushing strength. This is supported by average coefficient of determination values of 0.02 for each water content.

Figure 5-17 shows the correlations between biomass top size and mechanical durability for each of the five biomass types. Specifically, the biomass top size correlations are shown in Figure 5-17a for corn stover, Figure 5-17b for switchgrass, Figure 5-17c for miscanthus, Figure 5-17d for wheat straw and Figure 5-17e for sawdust. It is clear from these charts that there is very little correlation between biomass top size and mechanical durability. This is supported by average coefficient of determination values of 0.06, 0.02 and 0.03 for water contents of 0.02, 0.05 and 0.08, respectively.



(a)

(b) (c)

(d) (e)

Figure 5-15. Effect of biomass top size on particle density of briquettes composed of Emerald (bituminous) coal and (a) corn stover, (b) switchgrass, (c) miscanthus, (d) wheat straw and (e) sawdust

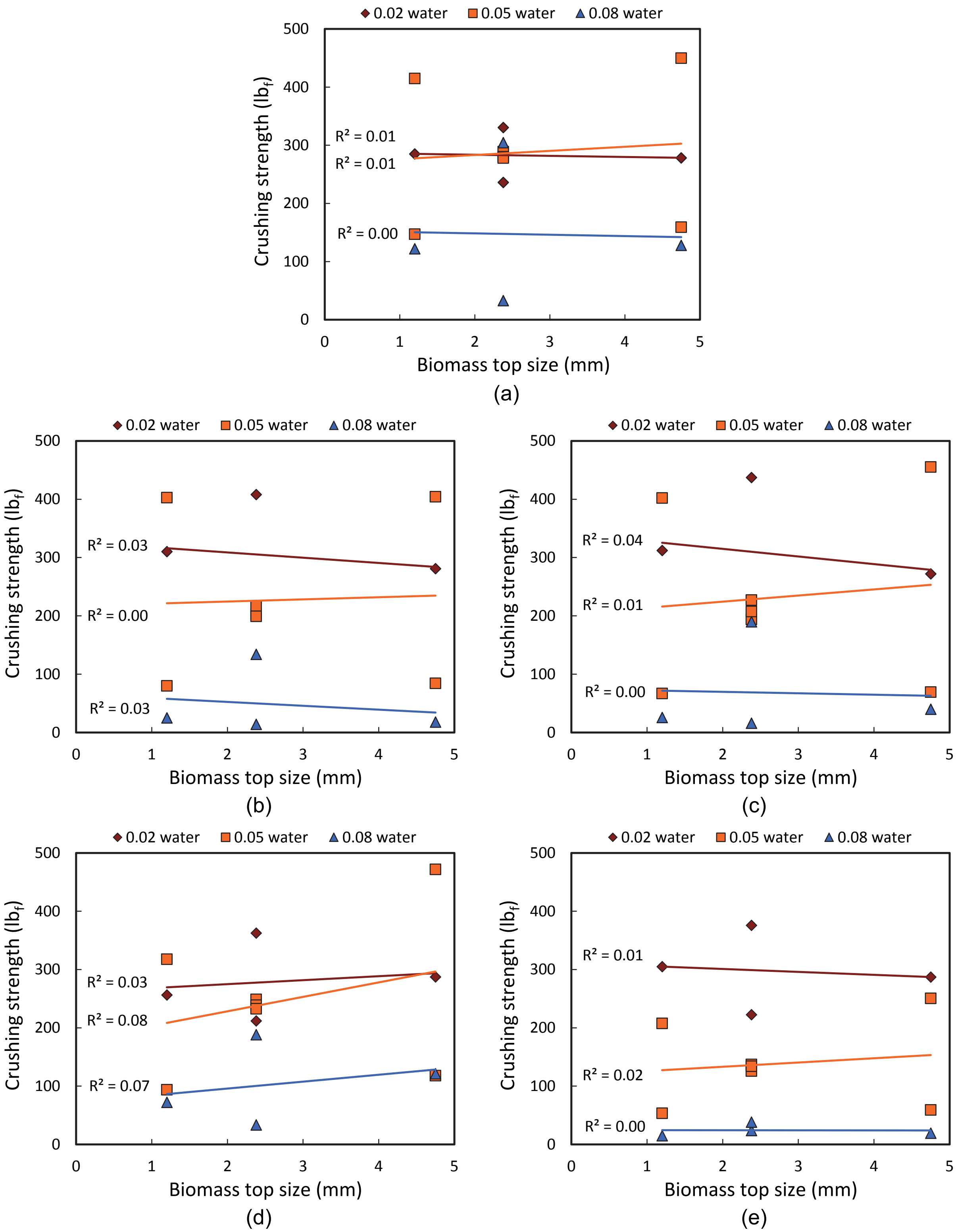


Figure 5-16. Effect of biomass top size on crushing strength of briquettes composed of Emerald (bituminous) coal and (a) corn stover, (b) switchgrass, (c) miscanthus, (d) wheat straw and (e) sawdust

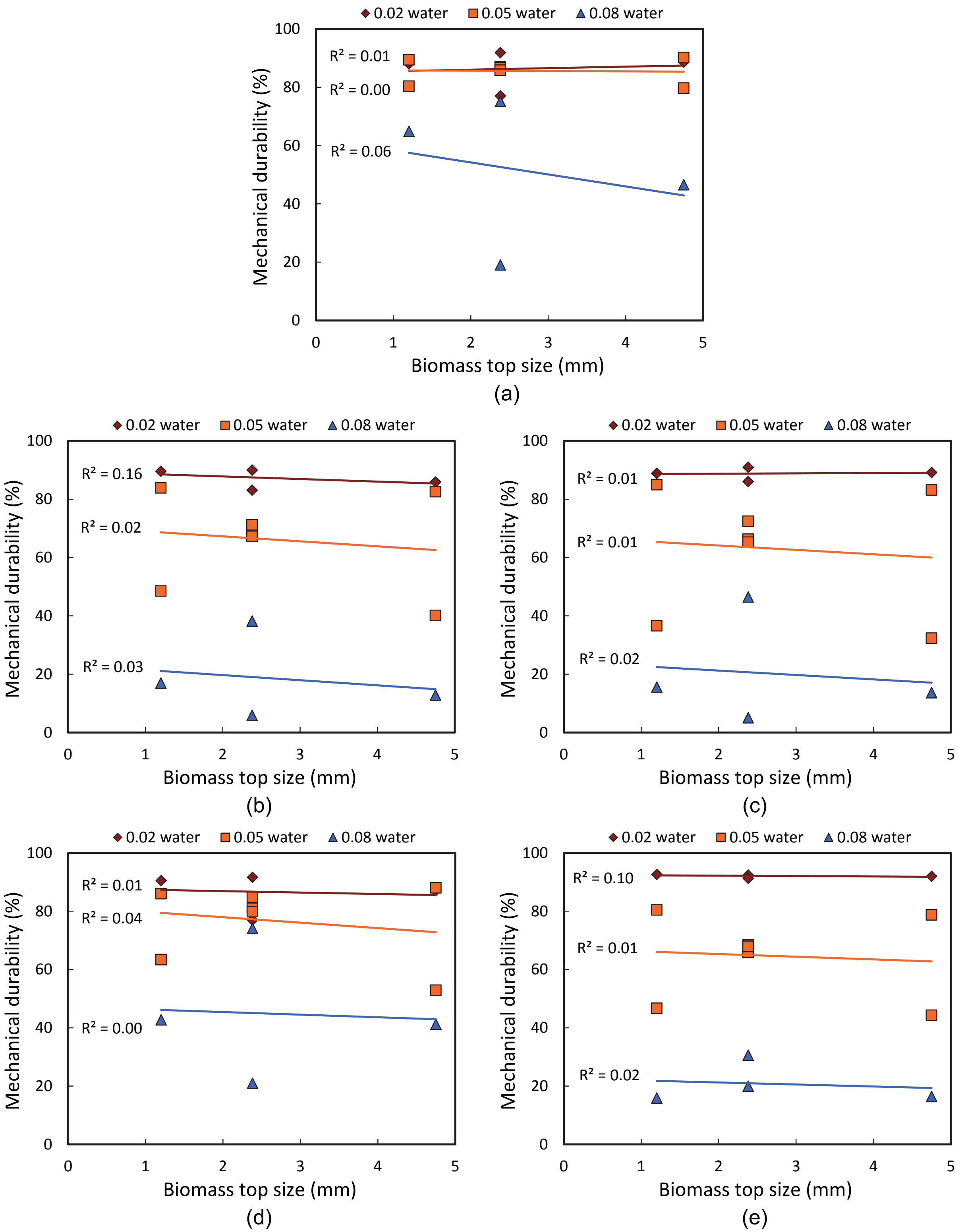


Figure 5-17. Effect of biomass top size on mechanical durability of briquettes composed of Emerald (bituminous) coal and (a) corn stover, (b) switchgrass, (c) miscanthus, (d) wheat straw and (e) sawdust

5.4.1.2 Statistical Analyses

The data sets presented in Table 5-4 through Table 5-8 were examined using the statistical analysis tools included in Design-Expert® 8 to determine the influence of each feedstock variable and to optimize the quality of briquettes. For each combination of Emerald coal and biomass, mathematical models were developed that relate the feedstock variables (i.e. water content, biomass content and biomass top size) to the measured briquette properties (i.e. particle density, crushing strength, and mechanical durability). The first step of model development was selection of the process order (e.g. linear, quadratic) of the mathematical model. This was accomplished by determining the process order with the lowest lack of fit p-value and the highest adjusted R-squared and predicted R-squared values. The selected model was then analyzed using the analysis of variance (ANOVA) function to determine the statistical significance of the entire model and of each individual term. All insignificant terms were then removed from the model, except those required to maintain hierarchy. Next, the fit of the model to the data was evaluated using various diagnostics tools. The following sections present the empirical mathematical models developed for briquettes composed of Emerald coal and corn stover and summarize the results of the statistical analyses. The results for the remaining four types of briquettes composed of Emerald coal and biomass are included in Appendix B.

5.4.1.2.1 Particle Density Model

A linear mathematical model was constructed that relates feed water content, biomass content and biomass top size to the particle density of briquettes composed of Emerald coal and corn stover. According to the model, the predicted particle density of briquettes is calculated by:

$$\rho = 1.20 - 0.85w + 0.0042s - 0.0039c \tag{Eq. 5-9}$$

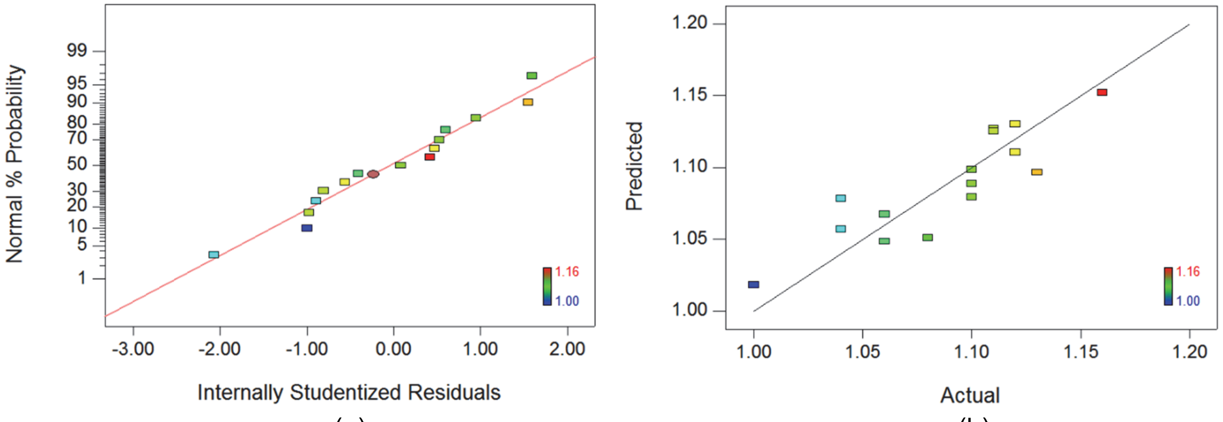
where ρ is the particle density (g/cm^3), w is the feed water content, s is the biomass top size (mm) and c is the biomass content (%). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using a number of numerical and graphical tools.

The ANOVA results were first inspected to numerically measure the statistical significance of the model. A summary of the results of this analysis are provided in Table 5-9. The most important statistical measure analyzed was the p-value, which represents the probability of obtaining a test statistic as extreme as the observed value, assuming the null hypothesis is true. As the p-value decreases, it becomes more likely that a model (or term) is causing an effect, and less likely that an effect is the result of chance. In common practice, the null hypothesis is rejected for models (or terms) with p-values less than 0.05, which in turn implies that the model (or term) is statistically significant. P-values greater than 0.10 imply that the model (or term) is not significant, while the significance of terms with p-values between 0.05 and 0.10 must be determined on a case-by-case basis. The p-value of the particle density model is 0.0007, which indicates that the predicted particle density values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the three model terms are 0.0039 (water content), 0.3568 (biomass top size) and 0.0005 (biomass content). This implies that water content and biomass content are statistically significant model terms, and thus have a major impact on accurate prediction of the particle density of briquettes. In contrast, biomass top size is not a significant model term, which implies that its impact on particle density quantified in the model is not statistically significant. This term was needed to maintain the hierarchy of the model, otherwise it would have been removed to improve the model. For example, a secondary term in a quadratic model would be removed if it were found to have a p-value greater than 0.10. This process is referred to as model reduction.

Table 5-9. ANOVA results for EM-CS particle density model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	0.019	3	6.28E-03	12.4493	0.0007
A-Water content	6.65E-03	1	6.65E-03	13.1991	0.0039
B-Biomass top size	4.66E-04	1	4.66E-04	0.92513	0.3568
C-Biomass content	0.012	1	0.012	23.9591	0.0005
Residual	5.55E-03	11	5.04E-04	--	--
Cor Total	0.024	14	--	--	--

Following the ANOVA, a number of diagnostic graphs were inspected to visually examine the residuals, which are differences in the actual measured particle density values and those predicted by the model. The purpose of examining the residuals is to look for any patterns that would indicate that anything other than noise is present in the data. One of the major ANOVA assumptions is that the residuals are normally distributed. Thus, this assumption was visually examined in a normal probability plot of studentized results, which is the recommended method to confirm the normality assumption. If the residuals are indeed normally distributed, the residuals will follow an approximately straight line. Figure 5-18a shows the normal probability plot of studentized residuals for the particle density model. It is clear from this figure that the residuals do indeed follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual particle density values was also examined to visually analyze the relationship between the measured particle density values and those predicted by the model. In this plot, a line drawn at 45 degrees (i.e. predicted = actual) should go through the middle of the data over the entire range of data points. Point clusters below or above the line indicated problems with the model over or under predicting responses. The predicted versus actual values plot is displayed in Figure 5-18b for the particle density model, which shows the desired data scatter about the line is present. This further exemplifies the statistical significance of the particle density model and indicates that it is well suited for prediction of briquette quality.



(a) (b)

Figure 5-18. Diagnostic graphs for visual inspection of ANOVA results for EM-CS particle density model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

5.4.1.2.2 Crushing Strength Model

A quadratic mathematical model was constructed that relates feed water content, biomass content and biomass top size to the crushing strength of briquettes composed of Emerald coal and corn stover. According to the model, the predicted crushing strength of briquettes is calculated by:

$$\sigma = 94.23 + 2390.00w + 8.68s + 4.63c + 140.63wc - 70030.23w^2 \quad \text{(Eq. 5-10)}$$

where σ is the crushing strength (lb_f), w is the feed water content, s is the biomass top size (mm) and c is the biomass content (%). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using the same numerical and graphical tools previously described. A summary of the ANOVA is provided in Table 5-10 for the crushing strength model. The p-value of the model is less than 0.0001, which indicates that the predicted crushing strength values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the model terms are 0.0003 (water content), 0.1807 (biomass top size), less than 0.0001 (biomass content), 0.0122 (water content x biomass content) and 0.0010 (water content^2). This implies that all of the model terms are statistically significant (except biomass top size), and thus have a major impact on accurate prediction of the crushing strength of briquettes. In contrast, biomass top size is not a significant model term, which implies that its impact on crushing strength quantified in the model is not statistically significant.

Table 5-10. ANOVA results for EM-CS crushing strength model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	170760	5	34152	36.60	< 0.0001
A-Water content	29208	1	29208	31.30	0.0003
B-Biomass top size	1965	1	1965	2.11	0.1807
C-Biomass content	106803	1	106803	114.46	< 0.0001
AC	9126	1	9126	9.78	0.0122
A^2	21044	1	21044	22.55	0.0010
Residual	8398	9	933	--	--
Cor Total	179158	14	--	--	--

To confirm the ANOVA normality assumption for the crushing strength model, the residuals were visually examined in a normal probability plot of studentized results. Figure 5-19a shows the normal probability plot of studentized residuals for the crushing strength model. It is clear from this figure that the residuals follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual values was also examined to visually analyze the relationship between the measured crushing strength values and those predicted by the model. The predicted versus actual plot is displayed in Figure 5-19b for the crushing strength model, which shows the desired data scatter about the 45 degree line is present. This further exemplifies the statistical significance of the crushing strength model and indicates that it is well suited for prediction of briquette quality.

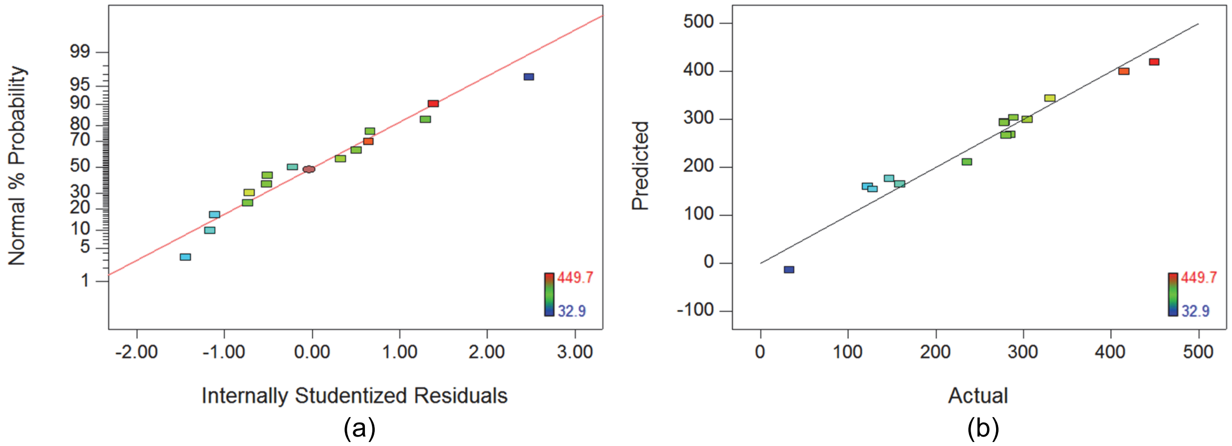


Figure 5-19. Diagnostic graphs for visual inspection of ANOVA results for EM-CS crushing strength model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

5.4.1.2.3 Mechanical Durability Model

A quadratic mathematical model was constructed that relates feed water content, biomass content and biomass top size to the mechanical durability of briquettes composed of Emerald coal and corn stover. According to the model, the predicted mechanical durability of briquettes is calculated by:

$$MD = 108.87 + 43.20w + 0.57s - 1.93c + 53.27wc - 15946.36w^2 \qquad \text{(Eq. 5-11)}$$

where MD is the mechanical durability (%), w is the feed water content, s is the biomass top size (mm) and c is the biomass content (%). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using the same numerical and graphical tools previously described. A summary of the ANOVA is provided in Table 5-11 for the mechanical durability model. The p-value of the model is less than 0.0001, which indicates that the predicted mechanical durability values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the model terms are less than 0.0001 (water content), 0.6454 (biomass top size), 0.0085 (biomass content), 0.0002 (water content x biomass content) and 0.0004 (water content^2). This implies that all of the model terms are statistically significant (except biomass top size), and thus have a major impact on accurate prediction of the mechanical durability of briquettes. In contrast, biomass top size is not a significant model term, which implies that its impact on mechanical durability quantified in the model is not statistically significant.

Table 5-11. ANOVA results for EM-CS mechanical durability model

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	5192	5	1038	27.68	< 0.0001
A-Water content	2129	1	2129	56.74	< 0.0001
B-Biomass top size	9	1	9	0.23	0.6454
C-Biomass content	422	1	422	11.25	0.0085
AC	1309	1	1309	34.91	0.0002
A^2	1091	1	1091	29.09	0.0004
Residual	338	9	38		
Cor Total	5529	14			

To confirm the ANOVA normality assumption for the mechanical durability model, the residuals were visually examined in a normal probability plot of studentized results. Figure 5-20a shows the normal probability plot of studentized residuals for the mechanical durability model. It is clear from this figure that the residuals follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual values was also examined to visually analyze the relationship between the measured mechanical durability values and those predicted by the model. The predicted versus actual plot is displayed in Figure 5-20b for the mechanical durability model, which shows the desired data scatter about the 45 degree line is present. This further exemplifies the statistical significance of the mechanical durability model and indicates that it is well suited for prediction of briquette quality.

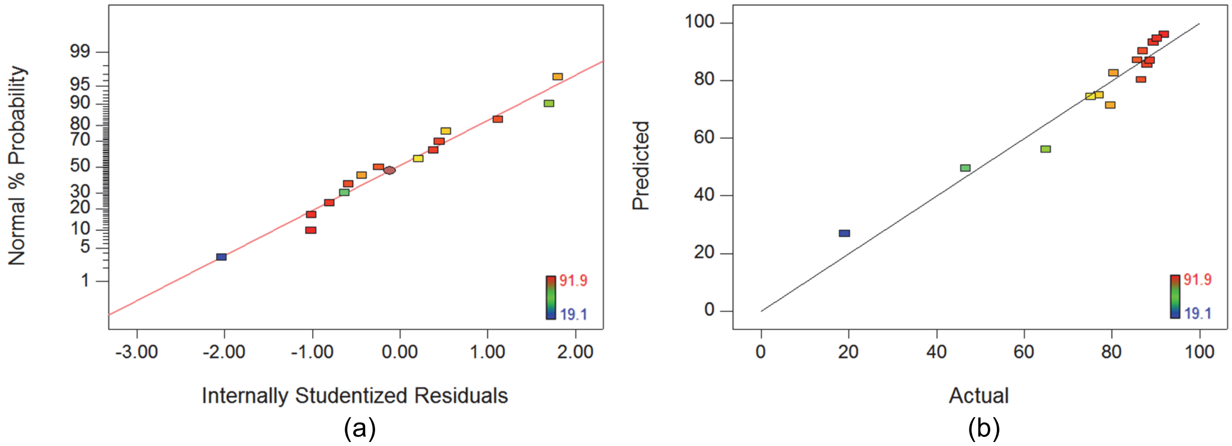


Figure 5-20. Diagnostic graphs for visual inspection of ANOVA results for EM-CS mechanical durability model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

5.4.1.3 Model Graphs

Following the development and statistical analysis of each mathematical model, several contour graphs were constructed to visually interpret and evaluate the results. To provide a clear interpretation of the influence of each feedstock variable on each briquette property, the contour graphs are assembled by common model terms. This section presents and discusses the contour graphs for the models developed for briquettes composed of Emerald coal and corn stover. The graphs for the remaining four types of briquettes composed of Emerald coal and biomass are included in Appendix B.

The influence of feed water content on the modeled responses for particle density, crushing strength and mechanical durability are presented in Figure 5-21. From this figure it is evident that the maximum particle density values (i.e. > 1.16 g/cm^3) occur at a water content of 0.02 with 10 percent biomass at a top size of 4.75 millimeters. In contrast, the minimum particle density (i.e. < 1.04 g/cm^3) values occur at a water content of 0.08 with 30 percent biomass at a top size of 1.20 millimeters. Figure 5-21 also clearly indicates that briquette crushing strength reaches a maximum value (i.e. > 400 lb$_f$) at a water content of 0.05 with 30 percent biomass at a top size of 4.75 millimeters and reaches a minimum value (i.e. < 50 lb$_f$) at a water content of 0.08 with 10 percent biomass at a top size of 1.20 millimeters. Finally, this figure shows that the mechanical durability of briquettes reaches a maximum value (i.e. > 95%) at a water content of 0.02 with 10 percent biomass at a top size of 4.75 millimeters. The figure also indicates that a mechanical durability value in excess of 95 percent is achievable at a water content of 0.05 with 30 percent biomass at a top size of 4.75 millimeters.

The modeled responses for particle density, crushing strength and mechanical durability with respect to biomass content and biomass top size are presented in Figure 5-22 and Figure 5-23, respectively. These figures present the same data that is displayed in Figure 5-21, but offer a different perspective that may be desirable in certain circumstances. Regardless of the chart examined, graphical evaluation of these mathematical models indicate the optimum values of feedstock variables with respect to the crushing strength and mechanical durability of briquettes composed of Emerald coal and corn stover. These values are a water content of 0.05, a biomass content of 30 percent and a biomass top size of 4.75 millimeters, which predict a crushing strength in excess of 400 pounds-force and a mechanical durability in excess of 95 percent. Numerical optimization of the feedstock variables can be conducted to verify this result.

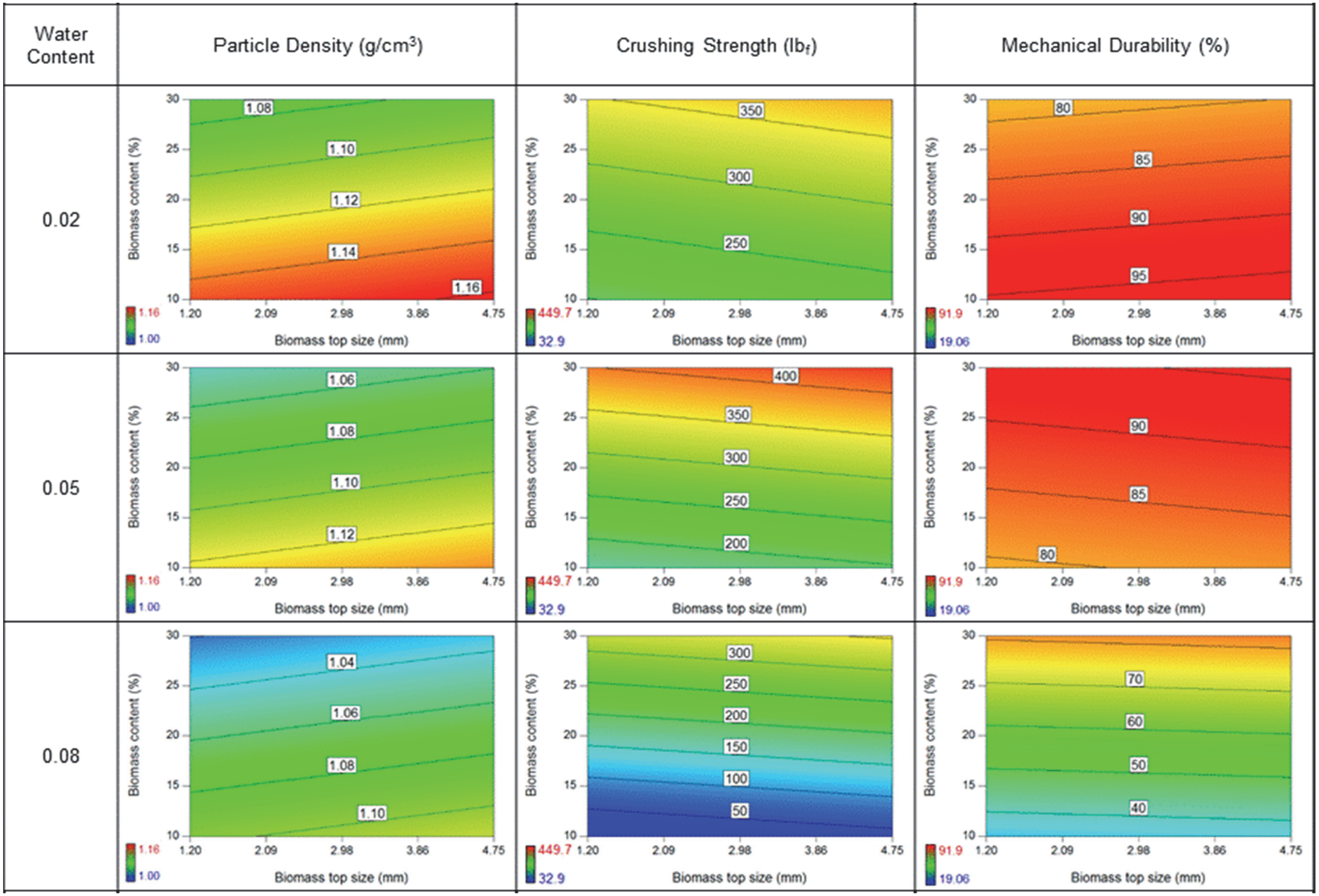


Figure 5-21. Influence of feed water content on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of Emerald (bituminous) coal and corn stover

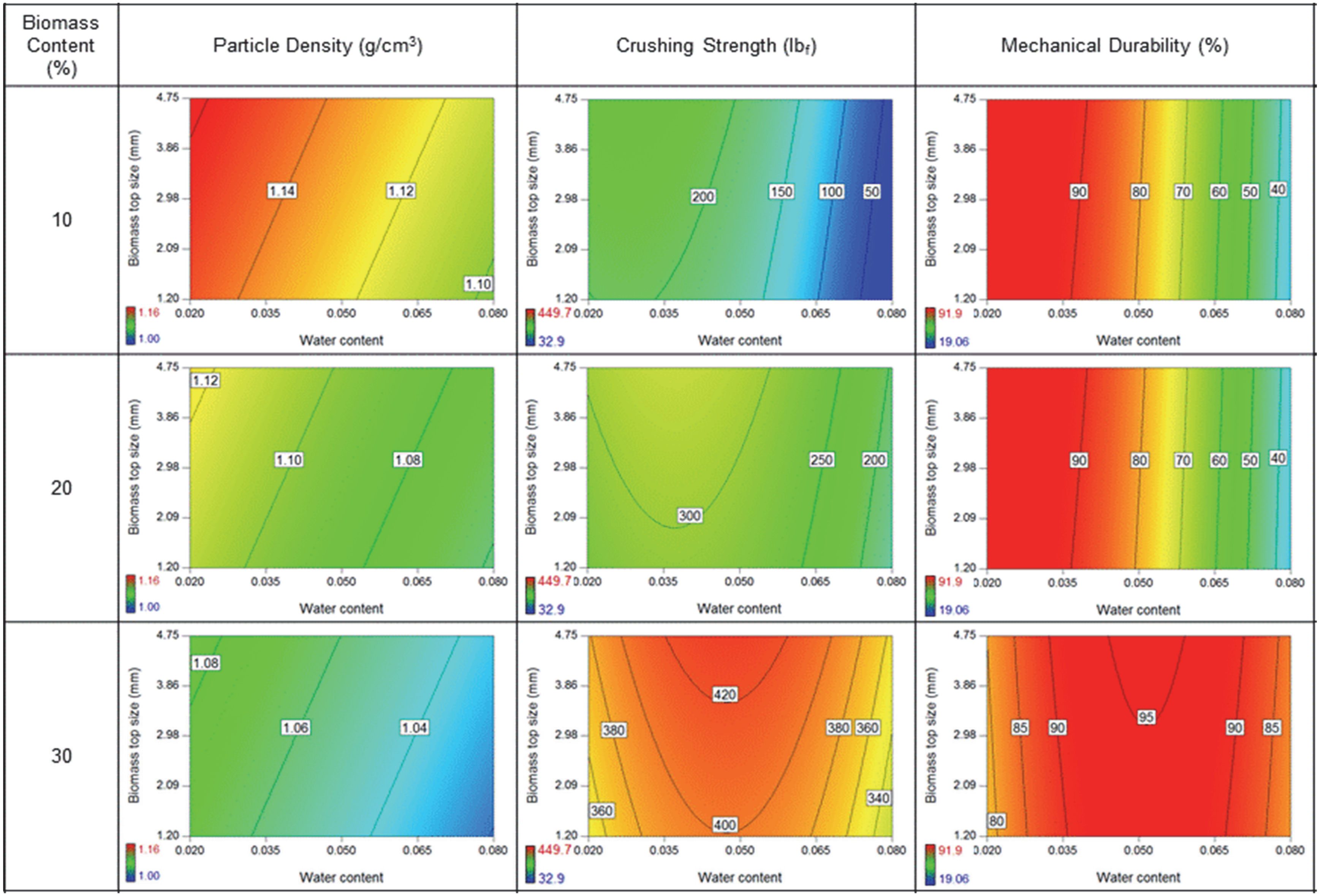


Figure 5-22. Influence of biomass content on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of Emerald (bituminous) coal and corn stover

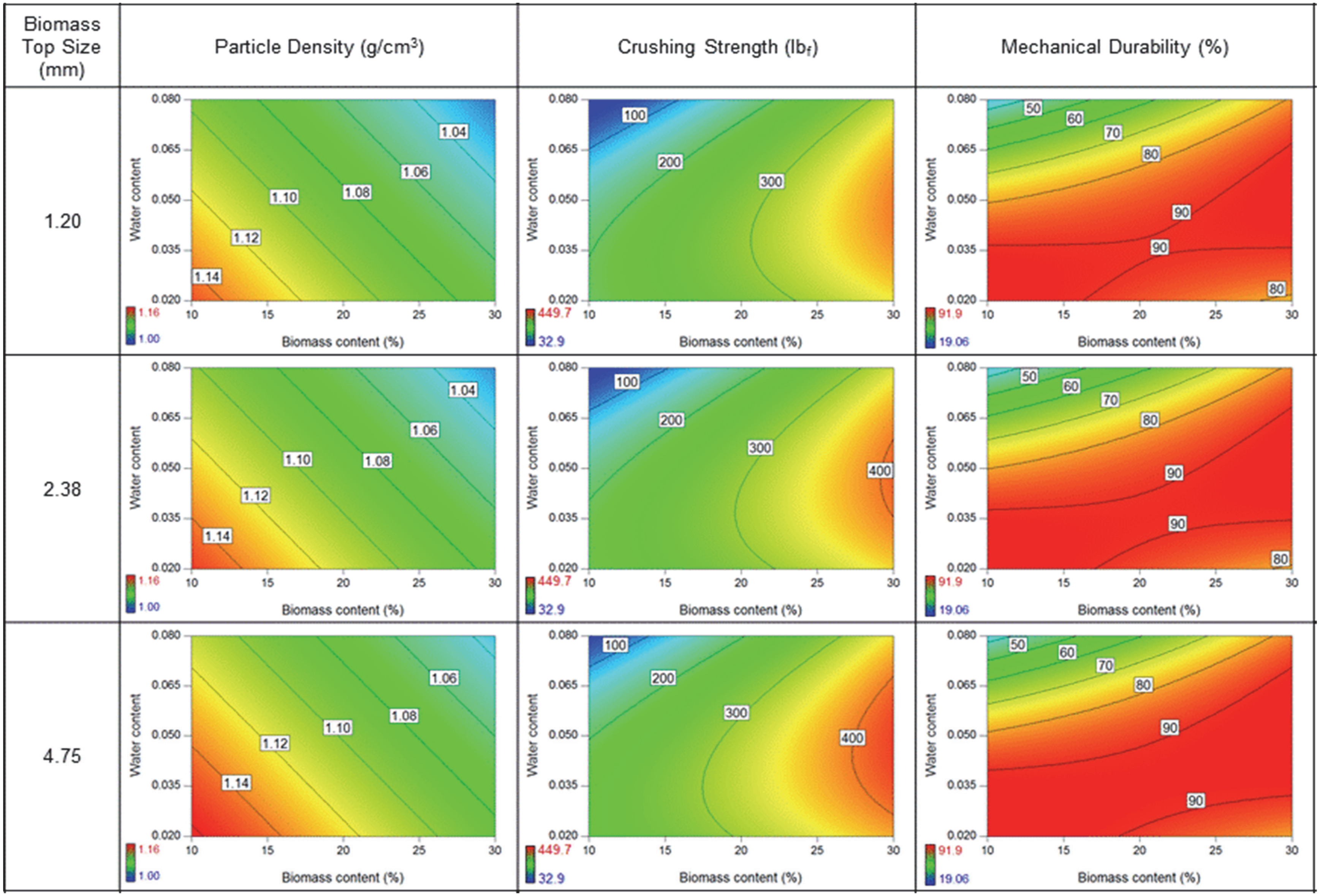


Figure 5-23. Influence of biomass top size on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of Emerald (bituminous) coal and corn stover

5.4.1.4 Numerical Optimization

Numerical optimization of the feedstock variables was conducted in Design-Expert® 8 using the tool included in the analysis package. This tool allows for specification of optimization criteria (i.e. goals), which can include maximizing or minimizing predicted responses and process variables, as well as setting target values for each parameter. The tool also allows for adjustment of the importance of each goal on a scale from one to five (1 being the least important, 5 being the most important). The results of the optimization routine include a specified value for each of the process (i.e. feedstock) variables, as well as the predicted values for each response (e.g. crushing strength). A desirability value is calculated for each solution to the optimization routine to provide a method to rank the solutions and to indicate the extent to which the combination of responses approaches a perfect solution (i.e. desirability = 1).

Optimization of the mathematical models developed for briquettes comprised of Emerald coal and corn stover was accomplished by specifying a maximization goal for both crushing strength and mechanical durability. The importance of the mechanical durability goal was set to five and the importance of the crushing strength goal was set to three. This configuration was selected after experimenting with the effect of the importance setting on the desirability of the solutions to the optimization routine. The routine generated 21 optimized solutions, all of which indicated a crushing strength in excess of 400 pounds-force and a mechanical durability in excess of 94 percent is achievable. As shown in Table 5-12, the most desirable solutions occur at a water content of 0.05 with 30 percent biomass at a top size of 4.75 millimeters.

Table 5-12. Numerical optimization results for EM-CS mathematical models

Number	Water Content	Biomass Top Size (mm)	Biomass Content (%)	Crushing Strength (lb_f)	Mechanical Durability (%)	Desirability
1	0.050	4.75	30	429.7	95.9	0.950
2	0.050	4.75	30	429.9	95.8	0.950
3	0.051	4.75	30	429.5	95.9	0.950
4	0.050	4.75	30	429.5	95.9	0.950
5	0.050	4.67	30	429.2	95.8	0.950
6	0.047	4.75	30	430.3	95.6	0.949
7	0.050	4.75	30	428.5	95.8	0.949
8	0.050	4.44	30	426.9	95.7	0.949
9	0.049	4.75	30	427.3	95.6	0.949
10	0.050	4.39	30	426.5	95.7	0.949

5.4.1.5 Comparison of Bituminous Coals

A series of verification tests were designed to evaluate the McClure River and Toms Creek coals. The objective of these tests was to verify that the optimum combinations of feedstock variables identified for each Emerald coal-biomass mixture can also produce strong and durable briquettes with the other bituminous coals, and to validate that an exhaustive optimization study is not required for each bituminous coal type. A secondary objective of these tests was to give a clear indication to the effect of coal and biomass type on the quality of coal-biomass briquettes. To accomplish this, an optimum set of feedstock variables was chosen for each biomass type from the 15 conditions evaluated for the Emerald coal evaluations. The optimum set of feedstock variables for the corn stover and wheat straw corresponded to standard test 12, which included a target water content of 0.05, a biomass content of 30 percent and a biomass top size of 4.75 millimeters. In contrast the optimum set of feedstock variables for the switchgrass, miscanthus and sawdust corresponded to standard test 01, which included a target water content of 0.02, a biomass content of 20 percent and a biomass top size of 1.20 millimeters. The results of the five sets of tests are summarized in Table 5-13 for the McClure River coal and in Table 5-14 for the Toms Creek coal.

Table 5-13. Summary of briquette characterization results for McClure River coal verification tests

Test ID	**Feed Water Content**	**Biomass Content (%)**	**Biomass Top Size (mm)**	**Briquette Water Content**	**Particle Density (g/cm^3)**	**Crushing Strength (lb$_f$)**	**Mechanical Durability (%)**
MR-MC-01	0.024	20	1.20	0.015	1.11	302.7	89.7
MR-SG-01	0.023	20	1.20	0.016	1.11	276.7	88.3
MR-SD-01	0.023	20	1.20	0.015	1.14	268.4	92.4
MR-CS-12	0.068	30	4.75	0.049	1.07	475.3	84.0
MR-WS-12	0.060	30	4.75	0.040	1.07	441.0	83.0

Table 5-14. Summary of briquette characterization results for Toms Creek coal verification tests

Test ID	**Feed Water Content**	**Biomass Content (%)**	**Biomass Top Size (mm)**	**Briquette Water Content**	**Particle Density (g/cm^3)**	**Crushing Strength (lb$_f$)**	**Mechanical Durability (%)**
TC-MC-01	0.022	20	1.20	0.015	1.13	220.0	77.1
TC-SG-01	0.021	20	1.20	0.016	1.11	206.8	80.4
TC-SD-01	0.021	20	1.20	0.014	1.15	206.2	88.1
TC-CS-12	0.060	30	4.75	0.046	1.10	447.0	74.0
TC-WS-12	0.046	30	4.75	0.045	1.09	374.3	68.3

To visualize the similarities in the measures responses for briquettes comprised of the three bituminous coals, the measured quality parameters for each coal type were plotted in a single chart. Figure 5-24 shows the similarities in the particle density of bituminous coal briquettes comprised of each biomass type. Specifically, the results are shown in Figure 5-24a for miscanthus, Figure 5-24b for switchgrass, Figure 5-24c for sawdust, Figure 5-24d for corn stover and Figure 5-24e for wheat straw. The measured particle density values for the briquettes composed of miscanthus ranged from 1.11 to 1.13 g/cm^3 for the three bituminous coals. The minimum value was attained with the McClure River coal, while both the Emerald and Toms Creek coals produced the maximum particle density value. Similarly, the measured particle density values for the briquettes composed of switchgrass ranged from 1.11 to 1.12 g/cm^3, with the maximum value corresponding to the Emerald coal briquettes and the minimum value corresponding to both the McClure River and the Toms Creek coal briquettes. The particle density values for the briquettes composed of sawdust and bituminous coal ranged from 1.14 to 1.15 g/cm^3, with the maximum value attained with the Toms Creek coal and the minimum value attained with both the Emerald and McClure River coal. These initial sets of results indicate that the three bituminous coals behave very similar with respect to the particle density of briquettes produced with biomass. These results also indicate that briquettes produced with sawdust generally have a greater particle density than briquettes composed of miscanthus and switchgrass. This result is certainly plausible due to the fact that woody biomass has a greater true density than agricultural biomass.

The measured particle density values for the briquettes composed of corn stover ranged from 1.07 to 1.10 g/cm^3 for the three bituminous coals. The minimum value was attained with the McClure River coal, while the Toms Creek coals produced the maximum particle density value. It is clear that these density values are substantially lower than the values obtained for the other agricultural biomass types (i.e. miscanthus and switchgrass). This result was due to the higher biomass content of the corn stover briquettes (i.e. 30%), as compared to the miscanthus and switchgrass briquettes (i.e. 20%). The incremental addition of biomass with a true density much lower than coal will clearly reduce the particle density of briquettes. Similarly, the measured particle density values for the briquettes composed of wheat straw ranged from 1.07 to 1.09 g/cm^3, with the maximum value corresponding to both the Emerald and Toms Creek coal briquettes and the minimum value corresponding to the McClure River coal briquettes. The results presented in Figure 5-24 clearly validate the similarity in particle density of the bituminous coal briquettes.

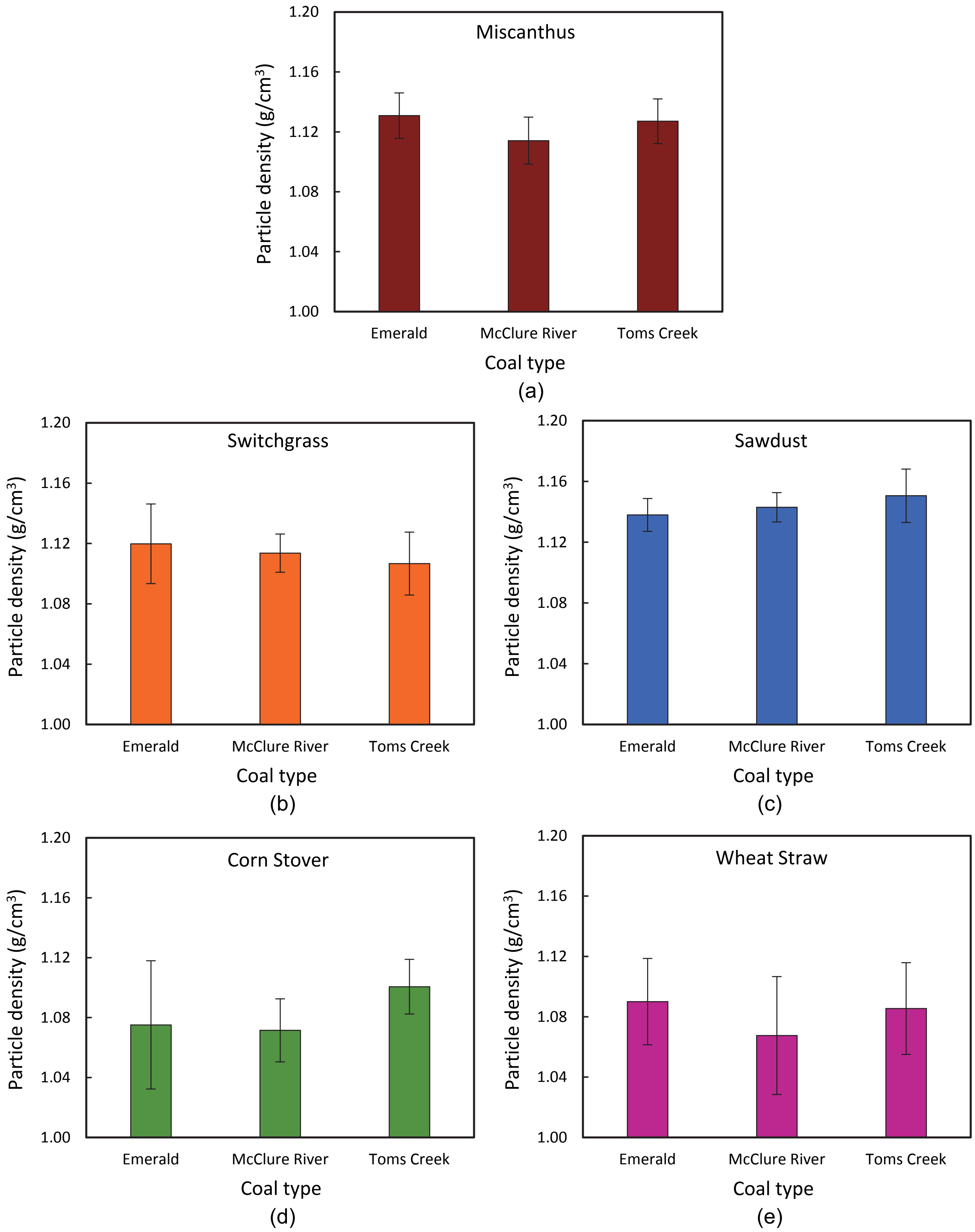
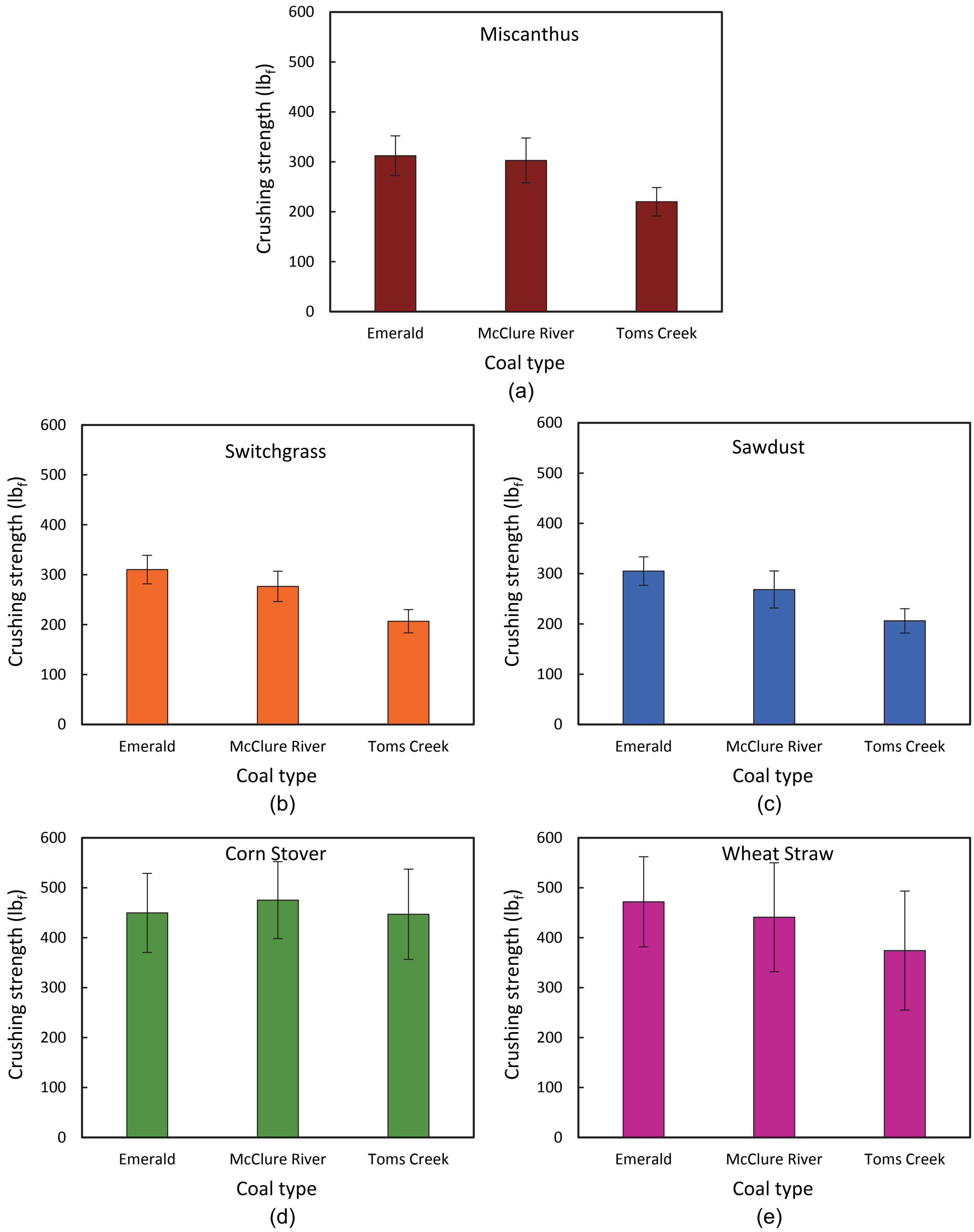


Figure 5-24. Comparison of particle density results for briquettes composed of bituminous coal and (a) miscanthus, (b) switchgrass, (c) sawdust, (d) corn stover and (e) wheat straw [Error bars indicate plus and minus one standard deviation from the mean]

Figure 5-25 shows the similarities in the crushing strength of bituminous coal briquettes comprised of each biomass type. Specifically, the results are shown in Figure 5-25a for miscanthus, Figure 5-25b for switchgrass, Figure 5-25c for sawdust, Figure 5-25d for corn stover and Figure 5-25e for wheat straw. The measured crushing strength values for the briquettes composed of miscanthus ranged from 220.0 to 312.2 lb$_f$ for the three bituminous coals. The minimum value was attained with the Toms Creek coal, while the Emerald coal produced the maximum crushing strength value. Similarly, the measured crushing strength values for the briquettes composed of switchgrass ranged from 206.8 to 310.3 lb$_f$, with the maximum value corresponding to the Emerald coal briquettes and the minimum value corresponding to the Toms Creek coal briquettes. The crushing strength values for the briquettes composed of sawdust and bituminous coal ranged from 206.2 to 305.0 lb$_f$. The maximum value was again attained with the Emerald coal and the minimum value was again attained with the Toms Creek coal. This reoccurring trend in briquette crushing strength values (i.e. Emerald = highest, Toms Creek = lowest) is likely the result of differences in the distribution modulus and ash content of the coals. As discussed in Chapter 4, this relative ranking of coal types with respect to briquette crushing strength was anticipated. These results also indicate that briquettes produced with miscanthus, switchgrass and sawdust generally exhibit similar crushing strengths.

The measured crushing strength values for the briquettes composed of corn stover ranged from 447.0 to 475.3 lb$_f$ for the three bituminous coals. As anticipated, the minimum value was attained with the Toms Creek coal, while the McClure River coal unexpectedly produced the maximum crushing strength. It is clear that these crushing strengths are substantially higher than the values obtained for the other agricultural biomass types (i.e. miscanthus and switchgrass). This result was due to the higher biomass content of the corn stover briquettes (i.e. 30%), as compared to the miscanthus and switchgrass briquettes (i.e. 20%). This was expected since the incremental addition of biomass was previously shown to increase the crushing strength of briquettes. Similarly, the measured crushing strength values for the briquettes composed of wheat straw ranged from 374.3 to 472.0 lb$_f$, with the maximum value corresponding to both the Emerald coal briquettes and the minimum value corresponding to the Toms Creek coal briquettes. The results presented in Figure 5-25 clearly show the similarities in the crushing strength of bituminous coal briquettes. While differences do exist in the measured values, they can be explained by further examination of the distribution modulus and ash content of each individual coal.



(a)

(b)

(c)

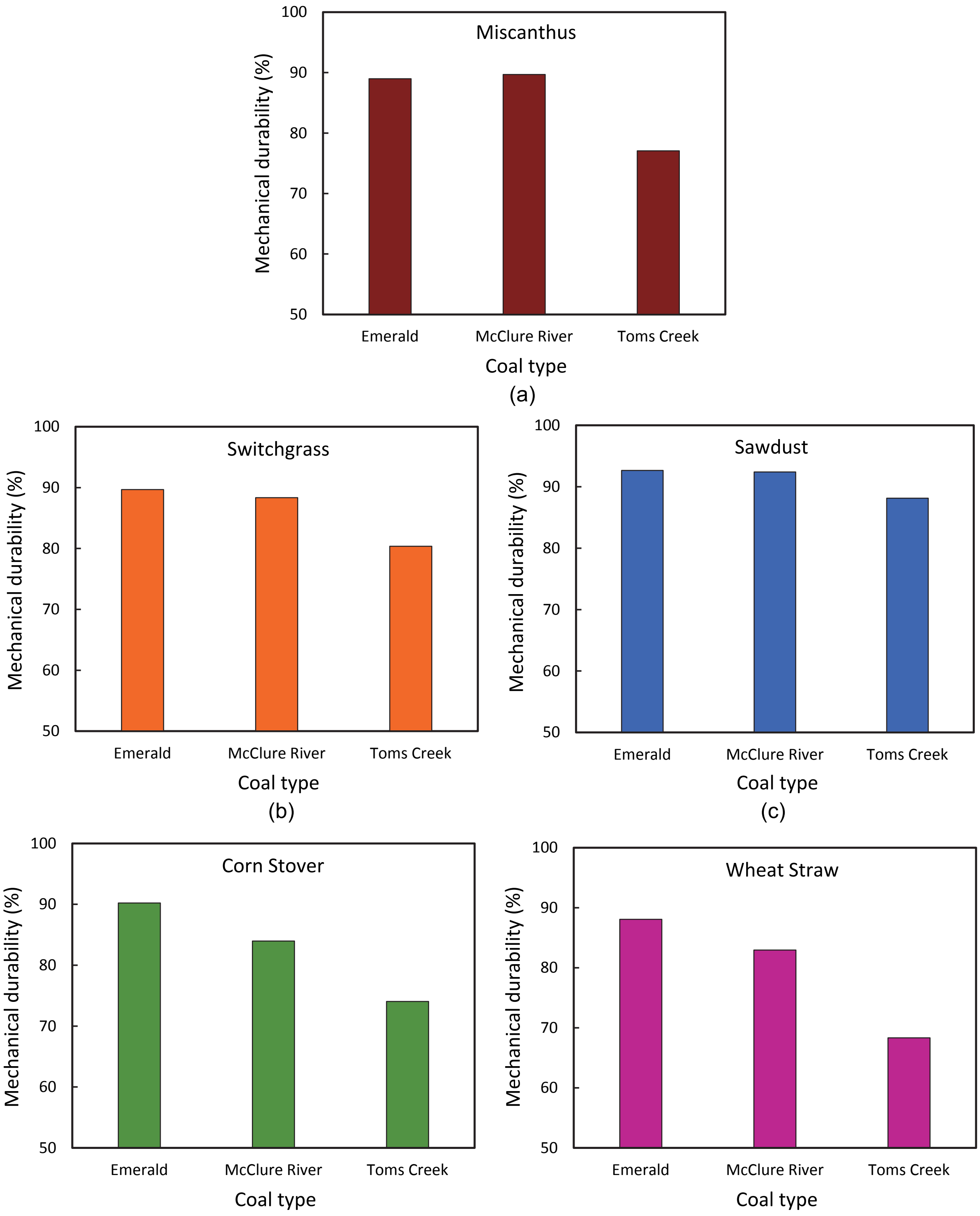
(d)

(e)

Figure 5-25. Comparison of crushing strength results for briquettes composed of bituminous coal and (a) miscanthus, (b) switchgrass, (c) sawdust, (d) corn stover and (e) wheat straw [Error bars indicate plus and minus one standard deviation from the mean]

Figure 5-26 shows the similarities in the mechanical durability of bituminous coal briquettes comprised of each biomass type. Specifically, the results are shown in Figure 5-26a for miscanthus, Figure 5-26b for switchgrass, Figure 5-26c for sawdust, Figure 5-26d for corn stover and Figure 5-26e for wheat straw. The mechanical durability values for the briquettes composed of miscanthus ranged from 77.1 to 89.7% for the three bituminous coals. The minimum value was attained with the Toms Creek coal, while the McClure River coal produced the maximum mechanical durability. Similarly, the mechanical durability values for the briquettes composed of switchgrass ranged from 80.4 to 89.7%, with the maximum value corresponding to the Emerald coal briquettes and the minimum value corresponding to the Toms Creek coal briquettes. The mechanical durability values for the briquettes composed of sawdust and bituminous coal ranged from 88.1 to 92.7%. The maximum value was again attained with the Emerald coal and the minimum value was again attained with the Toms Creek coal. This reoccurring trend in briquette mechanical durability values (i.e. Emerald = highest, Toms Creek = lowest) is likely the result of differences in the distribution modulus and ash content of the coals. As discussed in Chapter 4, this relative ranking of coal types with respect to the mechanical durability of briquettes was anticipated. These results also indicate that briquettes produced with sawdust generally exhibit greater mechanical durability than briquettes composed of miscanthus and switchgrass.

The mechanical durability of briquettes composed of corn stover ranged from 74.0 to 90.2% for the three bituminous coals. As anticipated, the minimum value was attained with the Toms Creek coal and the maximum value was attained with the Emerald coal. The effect of the higher biomass content of the corn stover briquettes compared to the miscanthus and switchgrass briquettes is not definitive. However, it appears that a wider range of mechanical durability values are attained with 30 percent biomass. Similarly, the mechanical durability of the briquettes composed of wheat straw ranged from 68.3 to 88.1%, with the maximum value corresponding to both the Emerald coal briquettes and the minimum value corresponding to the Toms Creek coal briquettes. The results presented in Figure 5-26 clearly show the similarities in the mechanical durability of bituminous coal briquettes. While differences do exist in the measured values, they can be explained by further examination of the distribution modulus and ash content of each individual coal type. Nonetheless, the Emerald coal appears to be the best bituminous coal for production of coal-biomass briquettes.



(a)

(b)

(c)

(d)

(e)

Figure 5-26. Comparison of mechanical durability results for briquettes composed of bituminous coal and (a) corn stover, (b) switchgrass, (c) miscanthus, (d) wheat straw and (e) sawdust

5.4.2 Evaluation of Additive Variables – Bituminous Coal

5.4.2.1 Summary of Results

The results of the additive variables evaluations for briquettes composed of Emerald coal, corn stover and pregelatinized wheat starch are summarized in Table 5-15. Each test that was conducted is identified by the standard test number assigned in Design-Expert® 8 according to the biomass content, starch content and cure time (i.e. 01 = biomass content of 10%, starch content of 0.0% and cure time of 1 day). In the following sections, correlations between each additive variable and the measured briquette properties are presented and discussed. Analysis of the results is also covered, including mathematical models developed for each response using the Design-Expert® 8 statistical analysis tools. In addition, contour graphs of the models are presented to visually interpret and evaluate the results. Finally, numerical optimization of the model was conducted to determine the combination of additive variables that produces the highest quality briquettes.

Table 5-15. Summary of briquette characterization results for briquettes composed of Emerald (bituminous) coal, corn stover and pregelatinized wheat starch

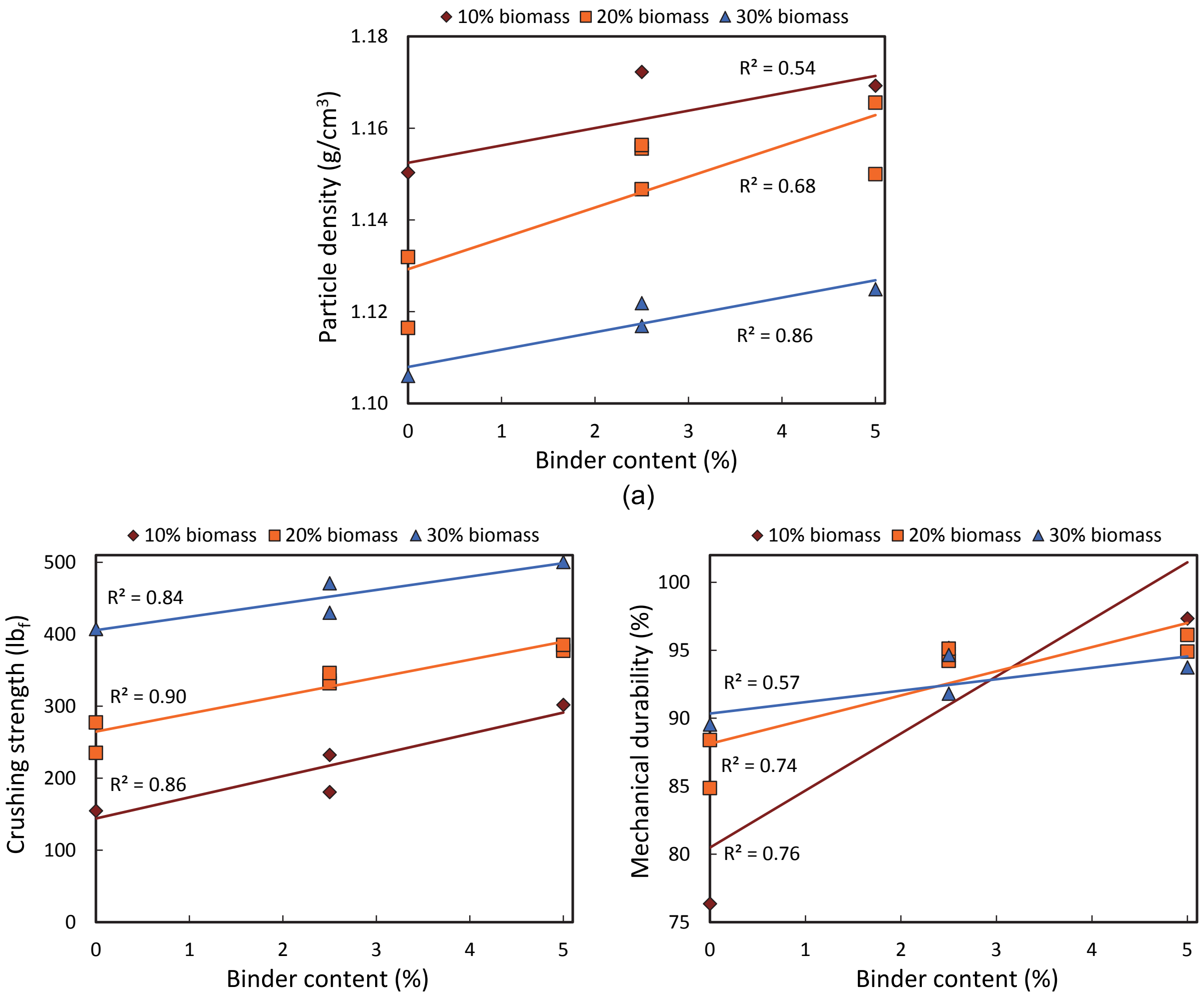
Test ID	Biomass Content (%)	Starch Content (%)	Cure Time (days)	Briquette Water Content	Particle Density (g/cm^3)	Crushing Strength (lb$_f$)	Mechanical Durability (%)
EM-CS-PGWS-01	10	0.0	1	0.019	1.15	154.9	76.4
EM-CS-PGWS-02	30	0.0	1	0.039	1.11	407.5	89.6
EM-CS-PGWS-03	10	5.0	1	0.026	1.17	302.1	97.4
EM-CS-PGWS-04	30	5.0	1	0.042	1.12	500.6	93.7
EM-CS-PGWS-05	10	2.5	0	0.035	1.16	180.9	95.0
EM-CS-PGWS-06	30	2.5	0	0.044	1.12	430.2	91.8
EM-CS-PGWS-07	10	2.5	7	0.021	1.17	232.4	95.2
EM-CS-PGWS-08	30	2.5	7	0.040	1.12	471.2	94.7
EM-CS-PGWS-09	20	0.0	0	0.044	1.12	235.4	84.9
EM-CS-PGWS-10	20	5.0	0	0.040	1.15	377.3	94.9
EM-CS-PGWS-11	20	0.0	7	0.029	1.13	277.6	88.4
EM-CS-PGWS-12	20	5.0	7	0.032	1.17	385.6	96.1
EM-CS-PGWS-13	20	2.5	1	0.032	1.15	332.2	94.3
EM-CS-PGWS-14	20	2.5	1	0.029	1.16	336.0	94.2
EM-CS-PGWS-15	20	2.5	1	0.031	1.16	346.2	95.1

5.4.2.1.1 Binder Content Correlations

The correlation between binder content and each measured briquette property were evaluated by linear regression analysis. To investigate these correlations, binder content was plotted versus each measured briquette property with the data points grouped by biomass content (i.e. 10, 20 and 30%). This approach was used because little or no correlation existed for the entire data set due to the influence of the other two mixture variables (i.e. biomass content and cure time). The binder content correlations were initially investigated with the data grouped separately by biomass content and cure time. From these investigations, it was found that binder content correlations were greatest with the data grouped by biomass content.

Figure 5-27a displays the correlation between binder content and the particle density of the briquettes. It is clear from this chart that binder content exhibits a positive correlation with particle density. For each of the three biomass contents, an increase in starch content led to a rise in the particle density of the briquettes. This was particularly apparent when the starch content was increased from 0.0 to 2.5 percent. However, when the starch content was increased from 2.5 to 5.0 percent, the particle density values remained fairly constant, particularly at a biomass content of 10 and 30 percent. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by biomass content. The strongest linear correlation was found for the briquettes produced with 30 percent biomass (i.e. $R^2 = 0.86$). The strength of this correlation successively declined with a reduction in biomass content. Specifically, the coefficient of determination for briquettes produced with 20 and 10 percent biomass was 0.68 and 0.54, respectively.

Figure 5-27b illustrates the correlation between binder content and the crushing strength of the briquettes. It is clear from this chart that binder content exhibits a strong positive correlation with crushing strength. Specifically, an increase in starch content led to a direct rise in the crushing strength of the briquettes for each of the three biomass contents. This correlation was expected, considering the sole purpose of starch addition to briquette feedstocks is the improvement of briquette quality. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by biomass content. The strongest linear correlation was found for the briquettes produced with 20 percent biomass (i.e. $R^2 = 0.90$), followed closely by briquettes produced with 10 and 30 percent biomass with coefficients of determination of 0.86 and 0.84, respectively.



(a)

(b)

(c)

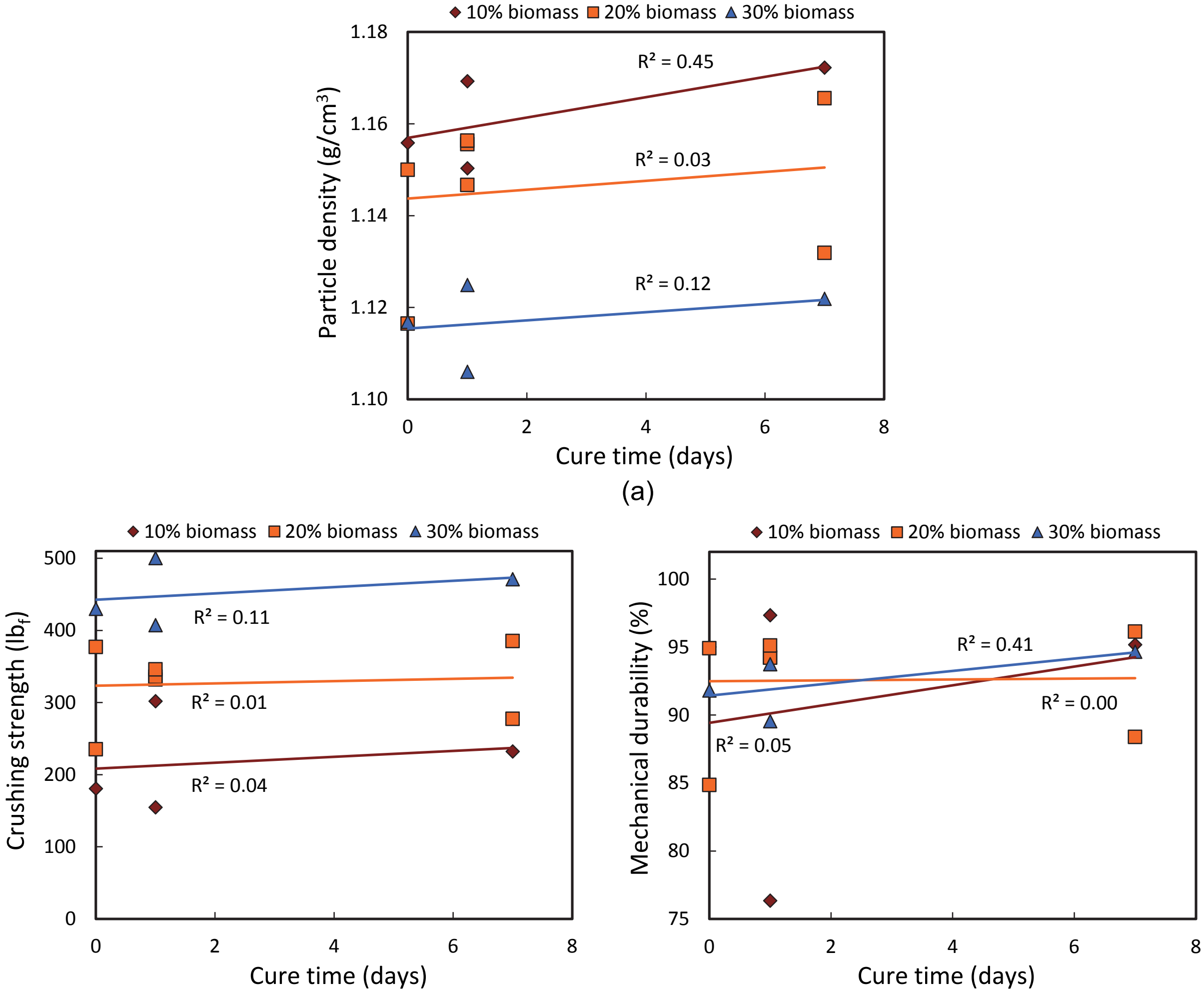
Figure 5-27. Effect of binder content of briquettes composed of Emerald (bituminous) coal, corn stover and pregelatinized wheat starch on (a) particle density, (b) crushing strength and (c) mechanical durability

Figure 5-27c shows the correlation between binder content and the mechanical durability of the briquettes. It is clear from this chart that binder content exhibits a positive correlation with mechanical durability. Specifically, an increase in starch content led to an overall increase in the mechanical durability of the briquettes for each of the three biomass contents. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by biomass content. The strongest linear correlation was found for the briquettes produced with 10 percent biomass (i.e. $R^2 = 0.76$). The strength of this correlation successively declined with an increase in biomass content to a coefficient of determination of 0.74 and 0.57 for briquettes produced with 20 and 30 percent biomass, respectively.

5.4.2.1.2 Cure Time Correlations

The correlation between briquette cure time and each measured property were also evaluated by linear regression analysis. To investigate these correlations, cure time was plotted versus each measured briquette property with the data points grouped by biomass content (i.e. 10, 20 and 30%). This approach was used because little or no correlation existed for the entire data set due to the influence of the other two mixture variables (i.e. biomass content and binder content). The cure time correlations were initially investigated with the data grouped separately by binder content and biomass content. From these investigations, it was found that cure time correlations were greatest with the data grouped by biomass content, although neither resulted in any significant correlations.

Figure 5-28a displays the correlation between cure time and the particle density of the briquettes. It is clear from this chart that there is very little correlation between briquette cure time and particle density, although a slight correlation exists for briquettes composed of 10 percent biomass. This is supported by coefficient of determination values of 0.45, 0.03 and 0.12 for biomass contents of 10, 20 and 30 percent, respectively. The most probable reason for the absence of any significant correlations is the interaction between binder content and particle density, which is concealed in this simple correlation investigation. Figure 5-28b illustrates the correlation between cure time and the crushing strength of the briquettes. It is clear from this chart that there is also very little correlation between briquette cure time and crushing strength. This is supported by coefficient of determination values of 0.04, 0.01 and 0.11 for biomass contents of 10, 20 and 30 percent, respectively. The most probable reason for the absence of any noteworthy correlations is the significant interaction between binder content and crushing strength, which is concealed in this analysis. Figure 5-28c shows the correlation between cure time and the mechanical durability of the briquettes. It is clear from this chart that there is also very little correlation between briquette cure time and crushing strength. This is supported by coefficient of determination values of 0.05, 0.00 and 0.41 for biomass contents of 10, 20 and 30 percent, respectively. The most probable reason for the absence of any significant correlations is the interaction between binder content and mechanical durability, which is concealed in this analysis.



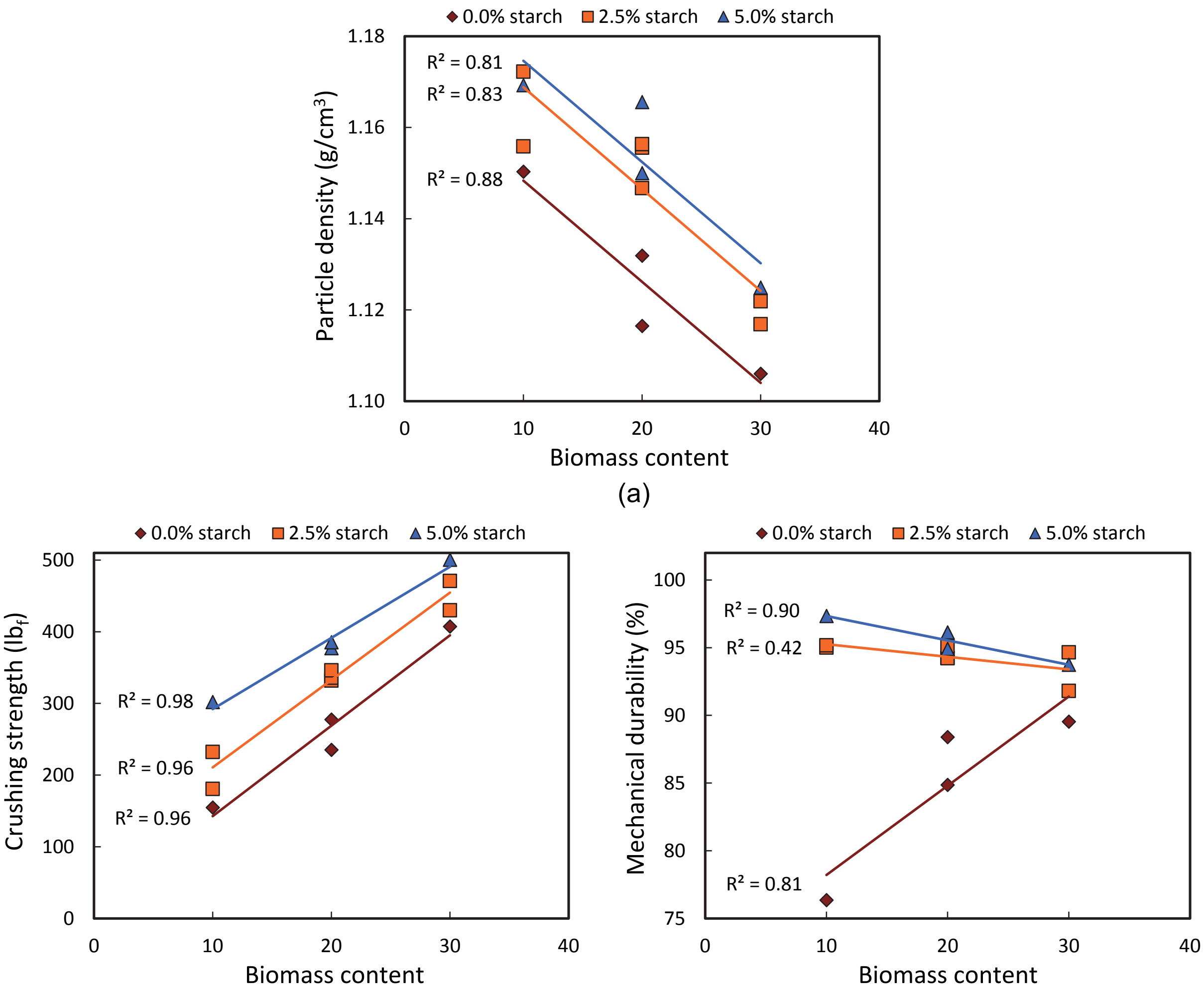
(a)

(b) (c)

Figure 5-28. Effect of cure time of briquettes composed of Emerald (bituminous) coal, corn stover and pregelatinized wheat starch on (a) particle density, (b) crushing strength and (c) mechanical durability

5.4.2.1.3 Biomass Content Correlations

The correlation between biomass content and each measured property were also evaluated by linear regression analysis. To investigate these correlations, biomass content was plotted versus each measured briquette property with the data points grouped by binder content (i.e. 0.0, 2.5 and 5.0%). This approach was used because little or no correlation existed for the entire data set due to the influence of the other two mixture variables (i.e. binder content and briquette cure time). The biomass content correlations were initially investigated with the data grouped separately by binder content and briquette cure time. From these investigations, it was determined that biomass content correlations were greatest with the data grouped by binder content.



(a)

(b)

(c)

Figure 5-29. Effect of biomass content of briquettes composed of Emerald (bituminous) coal, corn stover and pregelatinized wheat starch on (a) particle density, (b) crushing strength and (c) mechanical durability

Figure 5-29a displays the correlation between biomass content and the particle density of the briquettes. It is clear from this chart that biomass content exhibits a fairly strong negative correlation with particle density. For each of the three binder contents, an increase in biomass content caused a direct reduction in the particle density of the briquettes. This finding was expected since the addition of additional biomass with a true density much lower than coal will reduce the composite density of the mixture prior to briquette production. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by binder content. The strongest linear correlation was found for the briquettes produced with no starch (i.e. R^2 = 0.88). The strength of this correlation successively declined with an increase in starch content. Specifically, the coefficient of determination for briquettes produced with 2.5 and 5.0 percent starch was 0.83 and 0.81, respectively. These findings further prove that an increase in biomass content directly reduces the particle density of coal-biomass briquettes.

Figure 5-29b illustrates the correlation between biomass content and the crushing strength of the briquettes. It is clear from this chart that biomass content has a very strong positive correlation with crushing strength. Specifically, an increase in biomass content led to a direct rise in the crushing strength of the briquettes for each of the three binder contents. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by binder content. The strongest linear correlation was found for the briquettes produced with 5.0 percent starch (i.e. $R^2 = 0.98$), followed closely by briquettes produced with 2.5 and 0.0 percent starch (i.e. $R^2 = 0.96$ for both). These findings further validate that addition of biomass to coal briquettes improves the crushing strength of feedstocks and that low biomass content briquettes are typically lower in strength.

Figure 5-29c shows the correlation between biomass content and the mechanical durability of the briquettes. It is clear from this chart that the correlation between biomass content and mechanical durability depends heavily on binder content. Specifically, an increase in biomass content led to a sharp increase in the mechanical durability of the briquettes produced without starch (i.e. starch content = 0.0 %). In contrast, an increase in biomass content resulted in a modest decline in mechanical durability for briquettes produced with 2.5 and 5.0 percent starch. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by binder content. The strongest linear correlation was found for the briquettes produced with 5.0 percent starch (i.e. $R^2 = 0.90$), which was followed closely by briquettes produced without starch (i.e. $R^2 = 0.81$). However, the strength of this was significantly lower for briquettes produced with 2.5 percent starch (i.e. $R^2 = 0.42$). These findings suggest that addition of biomass to coal briquettes with a starch binder leads to a decrease in mechanical durability.

5.4.2.2 Statistical Analyses

The results of the additive variables evaluations were examined using the statistical analysis tools included in Design-Expert® 8 to determine the influence of each mixture variable and to optimize the quality of briquettes. Mathematical models were developed that relate the additive variables (i.e. binder content and cure time) and biomass content to the measured briquette properties (i.e. particle density, crushing strength, and mechanical durability). The first step of model development was selection of the process order (e.g. linear, quadratic) of the mathematical model. This was accomplished by determining the process order with the lowest lack of fit p-value and the highest adjusted R-squared and predicted R-squared values. The selected model was then analyzed using the analysis of variance (ANOVA) function to determine the statistical significance of the entire model and of each individual term. All insignificant terms were then removed from the model, except those required to maintain hierarchy. Next, the fit of the model to the data was evaluated using various diagnostics tools. The following sections present the empirical mathematical models developed for briquettes composed of Emerald coal, corn stover and pregelatinized wheat starch, and summarize the results of the statistical analyses.

5.4.2.2.1 Particle Density Model

A linear mathematical model was constructed that relates binder content, cure time and biomass content to the particle density of briquettes composed of Emerald coal, corn stover and pregelatinized wheat starch. According to the model, the predicted particle density of briquettes is calculated by:

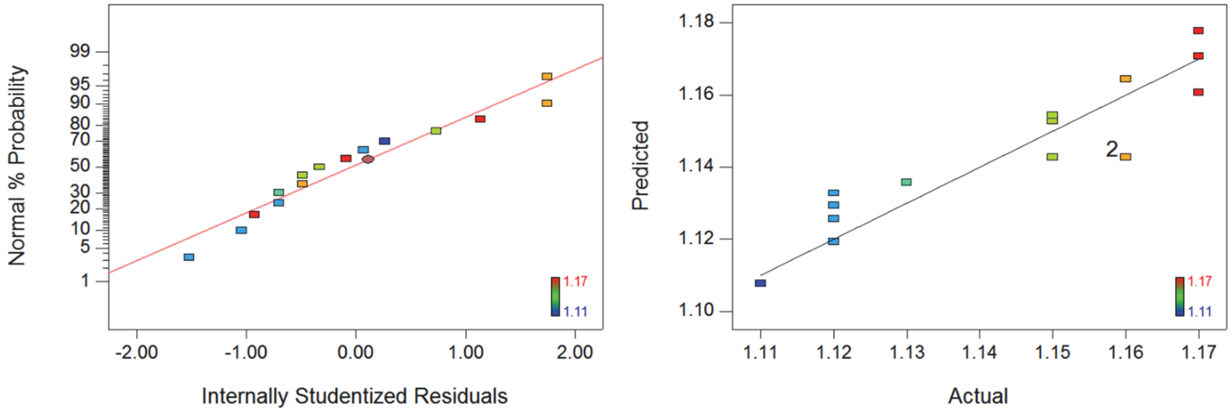
$$\rho = 1.17 + 0.0050b + 0.0009t - 0.0023c \quad \text{(Eq. 5-12)}$$

where ρ is the particle density (g/cm^3), b is the binder content (%), t is the cure time (days) and c is the biomass content (%). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using ANOVA to evaluate a number of variables. A summary of the ANOVA is provided in Table 5-16 for the particle density model. The p-value of the particle density model is 0.0002, which indicates that the predicted density values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the model terms are less than 0.0001 (biomass content), 0.0055 (binder content) and 0.3518 (cure time). This implies that biomass content and binder content are statistically significant model terms, and thus have a major impact on accurate prediction of the particle density of briquettes. In contrast, cure time is not a significant model term, which implies that its impact on particle density quantified in the model is not statistically significant. This term was needed to maintain the hierarchy of the model, otherwise it would have been removed to improve the model.

Table 5-16. ANOVA results for EM-CS-PGWS particle density model

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	5.40E-03	3	1.80E-03	17.06	0.0002
A-Biomass content	4.05E-03	1	4.05E-03	38.40	< 0.0001
B-Starch content	1.25E-03	1	1.25E-03	11.85	0.0055
C-Cure time	9.97E-05	1	9.97E-05	0.95	0.3518
Residual	1.16E-03	11	1.05E-04	--	--
Lack of Fit	1.09E-03	9	1.22E-04	3.65	0.2338
Pure Error	6.67E-05	2	3.33E-05	--	--
Cor Total	6.56E-03	14	--	--	--

To confirm the ANOVA normality assumption for the particle density model, the residuals were visually examined in a normal probability plot of studentized results. Figure 5-30a shows the normal probability plot of studentized residuals for the crushing strength model. It is clear from this figure that the residuals follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual values was also examined to visually analyze the relationship between the measured particle density values and those predicted by the model. The predicted versus actual plot is displayed in Figure 5-30b for the particle density model, which shows the desired data scatter about the 45 degree line is present. This further exemplifies the statistical significance of the particle density model and indicates that it is well suited for prediction of briquette quality.



(a) (b)

Figure 5-30. Diagnostic graphs for visual inspection of ANOVA results for EM-CS-PGWS particle density model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

5.4.2.2.2 Crushing Strength Model

A quadratic mathematical model was constructed that relates binder content, cure time and biomass content to the crushing strength of briquettes composed of Emerald coal and corn stover. According to the model, the predicted crushing strength of briquettes is calculated by:

$$\sigma = -17.18 + 35.33b + 38.79t + 13.09c - 0.54bc - 4.81t^2 \qquad \text{(Eq. 5-13)}$$

where σ is the crushing strength (lb_f), b is the binder content (%), t is the cure time (days) and c is the biomass content (%). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using ANOVA to evaluate a number of variables. A summary of the ANOVA is provided in Table 5-17 for the crushing strength model. The p-value of the model is less than 0.0001, which indicates that the predicted crushing strength values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the model terms are less than 0.0001 (biomass content), less than 0.0001 (starch content), 0.0011 (cure time), 0.0322 (biomass content x starch content) and 0.0011 (cure time^2). This implies that all of the model terms are statistically significant, and thus have a major impact on accurate prediction of the crushing strength of briquettes.

Table 5-17. ANOVA results for EM-CS-PGWS crushing strength model

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	1.45E+05	5	28911	253.13	< 0.0001
A-Biomass content	1.10E+05	1	1.10E+05	965.39	< 0.0001
B-Starch content	30037	1	30037	262.99	< 0.0001
C-Cure time	2556	1	2556	22.38	0.0011
AB	732	1	732	6.41	0.0322
C^2	2514	1	2514	22.01	0.0011
Residual	1028	9	114	--	--
Lack of Fit	923	7	132	2.52	0.3137
Pure Error	105	2	52	--	--
Cor Total	145583	14	--	--	--

To confirm the ANOVA normality assumption for the crushing strength model, the residuals were visually examined in a normal probability plot of studentized results. Figure 5-31a shows the normal probability plot of studentized residuals for the crushing strength model. It is clear from this figure that the residuals follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual values was also examined to visually analyze the relationship between the measured crushing strength values and those predicted by the model. The predicted versus actual plot is displayed in Figure 5-31b for the crushing strength model, which shows the desired data scatter about the 45 degree line is present. This further exemplifies the statistical significance of the crushing strength model and indicates that it is well suited for prediction of briquette quality.

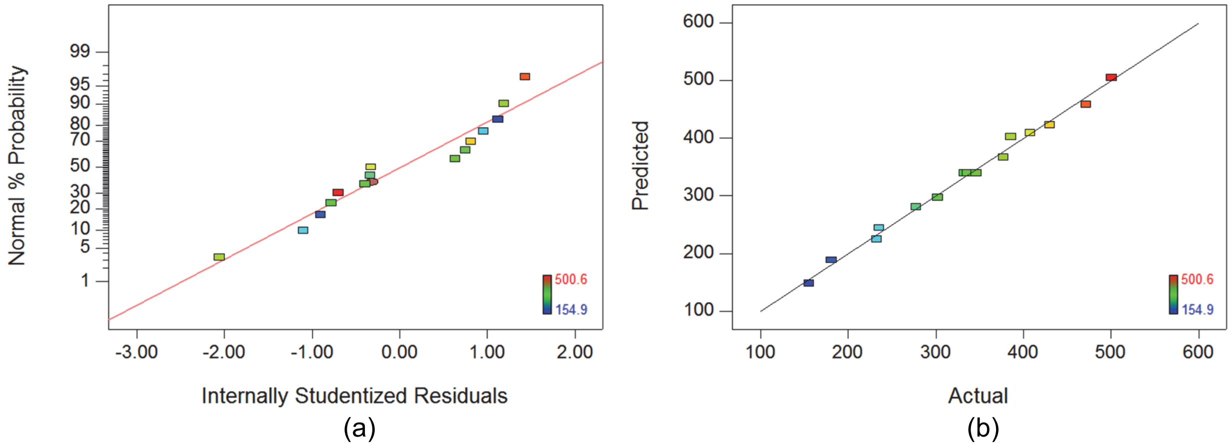


Figure 5-31. Diagnostic graphs for visual inspection of ANOVA results for EM-CS-PGWS crushing strength model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

5.4.2.2.3 *Mechanical Durability Model*

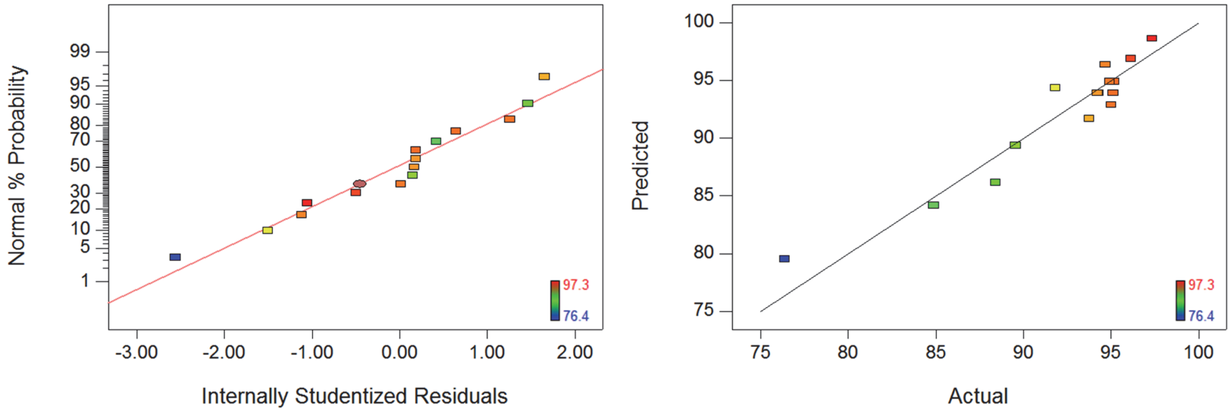
A quadratic mathematical model was constructed that relates binder content, cure time and biomass content to the mechanical durability of briquettes composed of Emerald coal and corn stover. According to the model, the predicted mechanical durability of briquettes is calculated by:

$$MD = 74.29 + 8.79b + 0.29t + 0.49c - 0.17bc - 0.66b^2 \qquad \text{(Eq. 5-14)}$$

where MD is the mechanical durability (%), b is the binder content (%), t is the cure time (days) and c is the biomass content (%). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using ANOVA to evaluate a number of variables. A summary of the ANOVA is provided in Table 5-18 for the mechanical durability model. The p-value of the model is 0.0002, which indicates that the predicted mechanical durability values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the model terms are 0.3360 (biomass content), less than 0.0001 (starch content), 0.1556 (cure time), 0.0026 (biomass content x starch content) and 0.0037 (starch content^2). This implies that the majority of the model terms are statistically significant (except biomass content and cure time), and thus have a major impact on accurate prediction of the mechanical durability of briquettes. In contrast, biomass content and cure time are not significant model terms, which implies that the impact of these variables on mechanical durability quantified in the model is not statistically significant.

Table 5-18. ANOVA results for EM-CS-PGWS mechanical durability model

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	380.25	5	76.05	18.24	0.0002
A-Biomass content	4.31	1	4.31	1.03	0.3360
B-Starch content	230.80	1	230.80	55.35	< 0.0001
C-Cure time	10.02	1	10.02	2.40	0.1556
AB	70.48	1	70.48	16.90	0.0026
B^2	63.00	1	63.00	15.11	0.0037
Residual	37.53	9	4.17	--	--
Lack of Fit	37.02	7	5.29	20.70	0.0468
Pure Error	0.51	2	0.26	--	--
Cor Total	417.78	14	--	--	--



(a) (b)

Figure 5-32. Diagnostic graphs for visual inspection of ANOVA results for EM-CS-PGWS mechanical durability model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

To confirm the ANOVA normality assumption for the mechanical durability model, the residuals were visually examined in a normal probability plot of studentized results. Figure 5-32a shows the normal probability plot of studentized residuals for the mechanical durability model. It is clear from this figure that the residuals follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual values was also examined to visually analyze the relationship between the measured mechanical durability values and those predicted by the model. The predicted versus actual plot is displayed in Figure 5-32b for the mechanical durability model, which shows the desired data scatter about the 45 degree line is present. This further exemplifies the statistical significance of the mechanical durability model and indicates that it is well suited for prediction of briquette quality.

5.4.2.3 Model Graphs

Following the development and statistical analysis of each mathematical model, several contour graphs were constructed to visually interpret and evaluate the results. To provide a clear interpretation of the influence of each mixture variable on each briquette property, the contour graphs are assembled by common model terms. The influence of binder content on the modeled responses for particle density, crushing strength and mechanical durability are presented in Figure 5-33. From this figure it is evident that the maximum particle density values (i.e. > 1.18 g/cm^3) occur at a starch content of 5.0 percent with 10 percent biomass and a cure time of 7 days. In contrast, the minimum particle density (i.e. < 1.11 g/cm^3) values occur with no starch, 30 percent biomass and no cure time. Figure 5-33 also clearly indicates that briquette crushing strength reaches a maximum value (i.e. > 500 lb$_f$) at a starch content of 5.0 percent with 30 percent biomass and a cure time of 4 to 5 days, and reaches a minimum value (i.e. < 200 lb$_f$) with no starch, 10 percent biomass and a cure time of 0 or 7 days. Finally, this figure shows that the mechanical durability of briquettes reaches a maximum value (i.e. 100%) at a starch content of 5.0 percent with 10 percent biomass and a cure time of 7 days, and reaches a minimum value with no starch, 10 percent biomass and no cure time. The figure also indicates that a mechanical durability value in excess of 96 percent is achievable at a starch content of 2.5 percent with 30 percent biomass and a cure time of 7 days.

The modeled responses for particle density, crushing strength and mechanical durability with respect to cure time and biomass content are presented in Figure 5-34 and Figure 5-35, respectively. These figures present the same data that is displayed in Figure 5-33, but offer a different perspective that may be desirable in certain circumstances. Regardless of the chart examined, a clear optimum set of mixture variables, with respect to both crushing strength and mechanical durability, is not evident for this briquette formulation. As a result, numerical optimization of the mixture variables is necessary to determine the ideal value for each variable and to predict the strength and durability of such optimum briquette formulations.

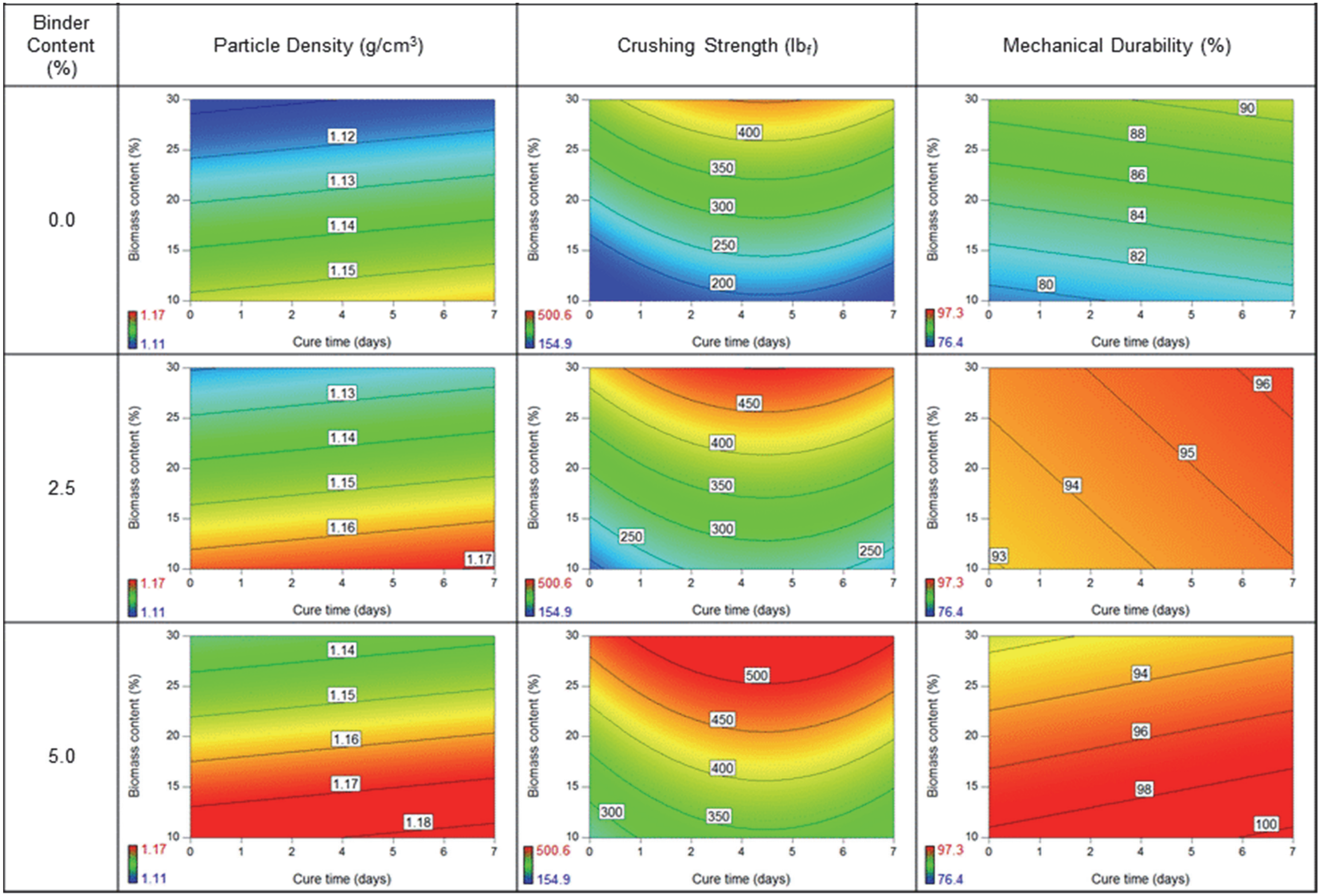


Figure 5-33. Influence of binder content on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of Emerald (bituminous) coal, corn stover and pregelatinized wheat starch

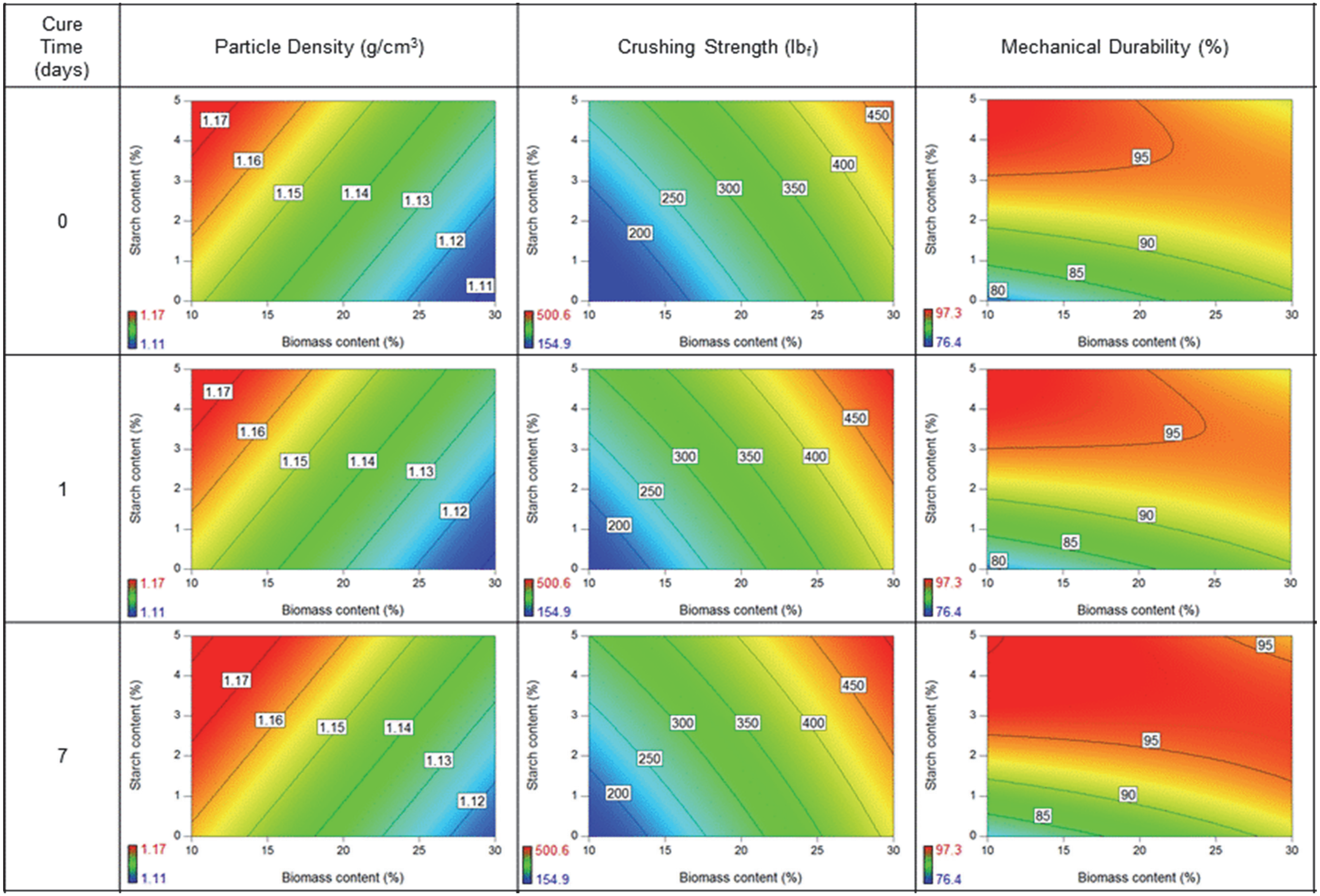


Figure 5-34. Influence of cure time on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of Emerald (bituminous) coal, corn stover and pregelatinized wheat starch

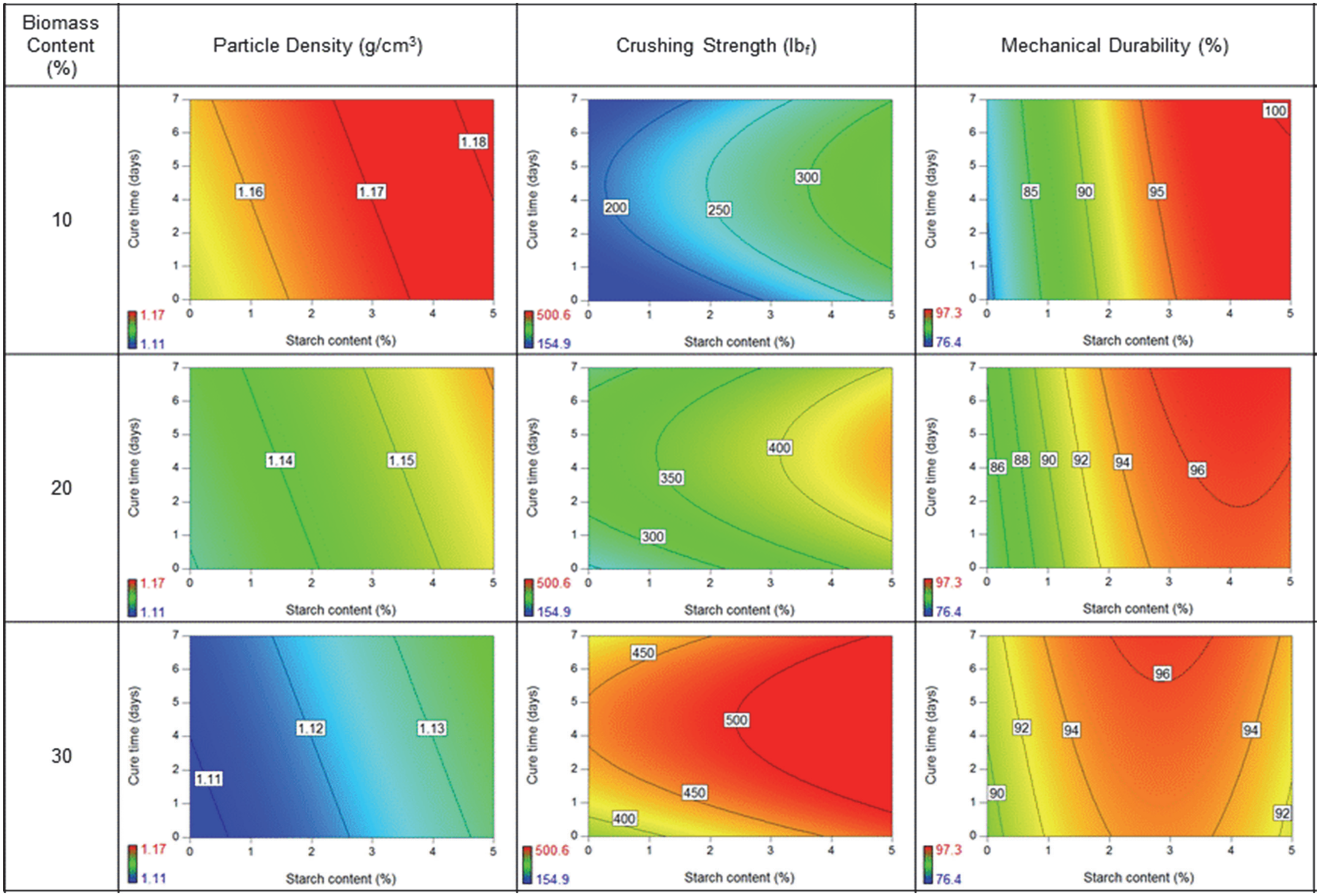


Figure 5-35. Influence of biomass content on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of Emerald (bituminous) coal, corn stover and pregelatinized wheat starch

5.4.2.4 Numerical Optimization

Numerical optimization of the mixture variables was conducted in Design-Expert® 8 using the tool included in the analysis package. This tool allows for specification of optimization criteria (i.e. goals), which can include maximizing or minimizing predicted responses and process variables, as well as setting target values for each parameter. The tool also allows for adjustment of the importance of each goal on a scale from one to five (1 being the least important, 5 being the most important). The results of the optimization routine include a specified value for each of the process variables, as well as the predicted values for each response. A desirability value is calculated for each solution to the optimization routine to provide a method to rank the solutions and to indicate the extent to which the combination of responses approaches a perfect solution.

Optimization of the mathematical models developed for briquettes comprised of Emerald coal, corn stover and pregelatinized wheat starch was accomplished by specifying a maximization goal for both crushing strength and mechanical durability. The importance of the mechanical durability goal was set to five and the importance of the crushing strength goal was set to three. This configuration was selected after experimenting with the effect of the importance setting on the desirability of the solutions to the optimization routine. The routine generated 16 optimized solutions, all of which specified a biomass content of 30 percent, a starch content in the range of 2.73 to 3.48 percent and a cure time of 3.9 to 6.1 days. As shown in Table 5-19, the top ten most desirable solutions were predicted to produce briquettes with a crushing strength of approximately 500 pounds-force and a mechanical durability in excess of 95 percent.

Table 5-19. Numerical optimization results for EM-CS-PGWS mathematical models

Number	**Biomass Content (%)**	**Starch Content (%)**	**Cure Time (days)**	**Crushing Strength (lb_f)**	**Mechanical Durability (%)**	**Desirability**
1	30	3.13	5.7	500.6	96.0	0.891
2	30	3.11	5.6	500.6	96.0	0.891
3	30	3.15	5.7	500.6	96.0	0.891
4	30	3.18	5.7	500.6	96.0	0.891
5	30	3.05	5.6	500.6	96.0	0.891
6	30	3.16	5.5	500.6	96.0	0.890
7	30	3.19	5.9	497.7	96.1	0.890
8	30	3.48	6.1	500.5	95.9	0.889
9	30	3.22	5.2	500.6	95.9	0.887
10	30	2.73	3.9	505.9	95.6	0.878

5.4.3 Evaluation of Mixture Variables – Sub-Bituminous Coal

5.4.3.1 Summary of Results

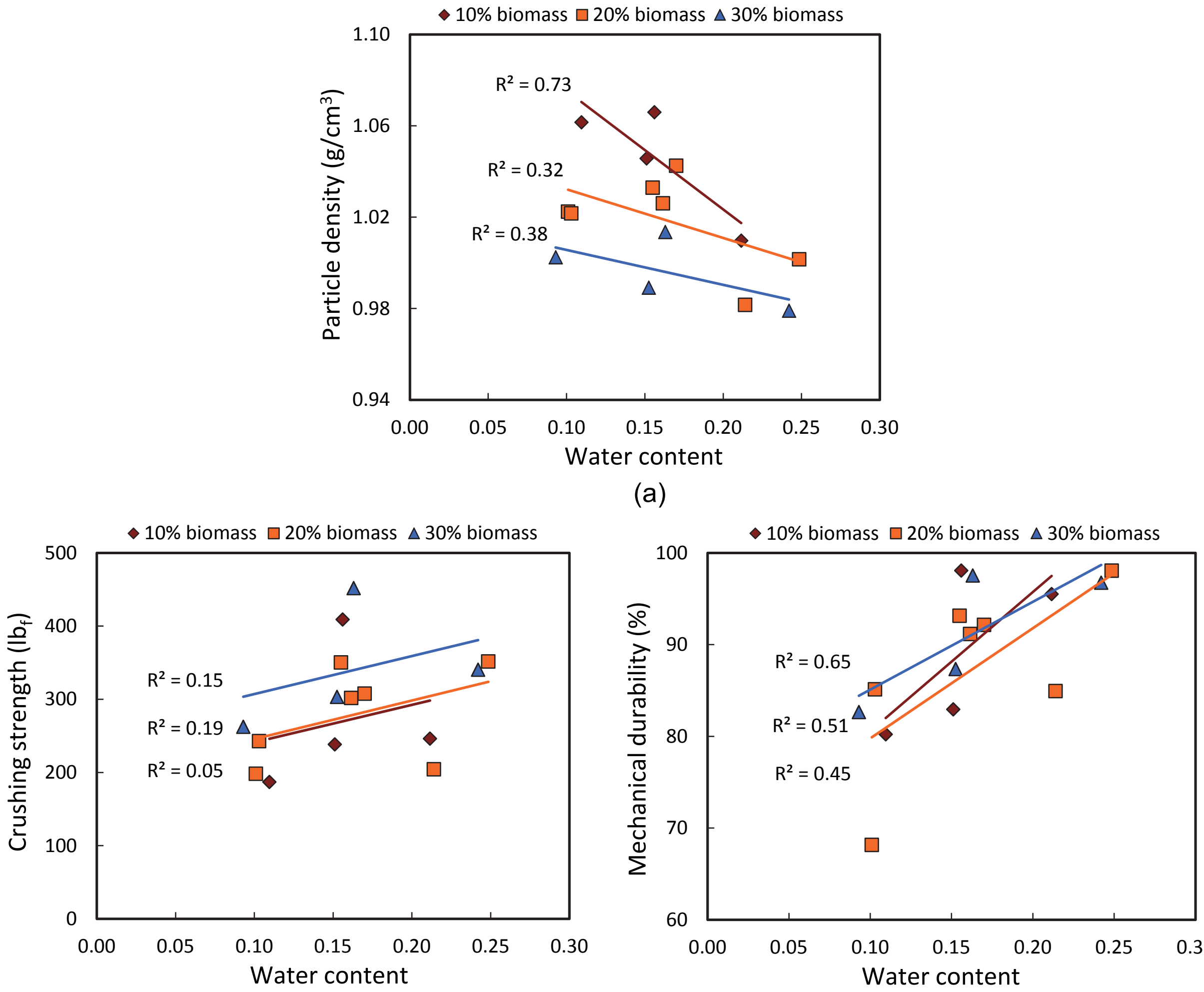
The results of the mixture variables evaluations for briquettes composed of Eagle Butte sub-bituminous coal, corn stover and pregelatinized wheat starch are summarized in Table 5-20. Each test that was conducted is identified by the standard test number assigned in Design-Expert® 8 according to the target feed water content, biomass content and starch content (i.e. 01 = target feed water content of 0.10, biomass content of 10% and starch content of 2.5%). In the following sections, correlations between each mixture variable and the measured briquette properties are presented and discussed. Analysis of the results is also covered, including mathematical models developed for each response using the Design-Expert® 8 statistical analysis tools. In addition, contour graphs of the models are presented to visually interpret and evaluate the results. Finally, numerical optimization of the model was conducted to determine the combination of mixture variables that produces the highest quality briquettes.

Table 5-20. Summary of characterization results for briquettes composed of Eagle Butte (sub-bituminous) coal, corn stover and pregelatinized wheat starch

Test ID	**Feed Water Content**	**Biomass Content (%)**	**Starch Content (%)**	**Briquette Water Content**	**Particle Density (g/cm^3)**	**Crushing Strength (lb_f)**	**Mechanical Durability (%)**
EB-CS-PGWS-01	0.110	10	2.5	0.100	1.06	187.2	80.2
EB-CS-PGWS-02	0.212	10	2.5	0.157	1.01	246.5	95.5
EB-CS-PGWS-03	0.093	30	2.5	0.096	1.00	262.5	82.7
EB-CS-PGWS-04	0.242	30	2.5	0.146	0.98	340.6	96.8
EB-CS-PGWS-05	0.101	20	0.0	0.095	1.02	198.4	68.2
EB-CS-PGWS-06	0.214	20	0.0	0.147	0.98	204.4	84.9
EB-CS-PGWS-07	0.103	20	5.0	0.094	1.02	242.9	85.1
EB-CS-PGWS-08	0.249	20	5.0	0.160	1.00	351.8	98.1
EB-CS-PGWS-09	0.151	10	0.0	0.124	1.05	238.5	83.0
EB-CS-PGWS-10	0.153	30	0.0	0.122	0.99	303.6	87.4
EB-CS-PGWS-11	0.156	10	5.0	0.126	1.07	409.1	98.1
EB-CS-PGWS-12	0.163	30	5.0	0.128	1.01	452.0	97.6
EB-CS-PGWS-13	0.170	20	2.5	0.122	1.04	307.9	92.2
EB-CS-PGWS-14	0.155	20	2.5	0.129	1.03	350.4	93.2
EB-CS-PGWS-15	0.162	20	2.5	0.122	1.03	302.0	91.2

5.4.3.1.1 Feed Water Content Correlations

The correlation between feed water content and each measured briquette property were evaluated by linear regression analysis. To investigate these correlations, water content was plotted versus each measured briquette property with the data points grouped by biomass content (i.e. 10, 20 and 30%). This approach was used because little or no correlation existed for the entire data set due to the influence of the other two mixture variables (i.e. biomass content and binder content). The water content correlations were initially investigated with the data grouped separately by biomass content and binder content. From these investigations, it was found that feed water content correlations were greatest with the data grouped by biomass content. Nonetheless, the correlations were not very strong due to the significant influence of both biomass content and binder content.



(a)

(b) (c)

Figure 5-36. Effect of feed water content on (a) particle density, (b) crushing strength and (c) mechanical durability for briquettes composed of Eagle Butte (sub-bituminous) coal, corn stover and pregelatinized wheat starch

Figure 5-36a displays the correlation between feed water content and the particle density of the briquettes. It is clear from this chart that water content generally exhibits a negative correlation with particle density. From the minimum to the maximum water content, the particle density of the briquettes dropped for all three biomass contents. However, the particle density reached a maximum value in the water content range of 0.15 to 0.17, and then dropped off when the water content approached or exceeded 0.20. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by biomass content. The strongest linear correlation was found for the briquettes produced with 10 percent biomass (i.e. $R^2 = 0.73$). The strength of the correlation was much lower for the briquettes with higher biomass content. Specifically, the coefficient of determination for briquettes produced with 20 and 30 percent biomass was 0.32 and 0.38, respectively.

Figure 5-36b illustrates the correlation between feed water content and the crushing strength of the briquettes. No obvious correlations exist in this data set due to the significant interaction between binder content and crushing strength, which is concealed in this analysis. However, it is fairly clear from this chart that maximum crushing strength values are achieved at approximately the same water content (i.e. 0.15 to 0.16) for all biomass content data sets. This suggests that this range of feed water contents is ideal for briquettes produced with sub-bituminous coal and biomass. The strength of the linear correlations was measured by determining the coefficient of determination for each data set grouped by biomass content. The strongest linear correlation was found for the briquettes produced with 20 percent biomass (i.e. $R^2 = 0.19$). In contrast, the coefficient of determination for briquettes produced with 10 and 30 percent biomass was 0.05 and 0.15, respectively.

Figure 5-36c shows the correlation between feed water content and the mechanical durability of briquettes. It is clear from this chart that a general positive correlation exists between water content and mechanical durability. The maximum mechanical durability values occurred between water contents of 0.15 and 0.16 for biomass contents of 10 and 30 percent. In contrast, the maximum mechanical durability for briquettes composed of 20 percent biomass occurred at a water content of 0.25. The most likely cause of this discrepancy is the difference in binder content for each data point, which is concealed in this analysis. The strongest correlation was found for briquettes produced with 30 percent biomass (i.e. $R^2 = 0.65$), which was followed closely by briquettes produced with 20 percent (i.e. $R^2 = 0.51$) and 10 percent (i.e. $R^2 = 0.45$) biomass.

5.4.3.1.2 Biomass Content Correlations

The correlation between biomass content and each measured briquette property were also evaluated by linear regression analysis. To investigate these correlations, biomass content was plotted versus each measured briquette property with the data points grouped by water content (i.e. 0.10, 0.15 and 0.20). This approach was used because little or no correlation existed for the entire data set due to the influence of the other two mixture variables (i.e. water content and binder content). The biomass content correlations were initially investigated with the data grouped separately by water content and binder content. From these investigations, it was found that feed water content correlations were greatest with the data grouped by water content. Nonetheless, the correlations were not very prominent due to the significant influence of both water content and binder content.

Figure 5-37a displays the correlation between biomass content and the particle density of the briquettes. It is clear from this chart that biomass content exhibits a negative correlation with particle density. For each of the three water contents, an increase in biomass content caused a direct reduction in the particle density of the briquettes. This finding was expected since the addition of additional biomass with a true density much lower than coal will reduce the composite density of the mixture prior to briquette production. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by water content. The strongest linear correlation was found for the briquettes with a feed water content of 0.10 (i.e. $R^2 = 0.95$). The strength of this correlation successively declined with an increase in water content. Specifically, the coefficient of determination for briquettes produced with a water content of 0.15 and 0.20 was 0.81 and 0.69, respectively. These findings further prove that an increase in biomass content directly reduces the particle density of coal-biomass briquettes.

Figure 5-37b illustrates the correlation between biomass content and the crushing strength of the briquettes. It is clear from this chart that biomass content generally exhibits a positive correlation with crushing strength. However, there were some discrepancies in the data, particularly at a water content of 0.15, where an increase in biomass content appears to initially reduce and then increase the crushing strength of the briquettes. This was likely due to the significant interaction between binder content and crushing strength, which is concealed in this analysis. The strongest linear correlation was found for briquettes produced with a water content of 0.10 (i.e. $R^2 = 0.74$). In contrast, the coefficient of determination for briquettes produced with water contents of 0.15 and 0.20 was 0.09 and 0.28, respectively.

Figure 5-37c shows the correlation between biomass content and the mechanical durability of briquettes. No obvious correlations exist in this data set due to the significant interaction between binder content and mechanical durability, which is concealed in this analysis. This lack of correlation is supported by average coefficient of determination values of 0.02, 0.02 and 0.01 for water contents of 0.10, 0.15 and 0.20, respectively.

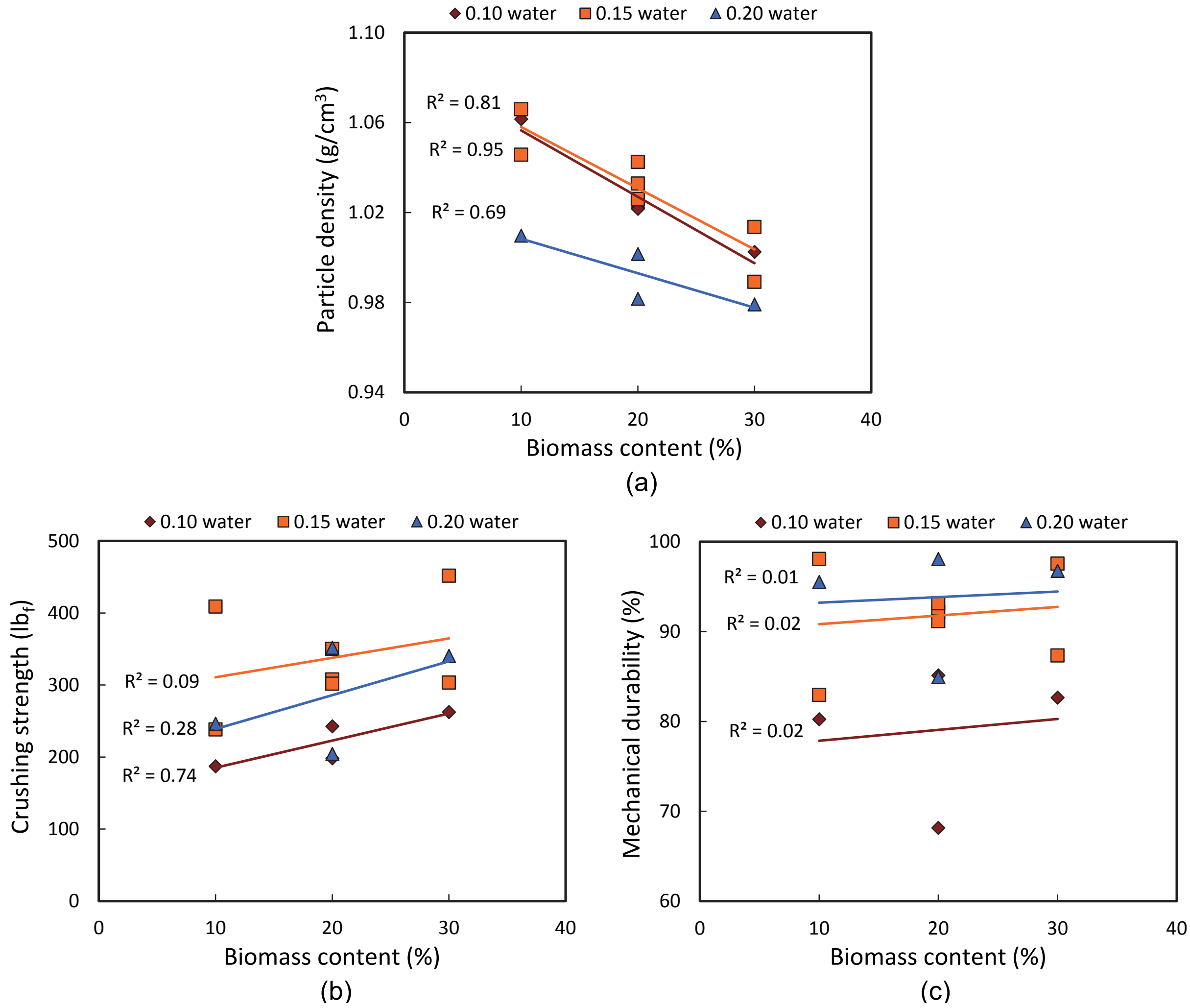


Figure 5-37. Effect of biomass content on (a) particle density, (b) crushing strength and (c) mechanical durability for briquettes composed of Eagle Butte (sub-bituminous) coal, corn stover and pregelatinized wheat starch

5.4.3.1.3 Binder Content Correlations

The correlation between binder content and each measured briquette property were evaluated by linear regression analysis. To investigate these correlations, binder content was plotted versus each measured briquette property with the data points grouped by feed water content (i.e. 0.10, 0.15 and 0.20). This approach was used because little or no correlation existed for the entire data set due to the influence of the other two mixture variables (i.e. water content and biomass content). The binder content correlations were initially investigated with the data grouped separately by water content and biomass content. From these investigations, it was found that binder content correlations were greatest with the data grouped by water content.

Figure 5-38a displays the correlation between binder content and the particle density of the briquettes. No obvious correlations exist in this data set due to the significant interaction between biomass content and particle density, which is concealed in this analysis. This lack of correlation is supported by average coefficient of determination values of 0.14, 0.00 and 0.29 for water contents of 0.10, 0.15 and 0.20, respectively.

Figure 5-38b illustrates the correlation between binder content and the crushing strength of briquettes. It is clear from this chart that binder content generally exhibits a positive correlation with crushing strength. Specifically, an increase in starch content led to a direct rise in the crushing strength of the briquettes for each of the three biomass contents. This correlation was expected, considering the sole purpose of starch addition to briquette feedstocks is the improvement of briquette quality. However, there was some scatter in the data as a result of the significant interaction between biomass content and crushing strength, which is concealed in this analysis. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by biomass content. The strongest linear correlation was found for the briquettes produced at a water content of 0.15 (i.e. $R^2 = 0.81$), followed closely by briquettes produced at a water content of 0.20 (i.e. $R^2 = 0.70$). In contrast, the coefficient of determination for briquettes produced with a water content of 0.10 was 0.26.

Figure 5-38c shows the correlation between binder content and the mechanical durability of briquettes. It is clear from this chart that binder content exhibits a strong positive correlation with mechanical durability. Specifically, an increase in starch content led to a sharp increase in the mechanical durability of the briquettes, regardless of the water content. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by biomass content. The strongest linear correlation was found for the briquettes produced with a water content of 0.15 (i.e. $R^2 = 0.93$), which was followed closely by briquettes produced with water contents of 0.10 (i.e. $R^2 = 0.85$) and 0.20 (i.e. $R^2 = 0.79$).

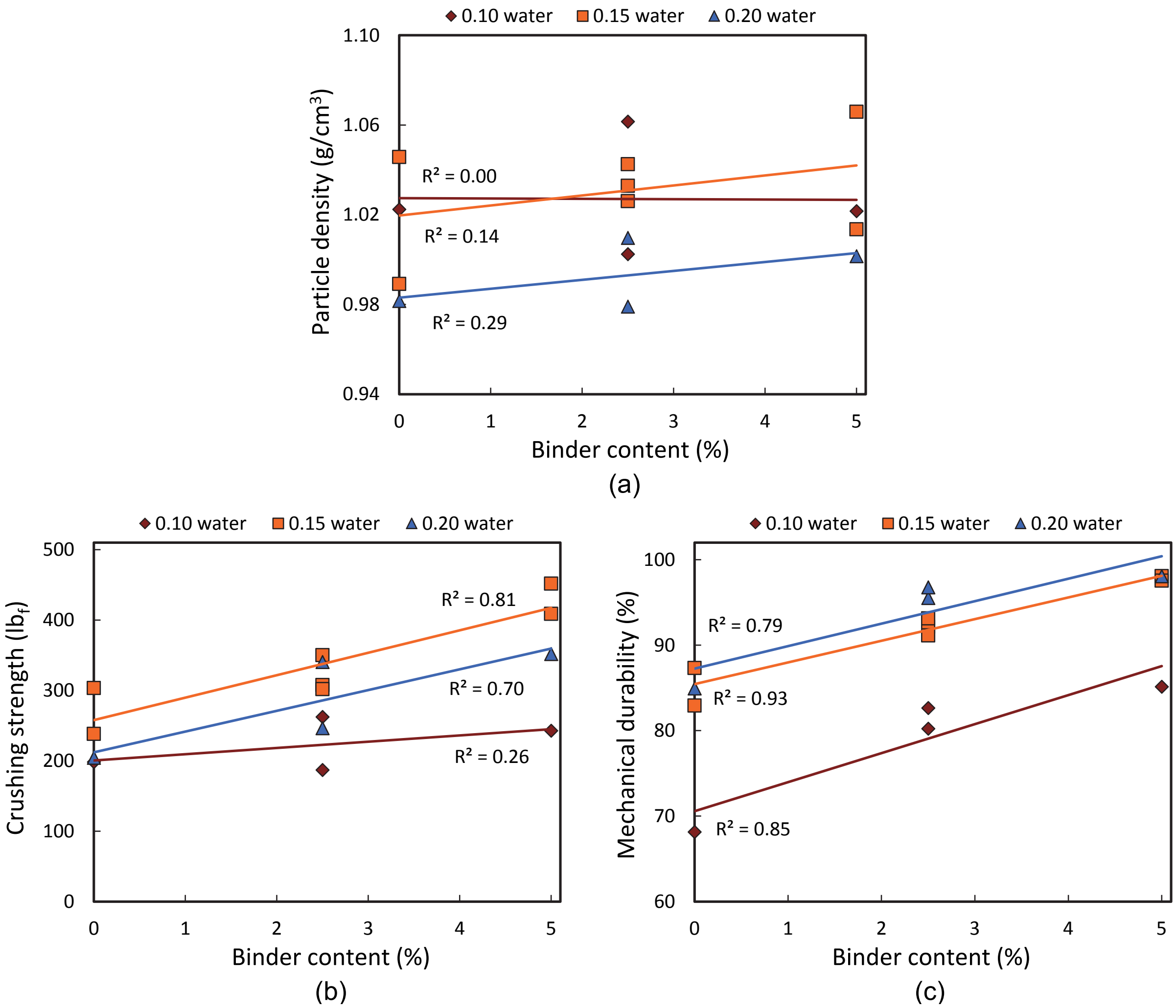


Figure 5-38. Effect of binder content on (a) particle density, (b) crushing strength and (c) mechanical durability for briquettes composed of Eagle Butte (sub-bituminous) coal, corn stover and pregelatinized wheat starch

5.4.3.2 Statistical Analyses

The results of the mixture variables evaluations were examined using the statistical analysis tools included in Design-Expert® 8 to determine the influence of each variable and to optimize the quality of briquettes. Mathematical models were developed that relate the mixture variables (i.e. water content, biomass content and binder content) to the measured briquette properties (i.e. particle density, crushing strength, and mechanical durability). The first step of model development was selection of the process order (e.g. linear, quadratic) of the mathematical model. This was accomplished by determining the process order with the lowest lack of fit p-value and the highest adjusted R-squared and predicted R-squared values. The selected model was then analyzed using the analysis of variance (ANOVA) function to determine the statistical significance of the entire model and of each individual term. All insignificant terms were then removed from the model, except those required to maintain hierarchy. Next, the fit of the model to the data was evaluated using various diagnostics tools. The following sections present the empirical mathematical models developed for briquettes composed of Eagle Butte coal, corn stover and pregelatinized wheat starch, and summarize the results of the statistical analyses.

5.4.3.2.1 Particle Density Model

A linear mathematical model was constructed that relates feed water content, biomass content and binder content to the particle density of briquettes composed of Eagle Butte coal, corn stover and pregelatinized wheat starch. According to the model, the predicted particle density of briquettes is calculated by:

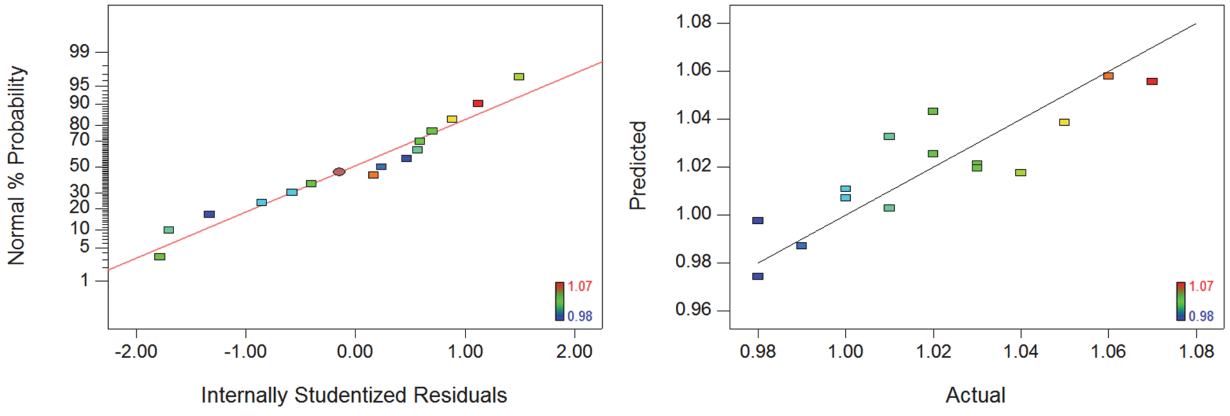
$$\rho = 1.10 - 0.25w - 0.0026c + 0.0036b \qquad \text{(Eq. 5-15)}$$

where ρ is the particle density (g/cm^3), w is the feed water content, c is the biomass content (%) and b is the binder content (%). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using ANOVA to evaluate a number of variables. A summary of the ANOVA is provided in Table 5-21 for the particle density model. The p-value of the particle density model is 0.0013, which indicates that the predicted density values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the model terms are 0.0147 (water content), 0.0007 (biomass content) and 0.1296 (binder content). This implies that water content and biomass content are statistically significant model terms, and thus have a major impact on accurate prediction of the particle density of briquettes. In contrast, binder content is not a significant model term, which implies that its impact on particle density quantified in the model is not statistically significant. This term was needed to maintain the hierarchy of the model, otherwise it would have been removed to improve the model.

Table 5-21. ANOVA results for EB-CS-PGWS particle density model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	8.01E-03	3	2.67E-03	10.92	0.0013
A-Water content	2.04E-03	1	2.04E-03	8.36	0.0147
B-Biomass content	5.22E-03	1	5.22E-03	21.38	0.0007
C-Binder content	6.56E-04	1	6.56E-04	2.68	0.1296
Residual	2.69E-03	11	2.44E-04	--	--
Cor Total	1.07E-02	14	--	--	--

To confirm the ANOVA normality assumption for the particle density model, the residuals were visually examined in a normal probability plot of studentized results. Figure 5-39a shows the normal probability plot of studentized residuals for the crushing strength model. It is clear from this figure that the residuals follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual values was also examined to visually analyze the relationship between the measured particle density values and those predicted by the model. The predicted versus actual plot is displayed in Figure 5-39b for the particle density model, which shows the desired data scatter about the 45 degree line is present. This further exemplifies the statistical significance of the particle density model and indicates that it is well suited for prediction of briquette quality.



(a) (b)

Figure 5-39. Diagnostic graphs for visual inspection of ANOVA results for EB-CS-PGWS particle density model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

5.4.3.2.2 Crushing Strength Model

A quadratic mathematical model was constructed that relates feed water content, biomass content and binder content to the crushing strength of briquettes composed of Eagle Butte coal, corn stover and pregelatinized wheat starch. According to the model, the predicted crushing strength of briquettes is calculated by:

$$\sigma = -333.30 + 6276.76w + 4.70c - 14.51b + 265.80wb - 19568.60w^2 \qquad \text{(Eq. 5-16)}$$

where σ is the crushing strength (lb$_f$), w is the feed water content, c is the biomass content (%) and b is the binder content (%). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using ANOVA to evaluate a number of variables. A summary of the ANOVA is provided in Table 5-22 for the crushing strength model. The p-value of the model is 0.0005, which indicates that the predicted crushing strength values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the model terms are 0.0011 (water content), 0.0031 (biomass content), 0.0005 (binder content), 0.0320 (water content x binder content) and 0.0007 (water content^2). This implies that all of the model terms are statistically significant, and thus have a major impact on accurate prediction of the crushing strength of briquettes.

Table 5-22. ANOVA results for EB-CS-PGWS crushing strength model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	75323	5	15065	14.37	0.0005
A-Water content	23479	1	23479	22.39	0.0011
B-Biomass content	16708	1	16708	15.94	0.0031
C-Binder content	30099	1	30099	28.71	0.0005
AC	6731	1	6731	6.42	0.0320
A^2	26286	1	26286	25.07	0.0007
Residual	9436	9	1048	--	--
Cor Total	84759	14	--	--	--

To confirm the ANOVA normality assumption for the crushing strength model, the residuals were visually examined in a normal probability plot of studentized results. Figure 5-40a shows the normal probability plot of studentized residuals for the crushing strength model. It is clear from this figure that the residuals follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual values was also examined to visually analyze the relationship between the measured crushing strength values and those predicted by the model. The predicted versus actual plot is displayed in Figure 5-40b for the crushing strength model, which shows the desired data scatter about the 45 degree line is present. This further exemplifies the statistical significance of the crushing strength model and indicates that it is well suited for prediction of briquette quality.

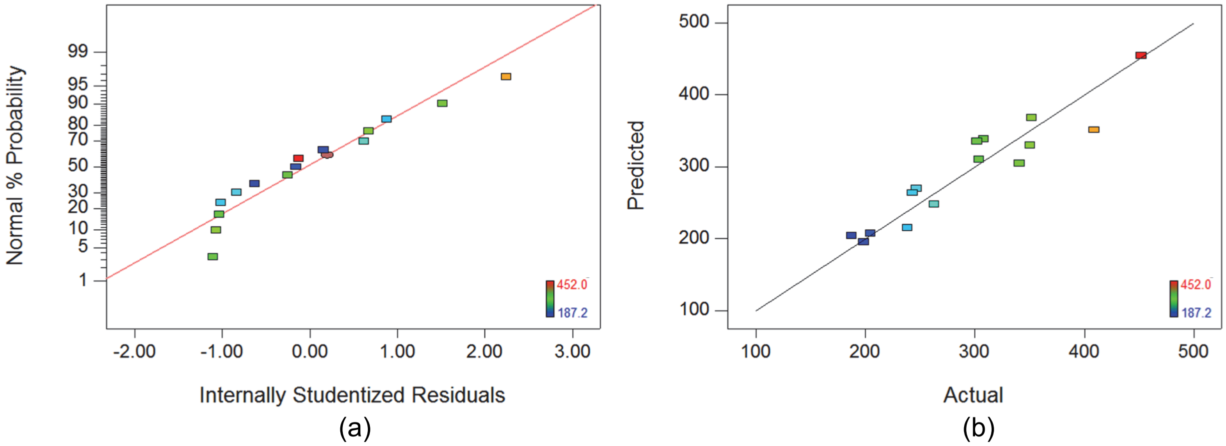


Figure 5-40. Diagnostic graphs for visual inspection of ANOVA results for EB-CS-PGWS crushing strength model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

5.4.3.2.3 Mechanical Durability Model

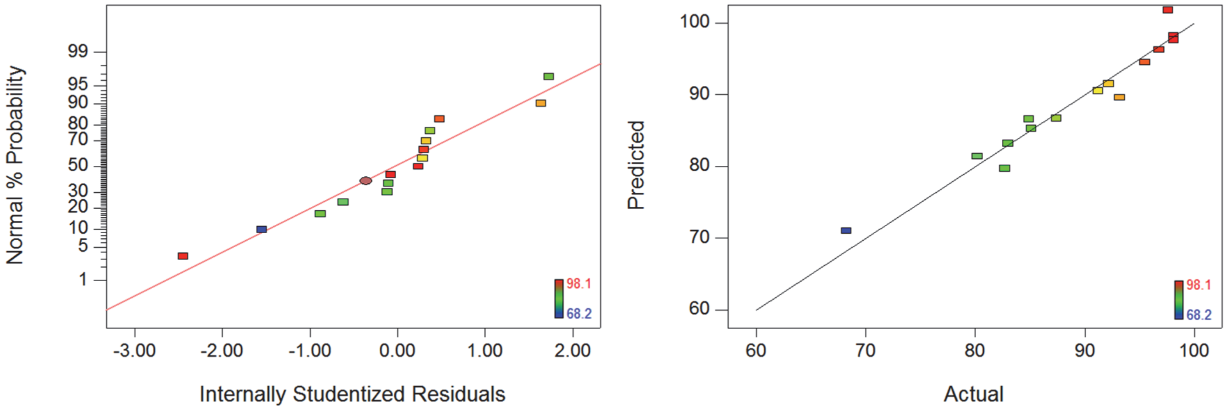
A quadratic mathematical model was constructed that relates feed water content, biomass content and binder content to the mechanical durability of briquettes composed of Eagle Butte coal, corn stover and pregelatinized wheat starch. According to the model, the predicted mechanical durability of briquettes is calculated by:

$$MD = 35.34 + 561.56w - 0.89c + 2.74b - 1344.23w^2 + 0.03c^2 \qquad \text{(Eq. 5-17)}$$

where MD is the mechanical durability (%), w is the feed water content, c is the biomass content (%) and b is the binder content (%). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using ANOVA to evaluate a number of variables. A summary of the ANOVA is provided in Table 5-23 for the mechanical durability model. The p-value of the model is less than 0.0001, which indicates that the predicted mechanical durability values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the model terms are less than 0.0001 (water content) 0.1061 (biomass content), less than 0.0001 (starch content), 0.0010 (water content^2) and 0.0702 (biomass content^2). This implies that all of the model terms are statistically significant (except biomass content), and thus have a major impact on accurate prediction of the mechanical durability of briquettes. In contrast, biomass content is not a significant model term, which implies that the impact of this variable on mechanical durability quantified in the model is not statistically significant.

Table 5-23. ANOVA results for EB-CS-PGWS mechanical durability model

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	941	5	188	31.04	< 0.0001
A-Water content	515	1	515	84.87	< 0.0001
B-Biomass content	20	1	20	3.22	0.1061
C-Binder content	364	1	364	60.01	< 0.0001
A^2	137	1	137	22.57	0.0010
B^2	26	1	26	4.22	0.0702
Residual	55	9	6	--	--
Cor Total	996	14	--	--	--



(a) (b)

Figure 5-41. Diagnostic graphs for visual inspection of ANOVA results for EB-CS-PGWS mechanical durability model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

To confirm the ANOVA normality assumption for the mechanical durability model, the residuals were visually examined in a normal probability plot of studentized results. Figure 5-41a shows the normal probability plot of studentized residuals for the mechanical durability model. It is clear from this figure that the residuals follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual values was also examined to visually analyze the relationship between the measured mechanical durability values and those predicted by the model. The predicted versus actual plot is displayed in Figure 5-41b for the mechanical durability model, which shows the desired data scatter about the 45 degree line is present. This further exemplifies the statistical significance of the mechanical durability model and indicates that it is well suited for prediction of briquette quality.

5.4.3.3 Model Graphs

Following the development and statistical analysis of each mathematical model, several contour graphs were constructed to visually interpret and evaluate the results. To provide a clear interpretation of the influence of each mixture variable on each briquette property, the contour graphs are assembled by common model terms. The influence of water content on the modeled responses for particle density, crushing strength and mechanical durability are presented in Figure 5-42. From this figure it is evident that the maximum particle density values (i.e. > 1.06 g/cm^3) occur at a water content of 0.10 with 10 percent biomass and a starch content of 5 percent. In contrast, the minimum particle density (i.e. < 0.98 g/cm^3) values occur at a water content of 0.20 with 30 percent biomass and no starch. Figure 5-42 also clearly indicates that briquette crushing strength reaches a maximum value (i.e. > 450 lb$_f$) at a water content of 0.20 with 30 percent biomass and a starch content of 5 percent, and reaches a minimum value (i.e. < 200 lb$_f$) at a water content of 0.10 with 10 percent biomass and no starch. Finally, this figure shows that the mechanical durability of briquettes reaches a maximum value (i.e. 100%) at a water content of 0.20 with both 10 and 30 percent biomass at a starch content of 5 percent, and reaches a minimum value at a water content of 0.10 with 10 to 20 percent biomass and no starch. The figure also indicates that very high crushing strength (i.e. > 400 lb$_f$) and mechanical durability (i.e. > 95%) values are achievable at a water content of 0.15 with 30 percent biomass and a starch content of 5 percent.

The modeled responses for particle density, crushing strength and mechanical durability with respect to biomass content and binder content are presented in Figure 5-43 and Figure 5-44, respectively. These figures present the same data that is displayed in Figure 5-42, but offer a different perspective that may be desirable in certain circumstances. Regardless of the chart examined, a clear optimum set of mixture variables, with respect to both crushing strength and mechanical durability, appears to be achievable at a water content of 0.20 with 30 percent biomass and 5 percent starch. At these conditions, the models predict a crushing strength in excess of 450 pounds-force and a mechanical durability near 100 percent. Numerical optimization of the mixture variables can be conducted to verify this result.

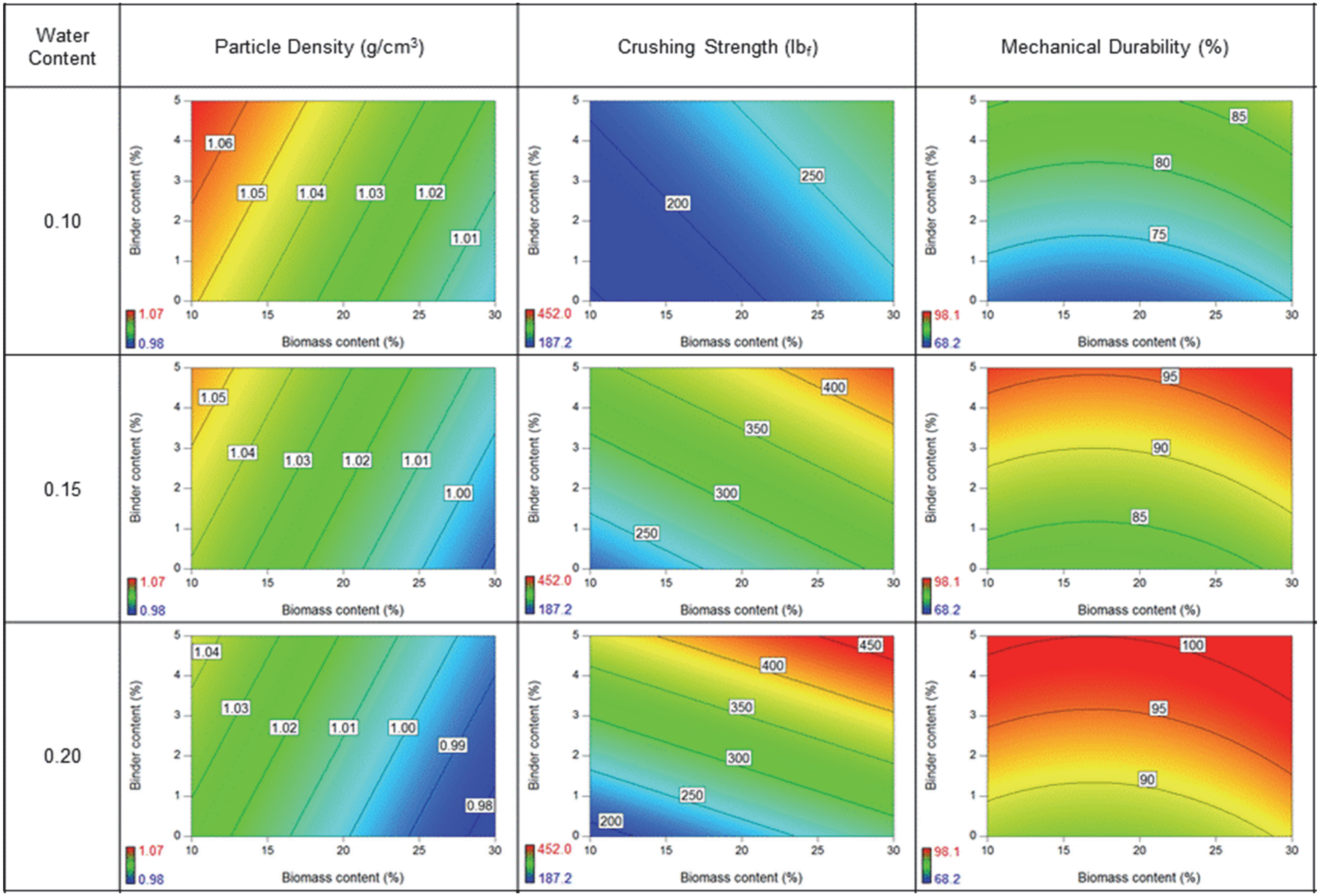


Figure 5-42. Influence of feed water content on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of Eagle Butte (sub-bituminous) coal, corn stover and pregelatinized wheat starch

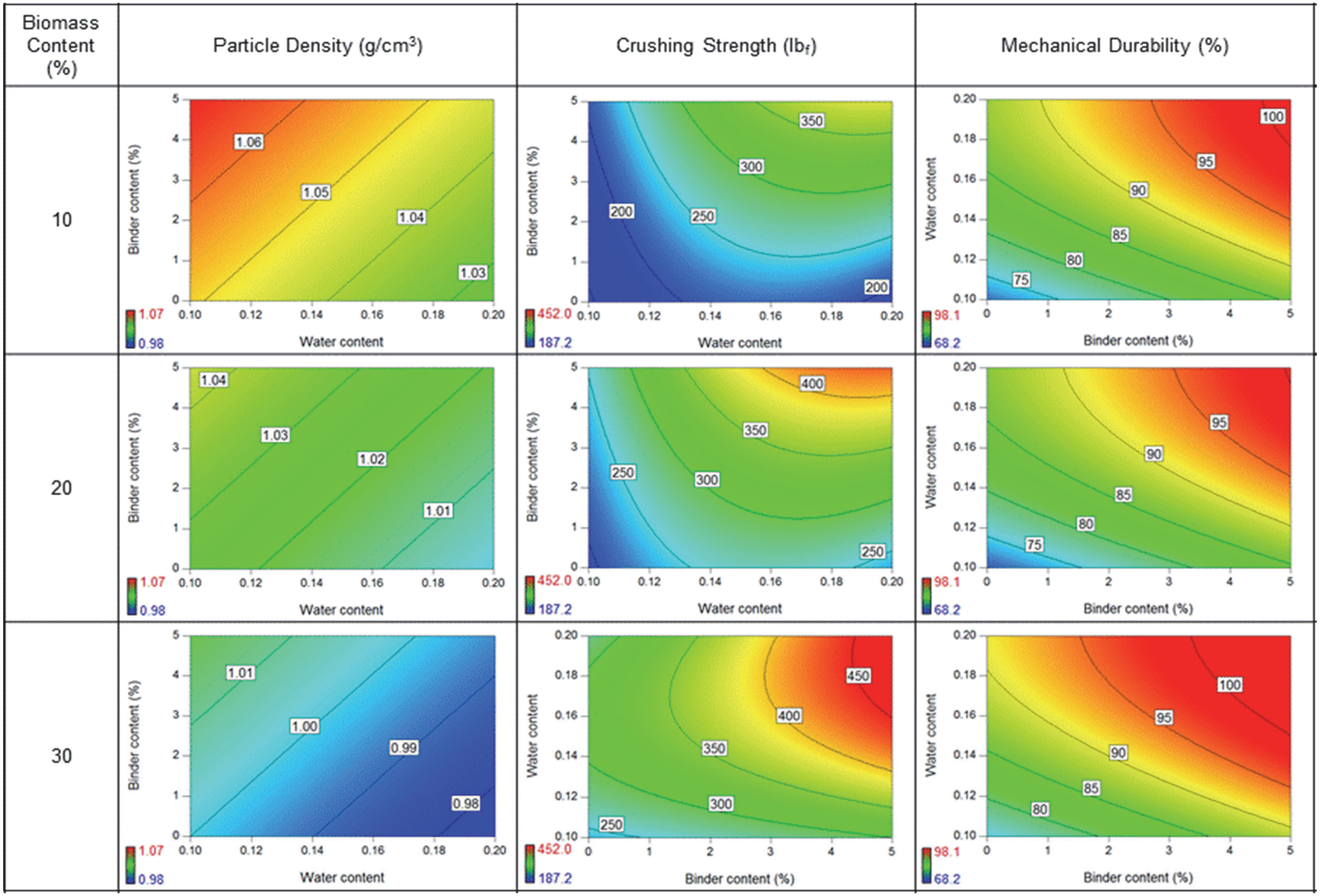


Figure 5-43. Influence of biomass content on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of Eagle Butte (sub-bituminous) coal, corn stover and pregelatinized wheat starch

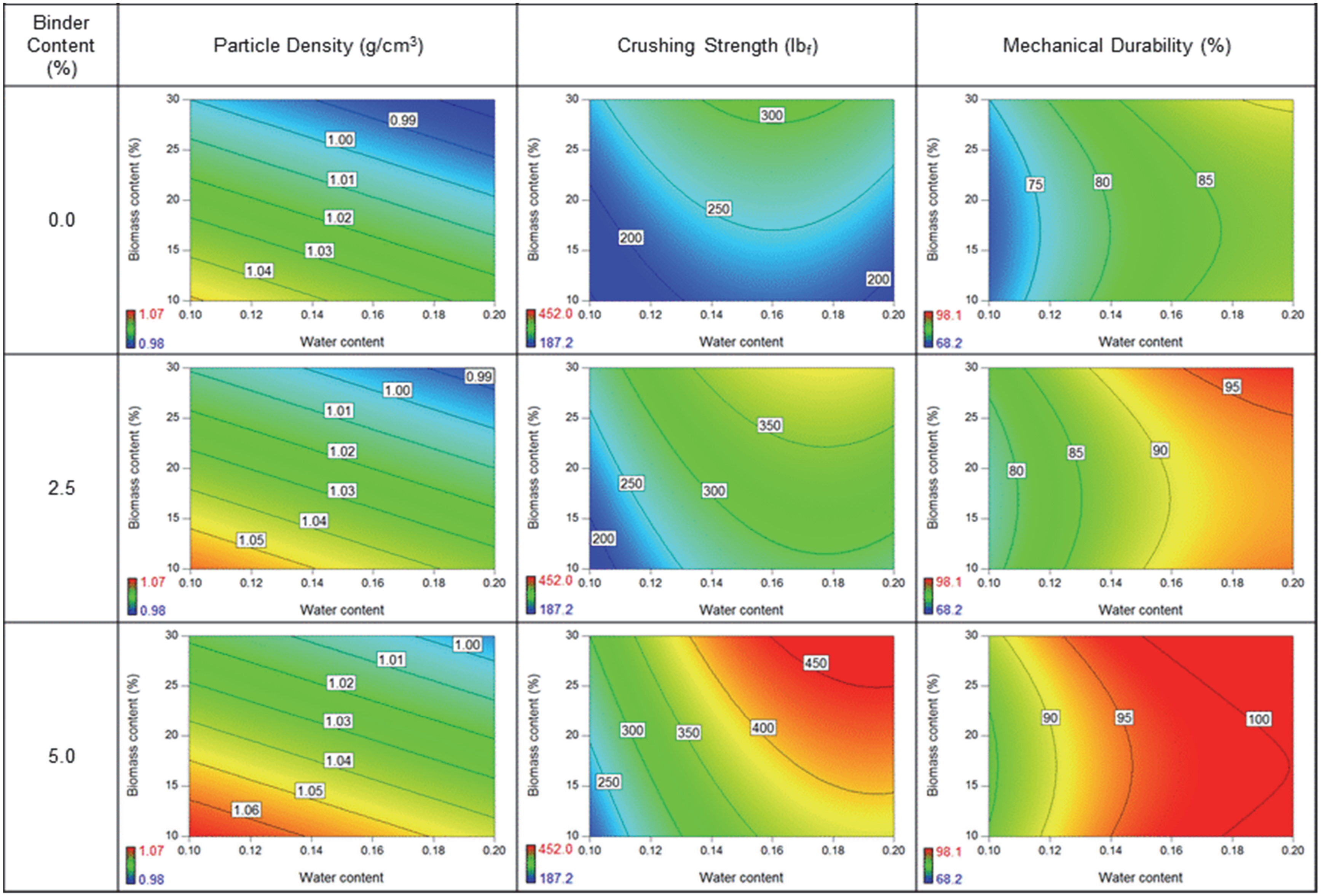


Figure 5-44. Influence of binder content on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of Eagle Butte (sub-bituminous) coal, corn stover and pregelatinized wheat starch

5.4.3.4 Numerical Optimization

Numerical optimization of the mixture variables was conducted in Design-Expert® 8 using the tool included in the analysis package. This tool allows for specification of optimization criteria (i.e. goals), which can include maximizing or minimizing predicted responses and process variables, as well as setting target values for each parameter. The tool also allows for adjustment of the importance of each goal on a scale from one to five (1 being the least important, 5 being the most important). The results of the optimization routine include a specified value for each of the process variables, as well as the predicted values for each response. A desirability value is calculated for each solution to the optimization routine to rank and evaluate the solutions.

Optimization of the mathematical models developed for briquettes comprised of Eagle Butte coal, corn stover and pregelatinized wheat starch was accomplished by specifying a maximization goal for both crushing strength and mechanical durability. The importance of the mechanical durability goal was set to five and the importance of the crushing strength goal was set to three. The routine generated 31 optimized solutions, all of which specified a water content of approximately 0.20, a biomass content of 30 percent, and a starch content of approximately 5 percent. As shown in Table 5-24, the top ten most desirable solutions were predicted to produce briquettes with a crushing strength of 470 to 475 pounds-force and a mechanical durability in excess of 100 percent. However, it is not possible to achieve mechanical durability values this high, but nonetheless high durability would be expected.

Table 5-24. Numerical optimization results for EB-CS-PGWS mathematical models

Number	**Water Content**	**Biomass Content (%)**	**Binder Content (%)**	**Crushing Strength (lb_f)**	**Mechanical Durability (%)**	**Desirability**
1	0.194	30	5.00	474.10	104.3	0.968
2	0.195	30	5.00	474.10	104.4	0.968
3	0.196	30	5.00	474.10	104.4	0.968
4	0.197	30	5.00	474.00	104.4	0.968
5	0.198	30	5.00	473.90	104.5	0.968
6	0.195	30	4.99	473.60	104.3	0.968
7	0.193	30	4.98	473.40	104.2	0.967
8	0.194	30	4.98	473.30	104.3	0.967
9	0.195	30	4.97	472.90	104.3	0.967
10	0.193	30	4.96	472.80	104.2	0.966

5.4.3.5 Comparison of Biomass Types

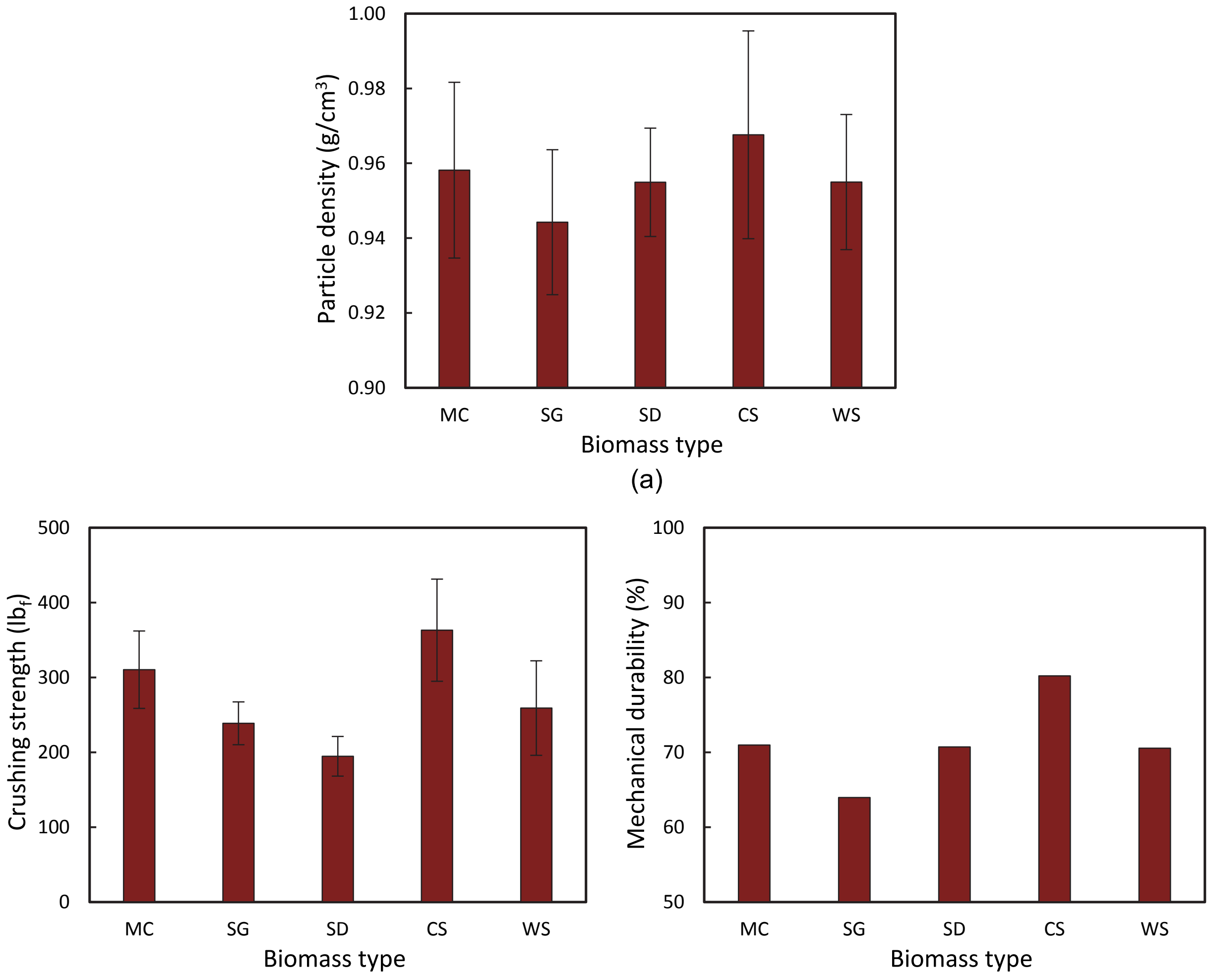
An additional series of tests were designed to evaluate the quality of briquettes produced with sub-bituminous coal and other types of biomass. The objective of these tests was to verify that the optimum combination of mixture variables identified for the Eagle Butte corn stover briquettes can also produce strong and durable briquettes with the other biomass types. To provide additional information on binderless briquetting mixtures of sub-bituminous coal and biomass, the decision was made to conduct the tests at optimum binderless conditions. The chosen optimum set of conditions was a target feed water content of 0.15, a biomass content of 30 percent and binder content of 0.0 percent, which corresponded to standard test 10 in the Design-Expert® 8 software. The results of these tests for each of the five types of biomass are summarized in Table 5-25.

Table 5-25. Summary of briquette characterization results for Eagle Butte biomass verification tests

Test ID	Feed Water Content	Biomass Content (%)	Binder Content (%)	Briquette Water Content	Particle Density (g/cm^3)	Crushing Strength (lb$_f$)	Mechanical Durability (%)
EB-MC-PGWS-10	0.133	30	0.0	0.129	0.96	310.4	71.0
EB-SG PGWS-10	0.130	30	0.0	0.132	0.94	238.8	64.0
EB-SD PGWS-10	0.130	30	0.0	0.130	0.95	194.7	70.7
EB-CS PGWS-10	0.152	30	0.0	0.134	0.97	363.2	80.2
EB-WS PGWS-10	0.150	30	0.0	0.132	0.95	259.1	70.5

To visualize the similarities and differences in the measured results, the particle density, crushing strength and mechanical durability values for each biomass type are plotted in Figure 5-45. The particle density results for each biomass types are presented in Figure 5-45a. This chart shows the average measured value and the calculated standard deviation of the measurements. From this chart, it is clear that the particle density of the sub-bituminous coal-biomass briquettes is very similar regardless of the type of biomass used. However, the particle density of briquettes composed of switchgrass was clearly the lowest (i.e. 0.94 g/cm^3). In contrast, the particle density of the briquettes composed of corn stover was the highest (i.e. 0.97 gcm^3).

Figure 5-45b illustrates the crushing strength results for each biomass type. This chart shows the average measured value and the calculated standard deviation of the measurements. The range of crushing strength values for the five biomass types was 194.7 to 363.2 pounds-force. The biomass type with the lowest crushing strength was the sawdust, while the corn stover exhibited the highest crushing strength. Clearly, biomass type has a fairly significant impact on the crushing strength of sub-bituminous coal briquettes. Figure 5-45c shows the mechanical durability results for each biomass type. The range of the measured values for the five biomass types was 64.0 to 80.2 percent. Once again, the corn stover exhibited the highest result, while the switchgrass was found to have the lowest mechanical durability. These results indicate that corn stover is the best type of biomass with respect to the quality of briquettes composed of sub-bituminous coal and biomass.



(a)

(b)

(c)

Figure 5-45. Effect of biomass type on (a) particle density, (b) crushing strength and (c) mechanical durability for briquettes composed of Eagle Butte (sub-bituminous) coal and each type of biomass [Error bars indicate plus and minus one standard deviation from the mean]

5.4.4 Evaluation of Roll Press Operating Parameters

5.4.4.1 Summary of Results

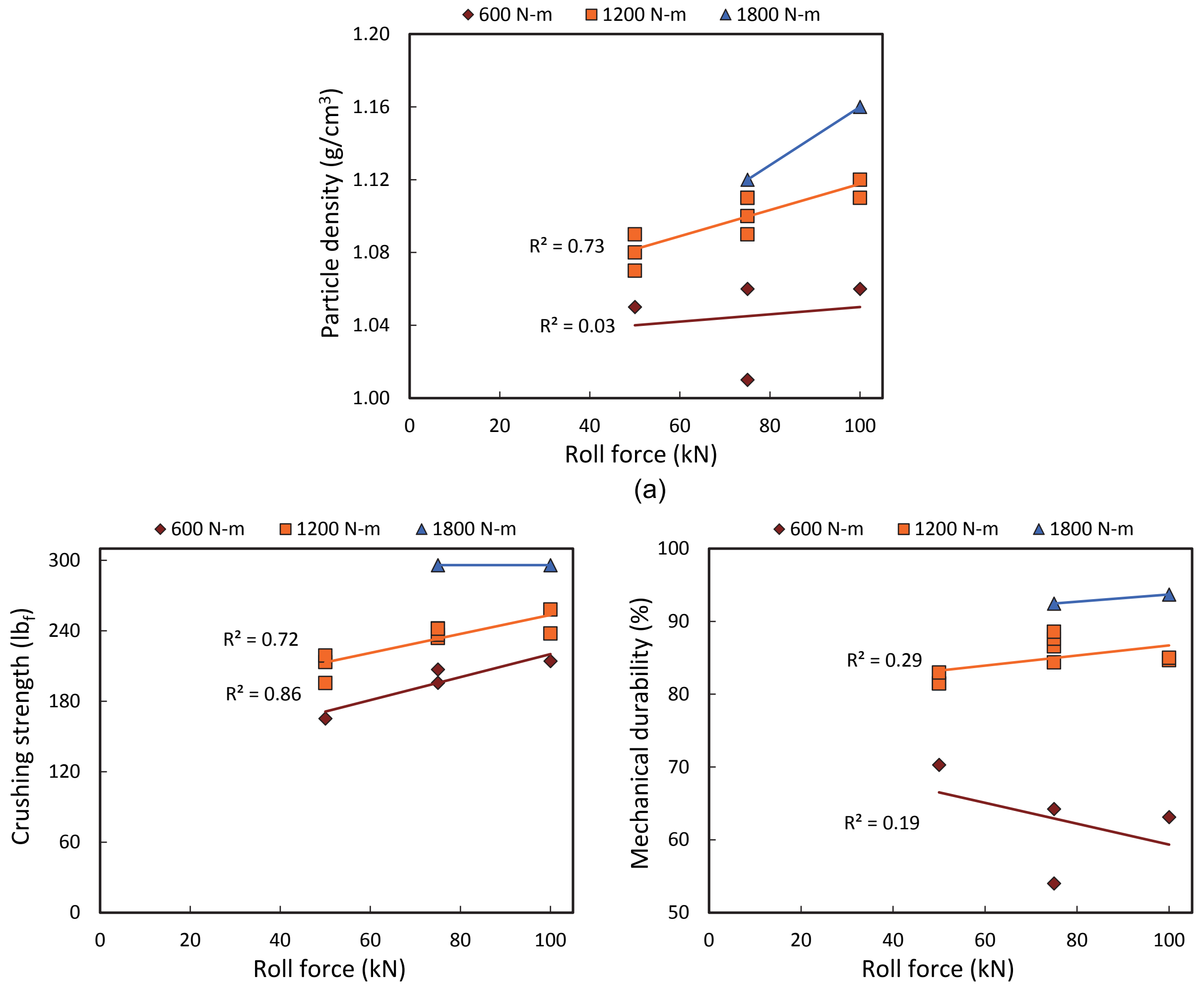
The results of the operating parameters evaluations for the Komarek B100R roll press are summarized in Table 5-26. Each test that was conducted is identified by the standard test number assigned in Design-Expert® 8 according to the roll force, roll torque and roll motor speed (i.e. 01 = roll force of 50 kN, roll torque of 1200 N-m and roll motor speed of 300 rpm). It should be noted that a roll torque of 1800 newton-meters was not sustainable at a roll force of 50 kilonewtons. Therefore, a roll torque of 1200 newton-meters was evaluated in the tests that initially specified these conditions. In the following sections, correlations between each operating variable and the measured briquette properties are presented and discussed. Analysis of the results is also covered, including mathematical models developed for each response using the Design-Expert® 8 statistical analysis tools. In addition, contour graphs of the models are presented to visually interpret and evaluate the results. Finally, numerical optimization of the model was conducted to determine the combination of operating parameters that produces the highest quality briquettes.

Table 5-26. Summary of briquette characterization results for evaluation of Komarek B100R roll press operating parameters

Test ID`	**Roll Force (kN)**	**Roll Torque (N-m)**	**Roll Speed (rpm)**	**Briquette Water Content**	**Particle Density (g/cm^3)**	**Crushing Strength (lb$_f$)**	**Mechanical Durability (%)**
MR-CS-MP-01	50	1200	300	0.020	1.09	195.6	81.5
MR-CS-MP-02	50	1200	900	0.024	1.07	213.5	81.5
MR-CS-MP-03	100	1200	300	0.027	1.12	237.8	84.7
MR-CS-MP-04	100	1200	900	0.026	1.11	258.2	85.0
MR-CS-MP-05	75	600	300	0.024	1.06	207.1	64.3
MR-CS-MP-06	75	600	900	0.024	1.01	195.8	54.0
MR-CS-MP-07	75	1200	300	0.028	1.09	242.2	84.4
MR-CS-MP-08	75	1800	900	0.019	1.12	295.9	92.5
MR-CS-MP-09	50	600	600	0.022	1.05	165.4	70.3
MR-CS-MP-10	100	600	600	0.026	1.06	214.3	63.1
MR-CS-MP-11	50	1200	600	0.020	1.08	219.1	83.0
MR-CS-MP-12	100	1800	600	0.021	1.16	295.9	93.7
MR-CS-MP-13	75	1200	600	0.024	1.11	234.0	86.6
MR-CS-MP-14	75	1200	600	0.024	1.10	236.7	87.7
MR-CS-MP-15	75	1200	600	0.022	1.11	241.9	88.6

5.4.4.1.1 Roll Force Correlations

The correlation between roll force and each measured briquette property were evaluated by linear regression analysis. To investigate these correlations, roll force was plotted versus each measured briquette property with the data points grouped by roll torque values (i.e. 600, 1200 and 1800 N-m). This approach was used because little or no correlation existed for the entire data set due to the influence of the other operating parameters (i.e. roll torque and roll speed). The roll force correlations were initially investigated with the data grouped separately by roll torque and roll speed. From these investigations, it was found that roll force correlations were greatest with the data grouped by roll torque.



(a)

(b) (c)

Figure 5-46. Effect of Komarek B100R roll force on (a) particle density, (b) crushing strength and (c) mechanical durability for briquettes composed of McClure River (bituminous) coal and corn stover

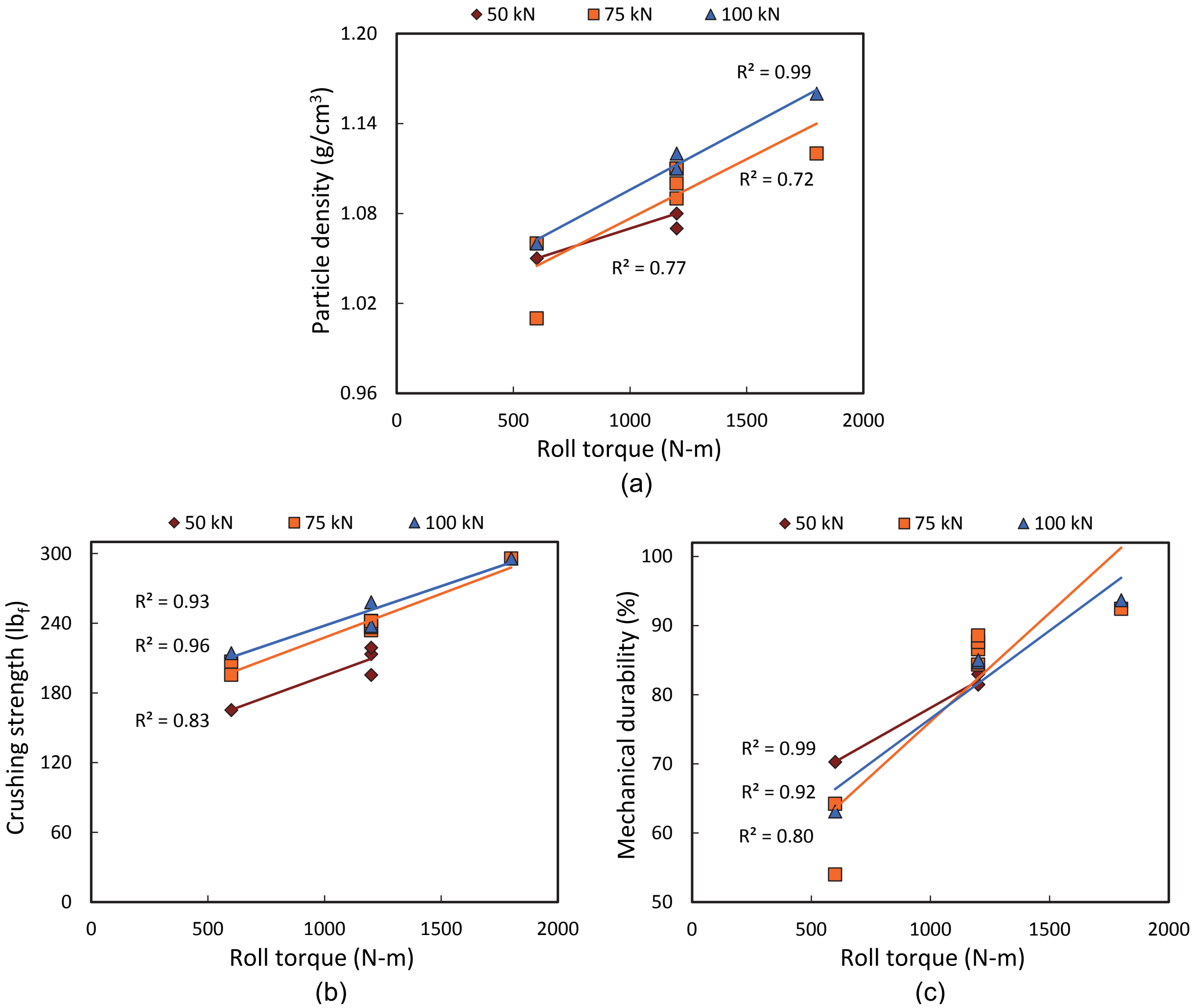
Figure 5-46a displays the correlation between roll force and the particle density of briquettes produced with the Komarek B100R roll press. It is clear from this chart that roll force generally exhibits a positive correlation with particle density. For each of the three roll torques tested, an increase in roll force led to an increase in the particle density of the briquettes, with the exception of one data point at a roll torque of 600 newton-meters. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by roll torque. However, this value was not determined for the briquettes produced at a roll torque of 1800 newton-meters since there were only two recorded data points. At a roll torque of 1200 newton-meters, the coefficient of determination was 0.73. In contrast, this value was only 0.03 for the briquettes produced at a roll torque of 600 newton-meters. These coefficients indicate that roll force and roll torque are not the only variables that influence the particle density of coal-biomass briquettes.

Figure 5-46b illustrates the correlation between roll force and the crushing strength of the briquettes. This chart clearly shows that there is a strong positive correlation between roll force and crushing strength for briquettes produced at roll torque values of 600 and 1200 newton-meters. In contrast, there is no clear correlation between roll force and crushing strength for the briquettes produced at a roll torque of 1800 newton-meters. The uncertainty of this result is amplified by the lack of data points at this operating condition. The strength of the linear correlations for the briquettes produced at roll torque values of 600 and 1200 newton-meters was determined by calculating the coefficient of determination values. The strongest linear correlation was found for the briquettes produced at a roll torque of 600 newton-meters (i.e. $R^2 = 0.86$). In comparison, the coefficient of determination for briquettes at a roll torque of 1200 newton-meters was 0.72.

Figure 5-46c shows the correlation between roll force and the mechanical durability of briquettes. It appears from this chart that there is a slight positive correlation between roll force and mechanical durability for briquettes produced with a roll torque of 1200 and 1800 newton-meters. Conversely, the mechanical durability of briquettes produced with a roll torque of 600 newton-meters exhibited a slight negative correlation with roll force. The strength of the linear correlations for the briquettes produced at roll torque values of 600 and 1200 newton-meters was determined by measuring the coefficient of determination values. The coefficient of determination values for the briquettes produced at a roll torque of 600 and 1200 newton-meters was 0.19 and 0.29, respectively.

5.4.4.1.2 Roll Torque Correlations

The correlation between roll torque and each measured briquette property were also evaluated by linear regression analysis. To investigate these correlations, roll torque was plotted versus each measured briquette property with the data points grouped by roll force values (i.e. 50, 75 and 100 kN). This approach was used because little or no correlation existed for the entire data set due to the influence of the other operating parameters (i.e. roll force and roll speed). The roll torque correlations were initially investigated with the data grouped separately by roll force and roll speed. From these investigations, it was found that roll torque correlations were greatest with the data grouped by roll force.



(a)

(b)

(c)

Figure 5-47. Effect of Komarek B100R roll torque on (a) particle density, (b) crushing strength and (c) mechanical durability for briquettes composed of McClure River (bituminous) coal and corn stover

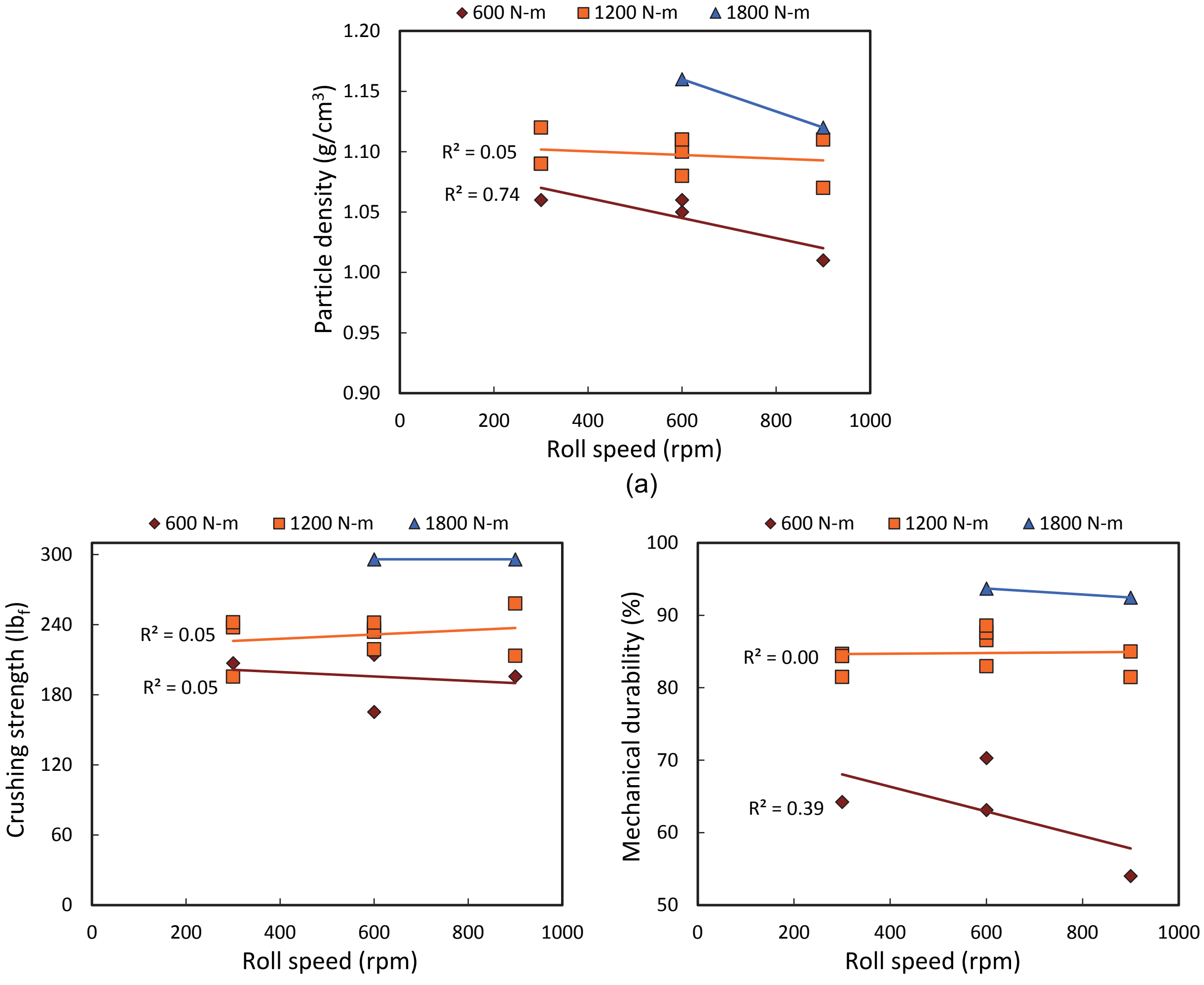
Figure 5-47a displays the correlation between roll torque and the particle density of briquettes produced with the Komarek B100R roll press. It is clear from this chart that there is a fairly strong positive correlation between roll torque and the particle density of the briquettes. For each of the roll forces evaluated, an increase in roll torque led to a direct increase in the particle density of the briquettes. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by roll force. The strongest correlation was observed for the briquettes produced with a roll force of 100 kilonewtons (i.e. $R^2 = 0.99$). In contrast, the coefficient of determination values for briquettes produced with roll forces of 75 and 50 kilonewtons were 0.72 and 0.77, respectively.

Figure 5-47b illustrates the correlation between roll torque and the crushing strength of the briquettes. This chart clearly shows that there is a positive correlation between roll torque and briquette crushing strength. An increase in roll torque directly corresponded to an increase in the crushing strength of the briquettes for each of the roll forces evaluated. The strength of these linear correlations was determined by calculating the coefficient of determination for each set of roll forces. Each of the values was high, which indicates that the linear correlation between roll torque and briquette crushing strength is strong. Specifically, the coefficient of determination values for briquettes produced at 50, 75 and 100 kilonewtons were 0.83, 0.96 and 0.93, respectively. These results suggest that the crushing strength of coal-biomass briquettes can be improved by increasing the roll torque applied during briquette production.

Figure 5-47c shows the correlation between roll torque and the mechanical durability of briquettes. As with the previous chart, it appears from this chart that there is a positive correlation between roll torque and the mechanical durability of briquettes. An increase in roll torque directly corresponded to an increase in the mechanical durability of the briquettes for each of the roll forces evaluated. The strength of these linear correlations was determined by calculating the coefficient of determination for each set of roll forces. The strongest linear correlation was found for the briquettes produced at a roll force of 50 kilonewtons (i.e. $R^2 = 0.99$). The strength of this correlation successively declined with an increase in roll force. Specifically, the coefficient of determination for briquettes produced at a roll force of 75 and 100 kilonewtons was 0.92 and 0.80, respectively. These results suggest that the mechanical durability of coal-biomass briquettes can be improved by increasing the roll torque applied during briquette production.

5.4.4.1.3 Roll Speed Correlations

The correlation between the roll motor speed and each measured briquette property were also evaluated by linear regression analysis. To investigate these correlations, roll speed was plotted versus each measured briquette property with the data points grouped by roll torque values (i.e. 600, 1200 and 1800 N-m). This approach was used because little or no correlation existed for the entire data set due to the influence of the other operating parameters (i.e. roll force and roll torque). The roll speed correlations were initially investigated with the data grouped separately by roll force and roll torque. From these investigations, it was found that roll speed correlations were greatest with the data grouped by roll torque.



(b) (c)

Figure 5-48. Effect of Komarek B100R roll speed on (a) particle density, (b) crushing strength and (c) mechanical durability for briquettes composed of McClure River (bituminous) coal and corn stover

Figure 5-48a displays the correlation between roll speed and the particle density of briquettes produced with the Komarek B100R roll press. From this char, it appears that a slight negative correlation exists between roll speed and particle density. For each of the three roll torques tested, an increase in roll speed led to a slight decrease in the particle density of the briquettes. The strength of these linear correlations was measured by determining the coefficient of determination for each data set grouped by roll torque. However, this value was not determined for the briquettes produced at a roll torque of 1800 newton-meters since there were only two recorded data points. At a roll torque of 1200 newton-meters, the coefficient of determination was 0.05, which indicates that the correlation is not significant. However, the coefficient of determination for the briquettes produced at a roll torque of 600 newton-meters was 0.74, which indicates that the linear correlation is much stronger for briquette produced under this condition.

Figure 5-48b illustrates the correlation between roll speed and the crushing strength of the briquettes. It is clear from this chart that there is very little correlation between roll speed and the crushing strength of briquettes. This is supported by coefficient of determination values of 0.05 for roll torque values of 600 and 1200 newton-meters. Again, this coefficient was not calculated for the briquettes produced at a roll torque of 1800 newton-meters since there were only two recorded data points. These results suggest that roll speed has no quantifiable impact on the crushing strength of coal-biomass briquettes.

Figure 5-48c shows the correlation between roll speed and the mechanical durability of briquettes. It appears from this chart that there is no correlation between roll speed and mechanical durability for briquettes produced with a roll torque of 1200 and 1800 newton-meters. Conversely, the mechanical durability of briquettes produced with a roll torque of 600 newton-meters exhibited a slight negative correlation with roll speed. The strength of the correlations for the briquettes produced with at roll toques of 600 and 1200 newton-meters was determined by calculating the coefficient of determination for each data set. The briquettes produced at a roll torque of 600 newton-meters were found to have a coefficient of determination 0.39. In contrast, the coefficient of determination for the briquettes produced at a roll torque of 1200 newton-meters was 0.00. These results suggest that roll speed has no quantifiable impact on the mechanical durability of briquettes produced at high torque values. However, roll speed may have an impact on the quality of briquettes produced at lower torque values. In this case, slower roll speed likely enables better aeration of the feed prior to briquette formation, which has a positive effect on briquette quality.

5.4.4.2 Statistical Analyses

The results of the operating parameter evaluations for the Komarek B100R roll press were examined using the statistical analysis tools included in Design-Expert® 8 to determine the influence of each variable and to optimize the quality of briquettes. Mathematical models were developed that relate the roll press operating parameters (i.e. roll force, roll torque and roll speed) to the measured briquette properties (i.e. particle density, crushing strength, and mechanical durability). The first step of model development was selection of the process order (e.g. linear, quadratic) of the mathematical model. This was accomplished by determining the process order with the lowest lack of fit p-value and the highest adjusted R-squared and predicted R-squared values. The selected model was then analyzed using the analysis of variance (ANOVA) function to determine the statistical significance of the entire model and of each individual term. All insignificant terms were then removed from the model, except those required to maintain hierarchy. Next, the fit of the model to the data was evaluated using various diagnostics tools. The following sections present the empirical mathematical models developed for briquettes produced with the Komarek B100R roll press and summarize the results of the statistical analyses.

5.4.4.2.1 Particle Density Model

A linear mathematical model was constructed that relates roll force, roll torque and roll speed to the particle density of briquettes produced with the Komarek B100R roll press. According to the model, the predicted particle density of briquettes is calculated by:

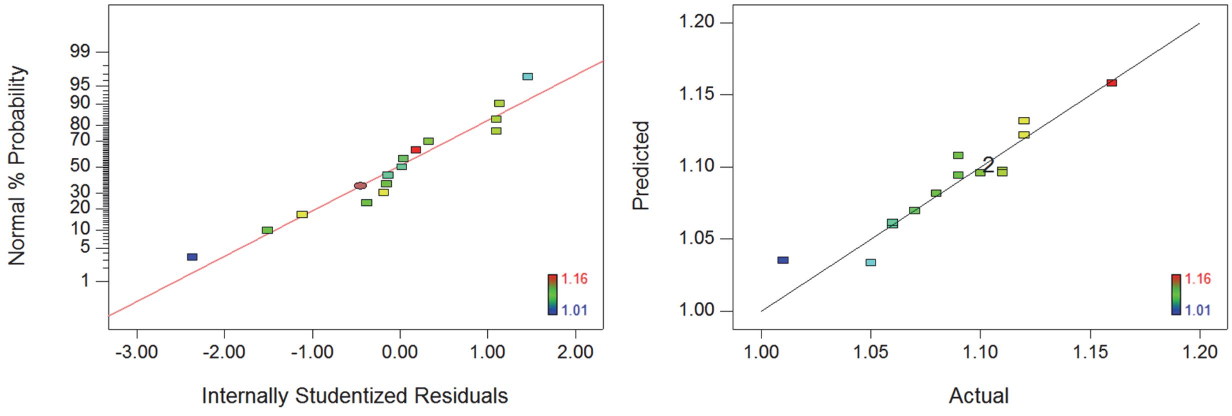
$$\rho = 0.98 + 0.00056f + 0.000081t - 0.000041s \qquad \text{(Eq. 5-18)}$$

where ρ is the particle density (g/cm^3), f is the roll torque (kN), t is the roll torque (N-m) and s is the roll motor speed (rpm). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using ANOVA to evaluate a number of variables. A summary of the ANOVA is provided in Table 5-27 for the particle density model. The p-value of the particle density model is less than 0.0001, which indicates that the predicted density values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the model terms are 0.0265 (roll speed), 0.0142 (roll force) and less than 0.0001 (roll torque). This implies that each of the operating parameters are statistically significant model terms, and thus have a major impact on accurate prediction of the particle density of briquettes. However, it should be distinguished that roll torque is the most statistically significant model parameter, and thus has the greatest effect on the particle density of coal-biomass briquettes according to this model.

Table 5-27. ANOVA results for Komarek B100R roll press particle density model

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	1.63E-02	3	5.44E-03	30.18	< 0.0001
A-Roll speed	1.18E-03	1	1.18E-03	6.56	0.0265
B-Roll force	1.52E-03	1	1.52E-03	8.46	0.0142
C-Roll torque	1.28E-02	1	1.28E-02	71.04	< 0.0001
Residual	1.98E-03	11	1.80E-04	--	--
Lack of Fit	1.92E-03	9	2.13E-04	6.38	0.1427
Pure Error	6.67E-05	2	3.33E-05	--	--
Cor Total	1.83E-02	14	--	--	--

To confirm the ANOVA normality assumption for the particle density model, the residuals were visually examined in a normal probability plot of studentized results. Figure 5-49a shows the normal probability plot of studentized results for the crushing strength model. It is clear from this figure that the residuals follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual values was also examined to visually analyze the relationship between the measured particle density values and those predicted by the model. The predicted versus actual plot is displayed in Figure 5-49b for the particle density model, which shows the desired data scatter about the 45 degree line is present. This further exemplifies the statistical significance of the particle density model and indicates that it is well suited for prediction of briquette quality.



(a) (b)

Figure 5-49. Diagnostic graphs for visual inspection of ANOVA results for Komarek B100R roll press particle density model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

5.4.4.2.2 Crushing Strength Model

A linear mathematical model was constructed that relates roll force, roll torque and roll speed to the crushing strength of briquettes produced with the Komarek B100R roll press. According to the model, the predicted crushing strength of briquettes is calculated by:

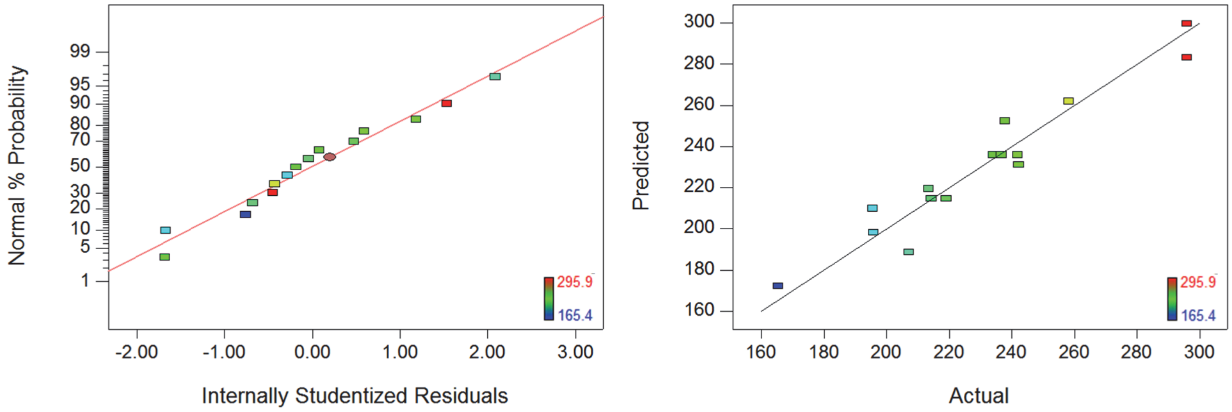
$$\sigma = 77.57 + 0.85f + 0.07t + 0.02s \qquad \text{(Eq. 5-19)}$$

where σ is the crushing strength (lb_f), f is the roll torque (kN), t is the roll torque (N-m) and s is the roll motor speed (rpm). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using ANOVA to evaluate a number of variables. A summary of the ANOVA is provided in Table 5-28 for the crushing strength model. The p-value of the model is less than 0.0001, which indicates that the predicted crushing strength values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the model terms are 0.2302 (roll speed), 0.0001 (roll force) and less than 0.0001 (roll torque). This implies that roll force and roll torque are statistically significant model terms, and thus have a major impact on accurate prediction of the crushing strength of briquettes. In contrast, roll speed is not a significant model term, which implies that its impact on crushing strength quantified in the model is not statistically significant. This term was needed to maintain the hierarchy of the model, otherwise it would have been removed to improve the model.

Table 5-28. ANOVA results for Komarek B100R roll press crushing strength model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	16364	3	5455	49.32	< 0.0001
A-Roll speed	178	1	178	1.61	0.2302
B-Roll force	3537	1	3537	31.98	0.0001
C-Roll torque	9900	1	9900	89.52	< 0.0001
Residual	1217	11	111	--	--
Lack of Fit	1184	9	132	8.16	0.1139
Pure Error	32	2	16	--	--
Cor Total	17580	14	--	--	--

To confirm the ANOVA normality assumption for the crushing strength model, the residuals were visually examined in a normal probability plot of studentized results. Figure 5-50a shows the normal probability plot of studentized results for the crushing strength model. It is clear from this figure that the residuals follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual values was also examined to visually analyze the relationship between the measured crushing strength values and those predicted by the model. The predicted versus actual plot is displayed in Figure 5-50b for the crushing strength model, which shows the desired data scatter about the 45 degree line is present. This further exemplifies the statistical significance of the crushing strength model and indicates that it is well suited for prediction of briquette quality.



(a) (b)

Figure 5-50. Diagnostic graphs for visual inspection of ANOVA results for Komarek B100R roll press crushing strength model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

5.4.4.2.3 Mechanical Durability Model

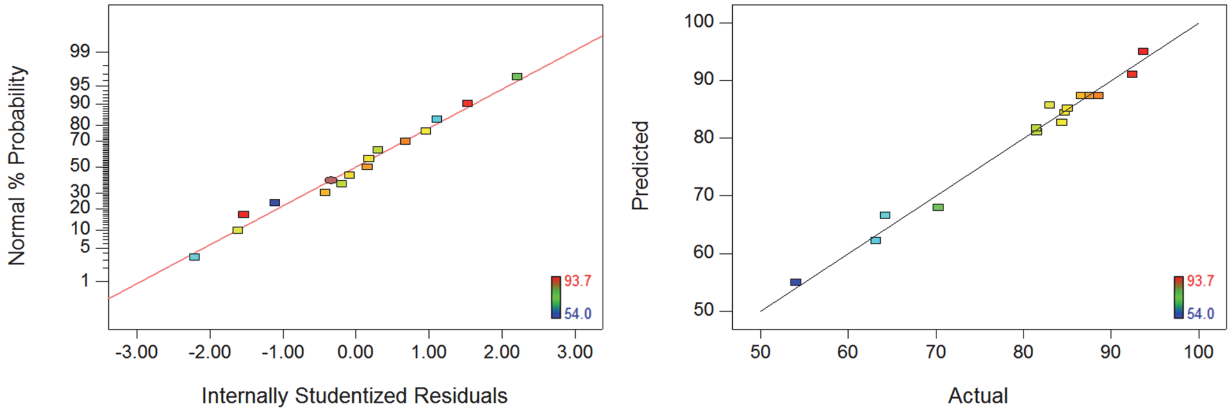
A quadratic mathematical model was constructed that relates roll force, roll torque and roll speed to the mechanical durability of briquettes produced with the Komarek B100R roll press. According to the model, the predicted mechanical durability of briquettes is calculated by:

$$MD = 51.18 - 0.30f + 0.05t + 0.02s + 0.00030ft + 0.000034ts - 0.000029t^2 - 0.000047s^2 \quad \text{(Eq. 5-20)}$$

where MD is the mechanical durability (%),*f* is the roll torque (kN), *t* is the roll torque (N-m) and *s* is the roll motor speed (rpm). The statistical significance of this model, in terms of its fit to the data from which it was derived, was analyzed using ANOVA to evaluate a number of variables. A summary of the ANOVA is provided in Table 5-29 for the mechanical durability model. The p-value of the model is less than 0.0001, which indicates that the predicted mechanical durability values would be highly unlikely under the null hypothesis and verifies that the model is indeed statistically significant. The p-values of the model terms are 0.6877 (roll speed), 0.0882 (roll force), less than 0.0001 (roll torque), 0.0046 (roll speed x roll torque), 0.0186 (roll force x roll torque), 0.0057 (roll speed^2) and 0.0002 (roll torque^2). This implies that the majority of the model terms are statistically significant (except roll speed), and thus have a major impact on accurate prediction of the mechanical durability of briquettes. In contrast, roll speed is not a significant model term, which implies that the impact of this variable on mechanical durability quantified in the model is not statistically significant.

Table 5-29. ANOVA results for Komarek B100R roll press mechanical durability model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	1870.12	7	267.16	63.90	< 0.0001
A-Roll speed	0.73	1	0.73	0.18	0.6877
B-Roll force	16.38	1	16.38	3.92	0.0882
C-Roll torque	398.35	1	398.35	95.28	< 0.0001
AC	70.25	1	70.25	16.80	0.0046
BC	38.92	1	38.92	9.31	0.0186
A^2	64.40	1	64.40	15.40	0.0057
C^2	209.10	1	209.10	50.02	0.0002
Residual	29.26	7	4.18	--	--
Lack of Fit	27.26	5	5.45	5.45	0.1623
Pure Error	2.00	2	1.00	--	--
Cor Total	1899.39	14	--	--	--



(a) (b)

Figure 5-51. Diagnostic graphs for visual inspection of ANOVA results for Komarek B100R roll press mechanical durability model: (a) normal probability plot of studentized results and (b) predicted versus actual values plot

To confirm the ANOVA normality assumption for the mechanical durability model, the residuals were visually examined in a normal probability plot of studentized results. Figure 5-51a shows the normal probability plot of studentized results for the mechanical durability model. It is clear from this figure that the residuals follow an approximately straight line, and thus are normally distributed. A plot of predicted versus actual values was also examined to visually analyze the relationship between the measured mechanical durability values and those predicted by the model. The predicted versus actual plot is displayed in Figure 5-51b for the mechanical durability model, which shows the desired data scatter about the 45 degree line is present. This further exemplifies the statistical significance of the mechanical durability model and indicates that it is well suited for prediction of briquette quality.

5.4.4.3 Model Graphs

Following the development and statistical analysis of each mathematical model, several contour graphs were constructed to visually interpret and evaluate the results. The influence of water content on the modeled responses for particle density, crushing strength and mechanical durability are presented in Figure 5-52. From this figure it is evident that the maximum particle density values (i.e. > 1.16 g/cm^3) occur at a roll force of 100 kN, a roll speed of 300 rpm and a roll torque of 1800 N-m. In contrast, the minimum particle density (i.e. < 1.04 g/cm^3) values occur at a roll force of 50 kN, a roll speed of 900 rpm and a roll torque of 600 N-m. This figure also clearly indicates that briquette crushing strength reaches a maximum value (i.e. > 300 lb$_f$) at a roll force of 100 kN, a roll speed of 900 rpm and a roll torque of 1800 N-m, and reaches a minimum value (i.e. < 180 lb$_f$) at a roll force of 50 kN, a roll speed of 300 rpm and a roll torque of 600 N-m. Finally, this figure shows that the mechanical durability of briquettes reaches a maximum value (i.e. > 95%) at a roll force of 100 kN, a roll speed of 900 rpm and a roll torque of 1800 N-m. In contrast, the minimum mechanical durability occurs at a roll force of 50 kN, a roll speed of 300 rpm and roll torque of 600 N-m.

The modeled responses for particle density, crushing strength and mechanical durability with respect to biomass content and binder content are presented in Figure 5-53 and Figure 5-54, respectively. These figures present the same data that is displayed in Figure 5-52, but offer a different perspective that may be desirable in certain circumstances. Regardless of the chart examined, a clear optimum set of mixture variables, with respect to both crushing strength and mechanical durability, appears to be achievable at a roll force of 100 kN, a roll speed of 900 rpm and roll torque of 1800 N-m. At these conditions, the models predict a crushing strength in excess of 300 pounds-force and a mechanical durability greater than 95 percent. Numerical optimization of the mixture variables can be conducted to verify this result.

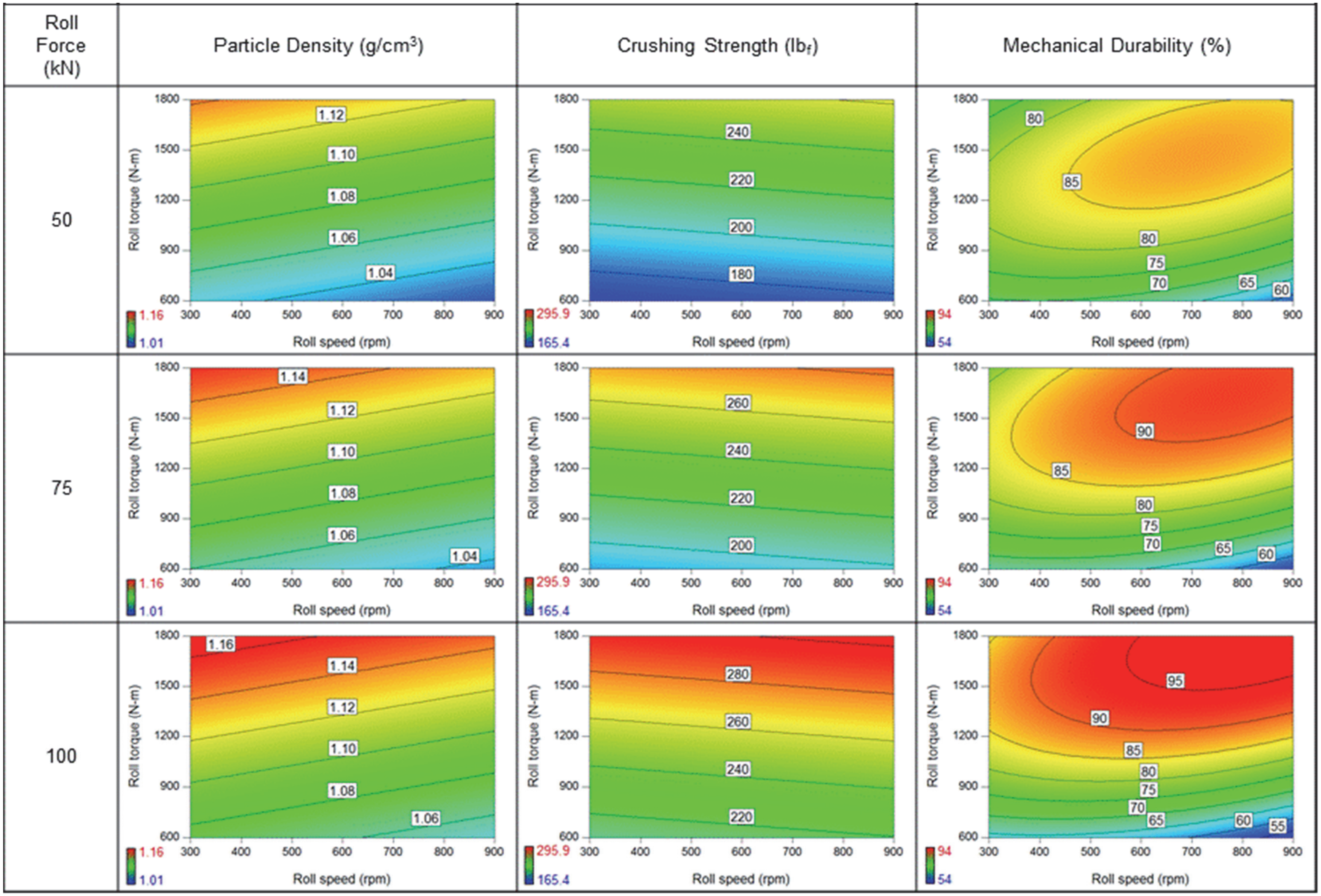


Figure 5-52. Influence of Komarek B100R roll force on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of McClure River (bituminous) coal and corn stover

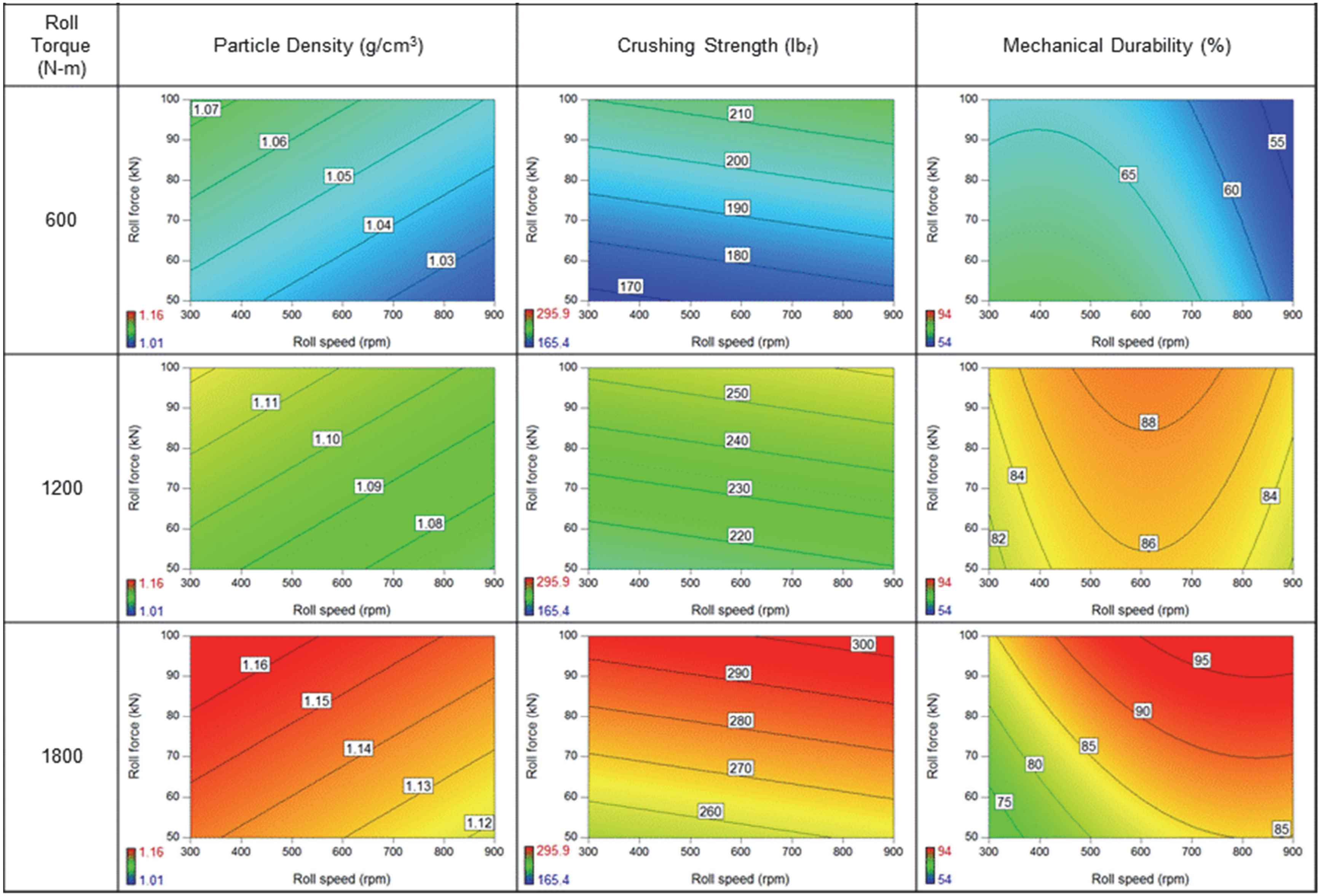


Figure 5-53. Influence of Komarek B100R roll torque on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of McClure River (bituminous) coal and corn stover

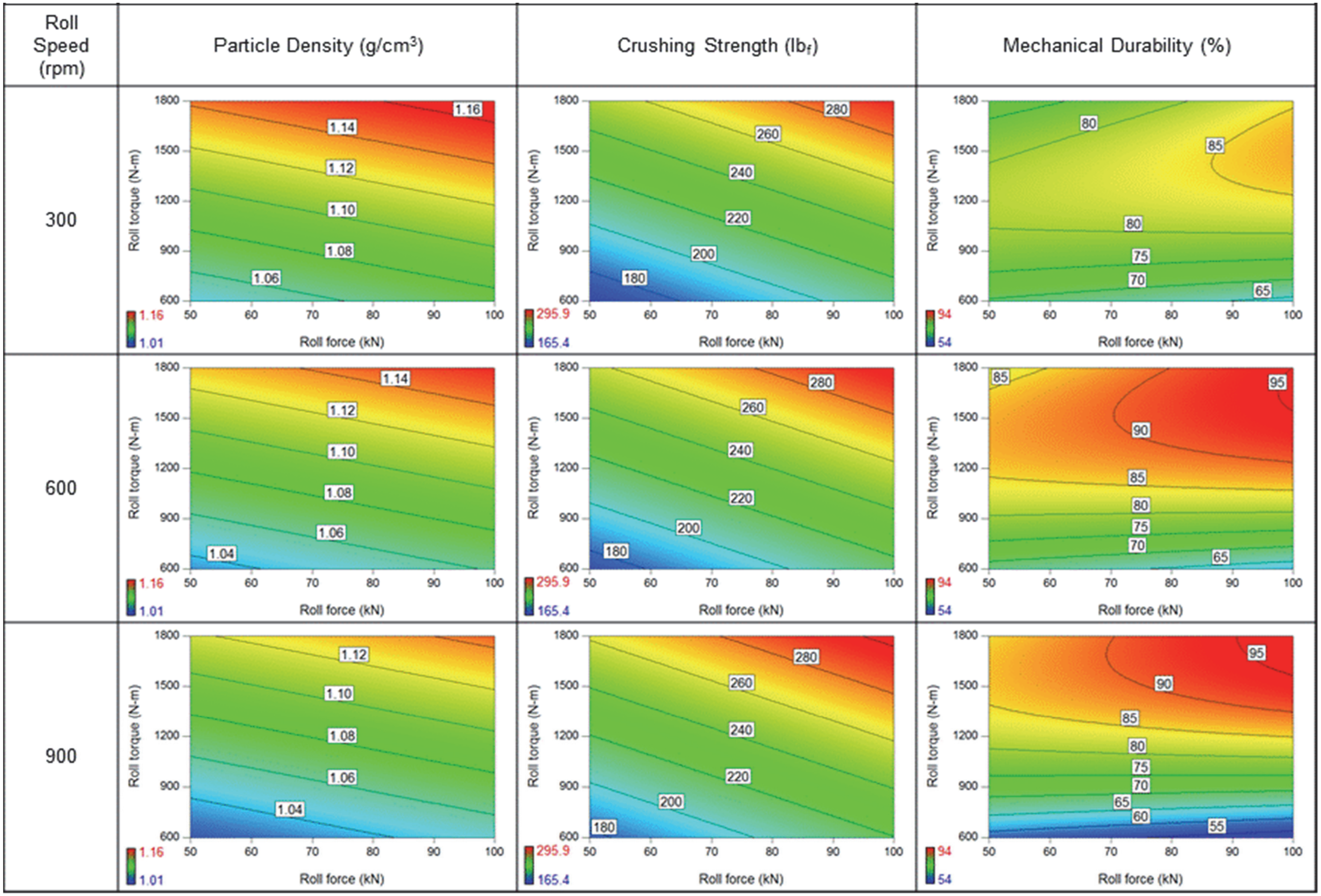


Figure 5-54. Influence of Komarek B100R roll speed on modeled responses for particle density, crushing strength and mechanical durability for briquettes composed of McClure River (bituminous) coal and corn stover

5.4.4.4 Numerical Optimization

Numerical optimization of the feedstock variables was conducted in Design-Expert® 8 using the tool included in the analysis package. This tool allows for specification of optimization criteria (i.e. goals), which can include maximizing or minimizing predicted responses and process variables, as well as setting target values for each parameter. The tool also allows for adjustment of the importance of each goal on a scale from one to five (1 being the least important, 5 being the most important). The results of the optimization routine include a specified value for each of the process variables, as well as the predicted values for each response. A desirability value is calculated for each solution to the optimization routine to provide a method to rank the solutions and to indicate the extent to which the combination of responses approaches a perfect solution.

Optimization of the mathematical models developed for briquettes comprised of Emerald coal, corn stover and pregelatinized wheat starch was accomplished by specifying a maximization goal for both crushing strength and mechanical durability. The importance of the mechanical durability goal was set to five and the importance of the crushing strength goal was set to three. This configuration was selected after experimenting with the effect of the importance setting on the desirability of the solutions to the optimization routine. The routine generated 19 optimized solutions, all of which specified a roll force of 100 kN, a roll torque of 1800 N-m and a roll speed of 819 to 840 rpm. As shown in Table 5-30, the top ten most desirable solutions were predicted to produce briquettes with a crushing strength of approximately 300 pounds-force and a mechanical durability in excess of 97.5 percent.

Table 5-30. Numerical optimization results for Komarek B100R roll press mathematical models

Number	Roll Speed (rpm)	Roll Force (kN)	Roll Torque (N-m)	Crushing Strength (lb_f)	Mechanical Durability (%)	Desirability
1	829	100	1800	303.3	97.6	0.966
2	826	100	1800	303.2	97.6	0.966
3	833	100	1800	303.3	97.6	0.966
4	837	100	1800	303.4	97.5	0.966
5	819	100	1797	303.0	97.5	0.966
6	832	100	1793	302.8	97.5	0.966
7	829	100	1792	302.7	97.5	0.966
8	840	100	1793	303.0	97.5	0.966
9	832	100	1786	302.3	97.5	0.966
10	823	100	1782	301.9	97.5	0.966

5.4.5 Detailed Characterization of Optimum Briquettes

A detailed characterization study was conducted to investigate important properties of two selected optimum types of coal-biomass briquettes. The purpose of this study was to verify the enhanced quality of the co-briquetted feedstocks and to provide additional information that may be useful for industrial consumers or other end users of coal-biomass briquettes. Two types of briquettes were examined for the detailed characterization study. The first type of briquettes were composed of the Emerald coal and sawdust, while the second type of briquettes were composed of Eagle Butte coal and corn stover. Both types of briquettes were subjected to a range of tests to fully characterize their physical properties, flow properties and gasification behavior. The following section present and discuss the results of these evaluations.

5.4.5.1 Characterization of Physical Properties

A summary of the results of the comprehensive physical evaluations of the two types of briquettes are included in Table 5-31. From these results, it is fairly clear that the EM-SD briquettes are superior in quality to the EB-CS briquettes. For example, the crushing strength and tensile strength of the EM-SD briquettes was 357.4 lb_f and 57.5 lb_f, as compared to 275.3 lb_f and 46.3 lb_f for the EB-CS briquettes. This corresponds to 29.8% higher crushing strength and a 24.2% higher tensile strength for the EM-SD briquettes. Nonetheless, the crushing strength of the EB-CS briquettes indicates that these briquettes are very strong, and thus high quality in this regard.

The mechanical durability of the EM-SD and EB-CS briquettes was 92.8% and 91.1%, respectively. These values were very similar and were both very good, which indicates that the briquettes would largely remain intact in the presence of attrition and impact forces encountered during handling and transportation. However, the weathered mechanical durability of the EM-SD (i.e. 39.4%) and EB-CS briquettes (i.e. 7.7%) briquettes was much lower, which indicates that the briquettes would experience a high degree of degradation in the presence of water. This is most likely a direct result of the water uptake values for the briquettes. For example, the initial and weathered water uptake of the EM-SD briquettes was 8.3% and 20.4%, respectively. In comparison, the initial and weathered water uptake of the EB-CS briquettes was 14.3% and 58.6%, respectively. These results suggest that a water resistant binder or some other post-production process would be required to reduce the water uptake of briquettes that will be exposed to precipitation or other moisture for any extended period of time.

Table 5-31. Summary of physical characterization results for Emerald-sawdust (EM-SD) and Eagle Butte-corn stover (EB-CS) briquettes

Briquette Property	Units	EM-SD	EB-CS
Tensile strength	lb_f	57.5	46.3
Crushing strength	lb_f	357.4	275.3
Spring constant	lb_f/in	4646	2842
Mechanical durability	%	92.8	91.1
Weathered mechanical durability	%	39.4	7.7
Attritability	%	97.4	96.9
Friability	%	97.1	98.4
Water content	--	0.018	0.163
Particle density	g/cm^3	1.13	0.94
Water uptake	%	8.3	14.3
Weathered water uptake	%	20.4	58.6

The attritability and friability of the EM-SD briquettes was 97.4% and 97.1%, respectively. Similarly, the EB-CS briquettes exhibited attritability and friability values of 96.9% and 98.4%, respectively. These results indicate that the briquettes would withstand attrition forces in handling and impact forces from drops encountered on conveyors or at other points prior to utilization. Another observation was the significant difference in the particle density of the two types of briquettes. Specifically, the EM-SD briquettes were determined to have a particle density of 1.13 g/cm^3, as compared to only 0.94 g/cm^3 for the EB-CS briquettes. This result was likely due to a combination of factors, including the higher true density of sawdust and the higher porosity of the EB-CS briquettes. The difference in porosity can be attributed to the higher water content of the EB-CS briquettes (i.e. $w = 0.163$) compared to the EM-SD briquettes (i.e. $w = 0.018$), which leads to increased air voids after drying the samples to calculate dry particle density.

5.4.5.2 Characterization of Flow Properties

Several tests were conducted to quantify the flow behavior of the EM-SD and EB-CS briquettes. Cohesive property tests and wall friction tests were performed to determine the opening sizes required to prevent arching and the required angle for mass flow. In addition, a compressibility test was performed to determine the relationship between bulk density and confining pressure. The cohesive properties of the briquettes are summarized by their respective flow functions, as shown in Figure 5-55 and Figure 5-56 for the EM-SD and EB-CS briquettes, respectively.

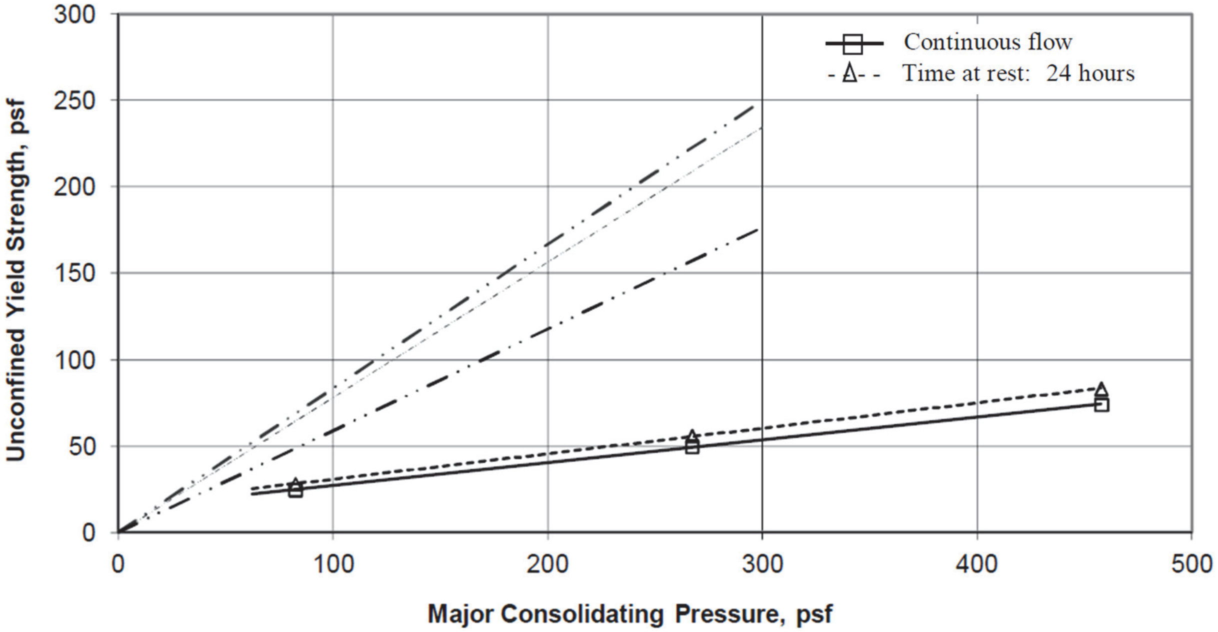


Figure 5-55. Flow function for determination of required hopper opening sizes for Emerald-sawdust (EM-SD) briquettes

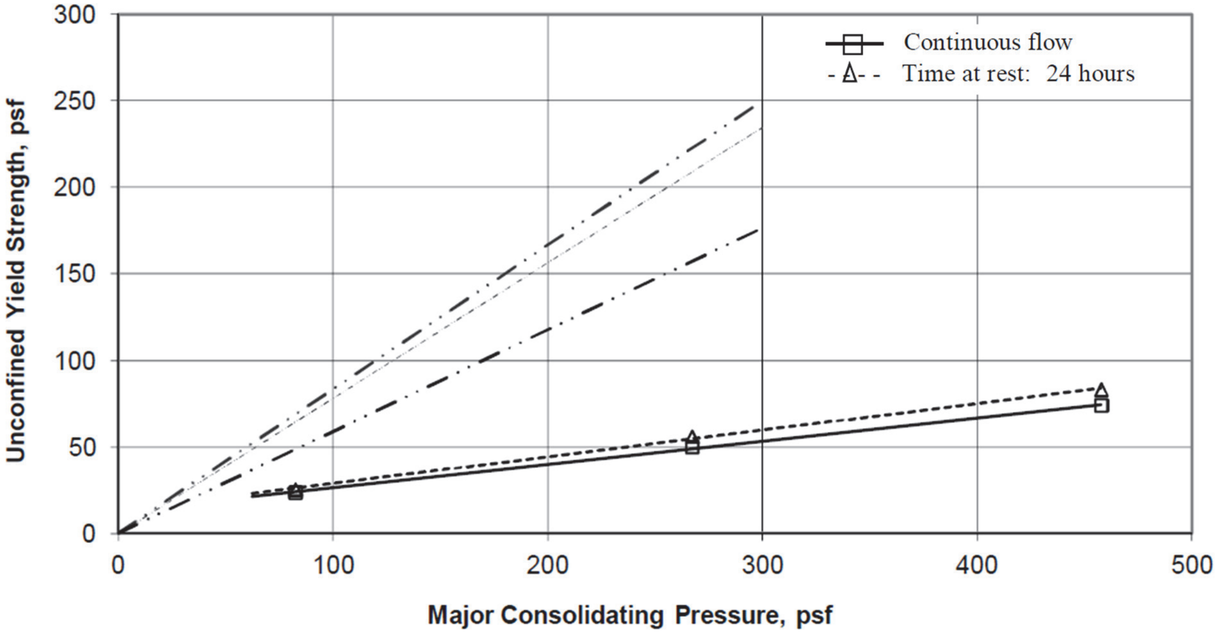


Figure 5-56. Flow function for determination of required hopper opening sizes for Eagle Butte-corn stover (EB-CS) briquettes

In these figures, the developed flow function for each material is plotted for continuous flow (i.e. no time at rest) and for a consolidation period of 24 hours. It is clearly shown that the unconfined yield strength required to cause flow of the briquettes is very low and increases at a slow rate with an increase in consolidation pressure. These results indicate that both the EM-SD and EB-CS briquettes exhibit superior flow properties and thus are unlikely to exhibit poor flow characteristics such as ratholing and arching. However, suitable hopper outlet sizes must be selected to ensure reliable flow for specific applications. The required outlet size must be selected with consideration to the temperature of the briquettes and the consolidating load (or effective head) applied by briquettes on one another. An example of the required hopper outlet dimensions to prevent ratholing in a funnel flow pattern and to prevent arching in a mass flow pattern are provided in Table 5-32 for the EM-SD and EB-CS briquettes. These values were calculated based on a temperature of 72 degrees Fahrenheit and an effective head of 10 feet.

Table 5-32. Required hopper outlet sizes to ensure reliable flow of Emerald-sawdust (EM-SD) and Eagle Butte-corn stover (EB-CS) briquettes

Briquette Sample	**Time at Rest (hr)**	**Funnel Flow**	**Mass Flow**	
		Conical Opening (ft)	**Conical Opening (ft)**	**Slot Opening (ft)**
EM-SD	0	7.7	1.0	0.5
	24	8.7	1.0	0.5
EB-CS	0	7.4	1.0	0.5
	24	8.3	1.0	0.5

There is very little difference in the conical opening required for the two types of briquettes to prevent arching in a funnel flow pattern. Specifically, the EM-SD briquettes require an opening with a diameter of 7.7 feet and the EB-SD briquettes require an opening with a diameter of 7.4 feet. However, it is important to point out that both types of briquettes require a slightly larger opening size to ensure reliable flow after 24 hours at rest. It is also clear from this analysis that a much larger conical opening is required to ensure reliable flow in a funnel flow pattern than in a mass flow pattern. The EM-SD and EB-SD briquettes only require a conical opening with a diameter of 1.0 foot to prevent arching in a mass flow pattern, which represents a significant reduction in outlet size. The required opening size is further reduced to prevent arching in a wedge shaped hoppers with a slot outlet (i.e. 0.5 ft).

In addition to proper outlet size, mass flow hoppers must be designed with an appropriate hopper angle to ensure a reliable flow pattern. The required hopper angle depends on the determined outlet size, storage time at rest and the friction between briquettes and the wall surface. To determine the required hopper angle, a series of wall friction tests are conducted to determine the angle of sliding friction between the wall surface and the briquettes. An example of the required hopper angles to prevent arching in a mass flow pattern is provided in Table 5-33 for the EM-SD and EB-CS briquettes. These values were calculated for flow through a circular opening with a diameter of one foot or a slot opening with a length of 1.5 feet and width of 0.5 feet and a temperature of 72 degrees Fahrenheit.

Table 5-33. Required hopper angles to ensure reliable mass flow for Emerald-sawdust (EM-SD) and Eagle Butte-corn stover (EB-CS) briquettes

Briquette Sample	Wall Surface Material	Conical Hopper Angle (deg. from vertical)	Wedge Hopper Angle (deg. from vertical)
EM-SD	2B Stainless Steel	28	40
	Carbon Steel	12	22
EB-CS	2B Stainless Steel	30	42
	Carbon Steel	19	29

These results show that a steeper hopper angle is required to ensure reliable flow for the EM-SD briquettes than the EB-CS briquettes. For example, a conical hopper constructed out of or lined with 2B stainless steel must have an angle of 28 degrees (from vertical) to ensure reliable flow of the EM-SD briquettes, as compared to a required angle of 30 degrees for the EB-SD briquettes. These results also prove that a steeper angle is required for a carbon steel surface than one fabricated from stainless steel. In addition, it is clearly shown that conical hoppers require steeper angles of inclination than wedge-shaped hoppers. For example, EM-SD briquettes against a 2B stainless steel surfaces require an additional 12 degrees of slope (i.e. 28 versus 40 degrees from vertical) for a conical hopper as compared to a wedge-shaped hopper.

The final variable that must be determined to design hoppers of required size and strength is the bulk density of briquettes as a function of confining pressure. Bulk density values are used to calculate the required opening sizes and hopper angles in addition to bin and feeder load requirements. The compressibility of briquettes can be defined as the change in bulk density divided by the change in confining pressure. The range of bulk density values for different confining pressure and the calculated compressibility for the EM-SD and EB-CS briquettes is displayed in Table 5-34. It is clear that the EM-SD briquettes exhibit a higher range of bulk densities (i.e. 46.2 to 46.6 lb/ft^3) than the EB-CS briquettes (i.e. 41.3 to 41.9 lb/ft^3). This was result was anticipated as the particle density of the EM-SD briquettes is substantially higher than the EB-CS briquettes, yet the shape is very similar. However, the compressibility of the EB-CS briquettes was found to be significantly greater than that of the EM-SD briquettes. Nonetheless, these results suggest that both types of briquettes exhibit excellent flow properties. As a result, design of bins and hoppers for reliable flow of coal-biomass briquettes is quite simple using the procedures outlined above.

Table 5-34. Bulk density and compressibility results for Emerald-sawdust (EM-SD) and Eagle Butte-corn stover (EB-CS) briquettes

Briquette Sample	**Consolidating Pressure (lb/ft^2)**	**Bulk Density (lb/ft^3)**	**Compressibility (ft^{-1})**
EM-SD	45	46.2	1.69E-04
	615	46.4	
	2415	46.6	
EB-CS	45	41.3	2.53E-04
	615	41.5	
	2415	41.9	

5.4.5.3 Characterization of Gasification Behavior

The gasification of the EM-SD and EB-CS briquettes was studied in a moving bed reactor with both pure oxygen and air as the oxidant at an oxygen to steam ratio of 2 to 1 (i.e. 1400 ml/min of air is approximately equal to 300 ml/min of oxygen). For the pure oxygen tests, oxygen was fed to the gasifier at a rate of 650 milliliters per minute and steam was fed at a rate of 1300 milliliters per minute. In contrast, air was fed to the gasifier at a rate of 1400 milliliters per minute for the second set of tests, while steam was fed at a rate of 600 milliliters per minute. The syngas was analyzed to determine the composition of hydrogen, carbon monoxide, methane and carbon dioxide. In addition, the energy content of the product gas was measured to calculate the cold gas efficiency of each gasification process. The results of these evaluations are provided in Table 5-35.

Table 5-35. Summary of gasification characterization results for Emerald-sawdust (EM-SD) and Eagle Butte-corn stover (EB-CS) briquettes (adapted from Bhagavatula, 2013)

Briquette Sample	**Oxidizing Conditions**			**Product Gas Composition**				**Cold Gas Efficiency (%)**
	Air Flow Rate (ml/min)	**Oxygen Flow Rate (ml/min)**	**Steam Flow Rate (ml/min)**	**H_2 (%)**	**CO (%)**	**CH_4 (%)**	**CO_2 (%)**	
EM-SD	--	650	1300	11.20	18.25	9.37	47.14	28.12
	1400	--	600	7.45	7.11	0.00	10.73	43.04
EB-CS	--	650	1300	19.47	24.80	3.81	49.20	45.48
	1400	--	600	13.98	10.14	0.00	10.48	63.50

The syngas produced from the reaction of pure oxygen and steam with the EM-SD briquettes had a composition of 11.20% hydrogen, 18.25% carbon monoxide, 9.37% methane and 47.14% carbon dioxide. In contrast, the syngas produced from the reaction of the same briquettes with air and steam had a composition of 7.45% hydrogen, 7.11% carbon monoxide, 0.00% methane and 10.73% carbon dioxide. Although the absolute value of the hydrogen and carbon monoxide concentrations decreased with air gasification, the ratio of hydrogen and carbon monoxide to carbon dioxide produced (i.e. $[H_2+CO]: CO_2$) increased from 0.62 to 1.36. As a result, the cold gas efficiency of the system increased from 28.12% to 43.04%. These product gas concentrations and cold gas efficiencies indicate that the EM-SD briquettes are a good gasification feedstock for the co-production of power and synthetic fuels (Bhagavatula, 2013).

The syngas produced from the reaction of pure oxygen and steam with the EB-CS briquettes had a composition of 19.47% hydrogen, 24.80% carbon monoxide, 3.81% methane and 49.20% carbon dioxide. In contrast, the syngas produced from the reaction of the same briquettes with air and steam had a composition of 13.98% hydrogen, 10.14% carbon monoxide, 0.00% methane and 10.48% carbon dioxide. Although the absolute value of the hydrogen and carbon monoxide concentrations decreased with air gasification, the ratio of hydrogen and carbon monoxide to carbon dioxide produced increased from 0.90 to 2.30. As a result, the cold gas efficiency of the system increased from 45.48% to 63.50%. The EB-CS feedstock is clearly superior to the EM-SD feedstock with respect to gasification performance. This is a direct result of the higher volatile matter content of sub-bituminous coal as compared to bituminous coal, which dramatically increases the energy conversion efficiency of the process. Also, the higher porosity of the EB-CS briquettes aids in the thermal decomposition of the feedstock, which in turn increases the cold gas efficiency. These product gas concentrations and cold gas efficiency values indicate that the EB-CS briquettes are an exceptional gasification feedstock for the co-production of power and synthetic fuels.

5.5 Summary and Conclusions

Experimental optimization of coal-biomass briquette production is an essential task to improve the strength and durability of briquettes. In support of this challenge, an exhaustive bench-scale study was conducted to examine the most significant feedstock, additive and roll press variables in coal-biomass briquette production. Additional work was performed to identify optimum process conditions for each variable, which were defined for this study as the conditions that contribute to production of coal-biomass briquettes with the greatest crushing strength and mechanical durability. In addition, work was conducted to compare and contrast the quality of briquettes composed of four coal types (i.e. 3 bituminous and 1 sub-bituminous) and five biomass types (i.e. corn stover, switchgrass, miscanthus, wheat straw and sawdust). Lastly, a comprehensive series of tests were conducted to characterize the physical properties, flow properties and gasification behavior of selected coal-biomass briquettes to verify the enhanced quality of co-briquetted feedstocks.

As a result of this study, the following conclusions can be drawn regarding bench-scale production of coal-biomass briquettes over the range of variables evaluated:

- Biomass content is the most statistically significant mixture variable with regard to the particle density of coal-biomass briquettes. For all types of coal and biomass evaluated, an increase in biomass content causes a direct reduction in particle density.
- Biomass content is the most statistically significant mixture variable with regard to the crushing strength of binderless coal-biomass briquettes. For all types of coal and biomass evaluated, an increase in biomass content causes a direct increase in crushing strength.
- Water content is the most statistically significant mixture variable with regard to the mechanical durability of binderless coal-biomass briquettes. For all types of coal and biomass evaluated, a clear optimum water content can be identified where mechanical durability reaches a maximum value.
- Biomass top size is not a statistically significant mixture variable with regard to the particle density, crushing strength and mechanical durability of coal-biomass briquettes.
- Differences in the quality of coal-biomass briquettes composed of different types of bituminous coal with identical top sizes can be attributed to differences in the distribution modulus and ash content of the coals. Briquette quality increases with a corresponding increase in distribution modulus and a corresponding decrease in ash content.
- Starch content is a very statistically significant mixture variable with regard to the crushing strength and mechanical durability of coal-biomass briquettes. An increase in starch content causes a direct increase in crushing strength and mechanical durability.

- Cure time is a statistically significant process variable with regard to the crushing strength of coal-biomass briquettes. A period of 6 days is recommended to cure the briquettes for which this variable was studied.
- Corn stover exhibits the best properties of the biomass types studied with regard to the crushing strength and mechanical durability of coal-biomass briquettes.
- Roll torque is the most statistically significant roll press operating variable with regard to the particle density, crushing strength and mechanical durability of coal-biomass briquettes. An increase in roll torque causes a direct increase in particle density, crushing strength and mechanical durability.
- Roll force is a statistically significant roll press operating variable with regard to the particle density, crushing strength and mechanical durability of coal-biomass briquettes. An increase in roll torque causes a direct increase in particle density, crushing strength and mechanical durability.
- Roll speed is a statistically significant roll press operating variable with regard to the particle density of coal-biomass briquettes. An increase in roll speed causes a direct reduction in particle density.
- Binderless coal-biomass briquettes produced at optimized conditions exhibit very high crushing strength and mechanical durability values, which indicate that the briquettes would largely remain competent in the presence of forces encountered in handling, storage and transportation.
- Binderless coal-biomass briquettes produced at optimized conditions exhibit poor water resistance, which indicates that additional investigation of this matter is required.
- Binderless coal-biomass briquettes produced at optimized conditions exhibit excellent flow properties, which indicates that proper hopper design is straightforward.
- Binderless coal-biomass briquettes produced at optimized conditions exhibit excellent gasification behavior with regard to product gas composition and cold gas efficiency. This confirms that coal-biomass briquettes are exceptional gasification feedstocks for the co-production of power and synthetic fuels.

5.6 References

Basu, P., Butler, J., & Leon, M. (2011). Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. *Renewable energy, 36*(1), 282-288.

Bhagavatula, A. (2013). [Gasification of coal-biomass briquettes]. Unpublished raw data.

Capes, C. (1980). Particle size enlargement. In J. Williams & T. Allen (Eds.), *Handbook of powder technology* (Vol. 1). Amsterdam, Netherlands: Elsevier Scientific Publishing Company.

Dec, R., & Komarek, R. (1997). Testing and scaling up compaction process using small laboratory roll press. *Proceedings of the 25th biennial conference of the Institute for Briquetting and Agglomeration*, 97-106, Albuquerque, NM: Institute for Briquetting and Agglomeration.

Drzymala, Z. (1993). *Industrial briquetting: Fundamentals and methods*. Warsaw, Poland: Polish Scientific Publishers.

Fernando, R. (2009). *Co-gasification and indirect cofiring of coal and biomass*. London, England: IEA Clean Coal Centre.

Honaker, R., Parekh, B., Taulbee, D., & Tao, D. (2005). *Premium fuel production from mining and timber waste using advanced separation and pelletizing technologies*. Washington, DC: U.S. Department of Energy.

Komarek, R. (1991). Binderless briquetting of peat, lignite, sub-bituminous and bituminous coals in roll press. *Proceedings of the 22nd biennial conference of the Institute for Briquetting and Agglomeration*, 233-242, Albuquerque, NM: Institute for Briquetting and Agglomeration.

Pietsch, W. (2002). *Agglomeration processes: Phenomena, technologies, equipment*. Weinheim, Germany: Wiley-VCH.

Rumpf, H. (1962). The strength of granules and agglomerates. In W. Knepper (Ed.), *Agglomeration*, 379-418. New York, NY: John Wiley and Sons.

Sami, M., Annamalai, K., & Wooldridge, M. (2001). Co-firing of coal and biomass fuel blends. *Progress in energy and combustion science, 27*(2), 171-214.

Scott, G., & Kilgour, D. (1969). The density of random close packing of spheres. *Journal of physics D: Applied physics, 2*(6), 863-866.

Shimasaki, K., Deguchi, T., Sugita, S., & Makino, E. (2003). *U.S. Patent No. 6,626,966*. Washington, DC: U.S. Patent and Trademark Office.

Taulbee, D., Neathery, J., Patil, D., Sowder, N., O'Daniel, B., & Montross, M. (2010). Combustion of Briquettes and Fuels Pellets Prepared from Blends of Biomass and Fine Coal. In R. Honaker (Ed.), *International coal preparation congress 2010 conference proceedings*. Littleton, CO: Society for Mining, Metallurgy, and Exploration.

Taulbee, D., Patil, D., Honaker, R., & Parekh, B. (2009). Briquetting of coal fines and sawdust Part I: Binder and briquetting-parameters evaluations. *International journal of coal preparation and utilization, 29*(1), 1-22.

Chapter 6

Water–Resistant Briquette Production

6.1 Abstract

A study was conducted to evaluate the potential for several proprietary wood-derived chemicals to improve the water resistance of coal-biomass briquettes. Two methods for application of the chemicals were examined: (1) conventional binder application as a powder prior to briquette production and (2) briquette coating. For the conventional binder application method, five of the six wood-derived chemicals significantly improved the water resistance of the coal-biomass briquettes. The best performing wood-derived chemical improved the water resistance of the briquettes by 63% and 77% at binder contents of 2.5% and 5.0%, respectively. For the briquette coating technique, initial results indicated that each of the wood-derived chemicals outperformed briquettes with no coating and four of the five chemicals outperformed briquettes with a paraffin wax coating. The best performing wood-derived chemical with respect to water resistance improved the water resistance of the briquettes by 97%. Similarly, the final mechanical durability of briquettes was improved by approximately 400% with the best performing wood-derived chemical. A series of detailed coating evaluations were performed which further exemplify the benefits of the wood-derived chemical coatings and validated the results of the preliminary tests. The detailed evaluations also provide insight to the influence of the chemical coatings on other important properties of coal-biomass briquettes. Furthermore, the results of the detailed evaluations provide evidence that these coatings can be successfully used to improve the durability and water resistance of briquettes comprised of different coal types (i.e. bituminous and sub-bituminous) and different biomass types (i.e. sawdust and corn stover). However, selection of the optimum wood-derived chemical for any coal-biomass briquette application depends primarily on the cost of each chemical and the desired level of briquette durability and water resistance. Therefore, it is recommended that the chemical coating type and application method be chosen independently for every unique coal-biomass briquette operation.

6.2 Introduction

6.2.1 Problem Statement

Co-utilization of biomass with coal in existing coal-fired facilities presents a unique opportunity to reduce greenhouse gas emissions and increase energy production from renewable resources. Significant interest in this opportunity has led to more than 150 coal-fired power stations across the world co-firing coal and biomass on a commercial or trial basis as of 2009 (Fernando, 2009). These co-firing experiences have revealed a number of technical challenges including upstream issues, such as biomass availability, transportation, storage, and handling, as well as problems encountered during energy conversion, such as fouling, corrosion, inconsistent feeding and segregation (Basu et al., 2011; Sami et al., 2001). Recent studies suggest that many of these challenges can be mitigated by reconstituting coal-biomass mixtures into larger particles. Specifically, roll press briquetting has been investigated to produce homogeneous, free-flowing feedstocks that minimize handling and segregation problems often encountered with combustion and gasification systems (Taulbee et al., 2010; Honaker et al., 2005). However, the absorption of water and subsequent disintegration of coal-biomass briquettes remains a major limitation to the design of low-cost storage and transportation systems for co-firing operations. As a result, there is a growing interest in the development of economically feasible methods to sustain the physical and mechanical integrity of fuel briquettes in the presence of water (Wang et al., 2011; Motaung et al., 2007; Saglam et al., 1990).

6.2.2 Briquette Water Resistance

Several different methods have been investigated to improve the water resistance of fuel briquettes. The most commonly employed method is coating individual fuel particles with a chemical binder prior to briquette production. For example, Bratton et al. (2010) evaluated a novel fine coal briquetting process that included the application of a proprietary binder to improve the strength and weathering properties of coal briquettes. The authors found that a wetting and drying cycle had minimal impact on the durability of coal briquettes produced with the proprietary binder. However, the cost of the novel binder is not discussed and thus is likely a limiting factor to this approach. Furthermore, Taulbee et al. (2009) investigated twelve different binders including molasses, guar gum, corn starch, wheat starch and paper sludge to improve the strength and water resistance of briquettes produced with fine coal and sawdust. The study found that the compressive strength of the coal-sawdust briquettes was significantly reduced after submergence in water for eight hours. These and other water soluble binders are generally not recommended to improve the water resistance of fuel briquettes (Mills, 1908).

Another method that has been investigated to improve the water resistance of fuel briquettes is coating with water insoluble chemicals. Chemical coatings can be applied by many different techniques including dipping, brushing, flow coating, roller coating and spraying (Freitag, 1996). Of these methods, dipping and spraying present the greatest opportunity for fuel briquette coating due to the size and shape of briquettes. Both methods generally require heating the material to reduce the viscosity, which leads to a reduction in film thickness and thus a reduction in chemical consumption. When the materials are heated prior to application, these techniques are referred to as hot dipping and hot spraying (Freitag, 1996).

Specific techniques for coating briquettes have been disclosed in patents filed in the United States and Australia. Goss (1938) patented a hot spraying mechanism for applying paraffin wax to wood briquettes for the purpose of protecting against the absorption of moisture. Lundwall (1939) developed a machine that employs the dipping technique to coat briquettes composed of metal cuttings with a mixture of water and Portland cement. Furthermore, Trechock (1973) described a spray coating method to overcome the problem of airborne dust associated with rail shipment of coke briquettes. Using this method, the briquettes are treated with an aqueous dispersion of solid film former such as sodium silicate, blackstrap molasses, turpentine resins and pitches derived from black coal or petroleum. Bates et al. (1988) disclosed a method of coating briquettes composed of brown coal, bituminous coal, anthracite or other carbonaceous materials such as wood. The patent describes a water based emulsion comprising an acrylic polymer based on acrylic ester monomer that can be applied by spraying or dipping. Finally, Shimasaki et al. (2003) developed a method of producing coal briquettes with high strength and excellent water resistance by mixing starch with the coal particles prior to briquette production and coating the surface of the briquettes with a heavy oil component simultaneously with or after briquette formation.

6.2.3 Research Objective

The purpose of this study was to evaluate the potential for several proprietary wood-derived chemicals to improve the water resistance of coal-biomass briquettes. A preliminary screening study was conducted to examine the technical feasibility of two application methods for each wood-derived chemical: (1) conventional binder application, wherein chemicals were mixed with coal and biomass particles prior to briquette production, and (2) coating application, wherein coal-biomass briquettes were dipped in heated chemicals to coat the exterior surface of the briquettes. To establish the relative performance of each wood-derived chemical for both application methods, additional evaluations were performed without chemicals and with commonly used chemicals. An additional series of detailed coating evaluations were conducted on optimal co-firing briquette formulations to validate the performance of the wood-derived chemical coatings and to measure several additional properties of the coated briquettes.

6.3 Experimental

6.3.1 Materials

All briquettes produced for the preliminary screening study were composed of bituminous coal and corn stover. The coal was obtained from the clean coal stockpile of Alpha Natural Resources' Emerald mine preparation plant in Waynesburg, Pennsylvania (referred to as Emerald coal). Prior to briquetting, the coal was successively crushed in a jaw crusher, roll crusher and a grinder. The coal was then screened to a top size of one millimeter using a Uniflex two-deck screen, air dried for one week, split into two-kilogram lots and stored in sealed plastic bags. The moisture content of the coal prior to briquette production was 1.60% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The size distribution of the crushed coal was measured by wet screening and analyzed using the Rosin-Rammler equation (Figure 6-1). Based on this analysis, the Emerald coal was found to have a mass median diameter of 301 microns, a size modulus of 0.43 and a distribution modulus of 1.02. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the coal (Table 6-1). Notable results of the analyses include a moisture and ash free heating value of 15,268 Btu/lb, an ash content of 9.37% (dry basis) and a sulfur content of 3.04% (dry basis).

Two types of briquettes were produced for the detailed coating evaluations. The first type of briquettes were composed of the Emerald coal and sawdust, while the second type of briquettes were composed of a sub-bituminous coal and corn stover. The sub-bituminous coal was obtained from the raw coal stockpile of Alpha Natural Resources' Eagle Butte mine in Gillette, Wyoming (referred to as Eagle Butte coal). Prior to briquetting, this coal was successively crushed in a jaw crusher, roll crusher and grinder. The coal was then screened to a top size of one millimeter using a Uniflex two-deck screen, air dried for one week, oven dried at 105 degrees Celsius for 48 hours, split into two-kilogram lots and stored in sealed plastic bags. The moisture content of the Eagle Butte coal prior to briquette production was 1.70% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. The size distribution was again analyzed using the Rosin-Rammler equation (Figure 6-1), which indicated that the coal had a mass median diameter of 295 microns, a size modulus of 0.41 and a distribution modulus of 1.16. Ultimate and proximate analyses were also conducted to characterize the chemical composition of the Eagle Butte coal (Table 6-1). Notable results of the analyses include a moisture and ash free heating value of 12,474 Btu/lb and an ash content of 7.89% (dry basis).

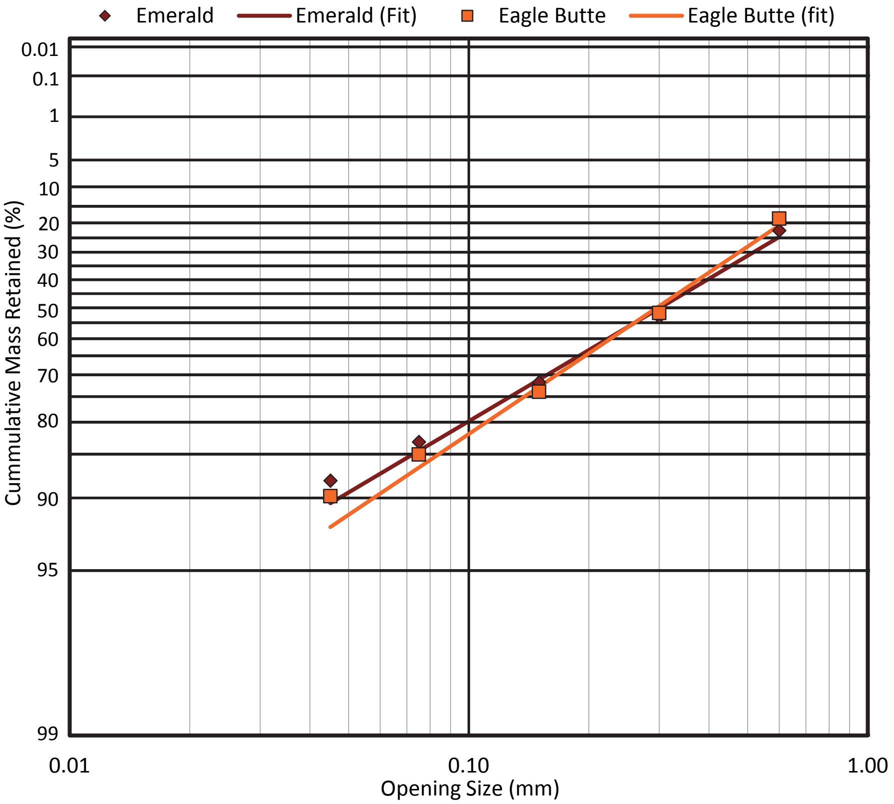


Figure 6-1. Particle-size distribution of coal samples

Table 6-1. Chemical properties of coal and biomass feedstocks

Chemical Property	Emerald		Eagle Butte		Corn Stover		Sawdust	
	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis
Moisture (%)	4.28	--	29.08	--	12.95	--	14.08	--
Ash (%)	8.97	9.37	5.60	7.89	4.36	5.01	0.22	0.26
Sulfur (%)	3.04	3.18	0.64	0.90	0.09	0.10	0.03	0.03
Volatiles (%)	37.59	39.27	40.89	57.66	71.49	82.13	78.64	81.53
Fixed Carbon (%)	49.16	51.36	24.43	34.45	11.19	12.86	7.05	8.21
Carbon (%)	74.26	77.58	47.08	66.38	46.37	53.27	51.66	60.12
Hydrogen (%)	4.91	5.13	4.00	5.64	4.94	5.67	5.40	6.28
Nitrogen (%)	1.39	1.45	0.70	0.99	0.54	0.62	0.02	0.02
Oxygen (%)	3.15	3.29	12.91	18.20	30.75	35.33	28.60	33.29
HHV (Btu/lb)	13,245	13,837	8,149	11,490	7,028	8,073	8,110	9,439
MAF HHV (Btu/lb)	--	15,268	--	12,474	--	8,499	--	9,464

The corn stover used for this study was obtained as large round bales from a farm in Blacksburg, Virginia operated by Virginia Tech. The bales were processed in a Jordan Reduction Solutions knife mill equipped with a 4.75-millimeter screen and stored in a sealed bulk bag prior to use. Particle-size distribution was not determined for the processed corn stover because previous attempts to collect this information has indicated that the results are skewed due to the elongated shape of the milled particles (i.e. elongated particles tend to screen differently than round particles). Prior to briquette production the moisture content of the corn stover was 11.35% (dry basis), which was determined by oven drying at 105 degrees Celsius for 24 hours. Ultimate and proximate analyses were conducted on the corn stover sample, the results of which are presented in Table 6-1. Notable results of the analyses include a moisture and ash free heating value of 8,499 Btu/lb, an ash content of 5.01% (dry basis) and a sulfur content of 0.10% (dry basis).

The sawdust used for this study was kiln-dried eastern white pine dust and shavings, which was obtained in bulk bags from Turman Sawmill in Hillsville, Virginia. Prior to briquette production, the sawdust was screened to a top size of 1.2 millimeters using a Sweco vibrating separator and stored in five gallon buckets. Again, particle-size distribution was not determined due to the inherently low accuracy of such measurements. The moisture content of the sawdust was reduced to 0.20% by oven drying at 105 degrees Celsius for 24 hours. The ultimate and proximate analyses results for the sawdust sample are displayed in Table 6-1. Notable results of the analyses include a moisture and ash free heating value of 9,464 Btu/lb, an ash content of 0.26% (dry basis) and a sulfur content of 0.03% (dry basis).

Several different chemicals were evaluated throughout this study for the ability to improve the water resistance of coal-biomass briquettes. For conventional binder tests, the chemicals evaluated included pregelatinized wheat starch, obtained from Archer Daniels Midland Company, and six proprietary wood-derived chemicals provided by Georgia-Pacific Chemicals (G16, G88, G89, G90, G97 and G98). All of the wood-derived chemicals were solid at room temperature except G16, which was a highly viscous liquid at room temperature. For briquette coating tests, the chemicals evaluated included paraffin wax and the five solid-state chemicals provided by Georgia-Pacific (G88, G89, G90, G97 and G98). The G97 chemical was used for the additional detailed coating evaluations because of the performance and relative cost of this chemical.

6.3.2 Briquette Production

Pill-shaped briquettes (approximately 43 x 19 x 14 mm) were produced with a Komarek B-100R laboratory roll press equipped with 13-centimeter diameter rolls. The machine is comprised of two counter rotating rolls, two hydraulic cylinders, a horizontal tapered screw and a paddle feeder. A schematic diagram of the roll press and the laboratory installation are depicted in Figure 5-6.

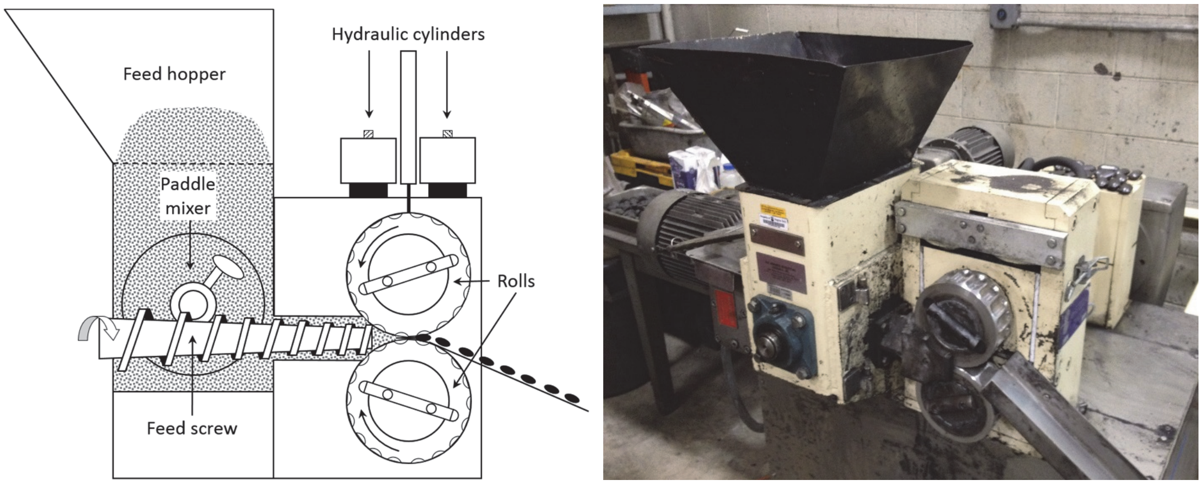


Figure 6-2. Komarek B-100R roll press (left) schematic diagram (modified from Guigon & Simon, 2003) and (right) laboratory installation

The hydraulic cylinders control the position of the upper roll and thus control the gap between the rolls. The paddle feeder is driven by a fixed speed motor and distributes the material to the horizontal screw that in turn feeds material to the rolls. The counter rotating rolls and the horizontal screw are driven by variable speed motors, which enable adjustment of the torque applied to the material from the rolls and screw. For all laboratory experiments, the rolls of the B-100R were driven at a motor speed of 450 rotations per minute with 100 kilonewtons of hydraulic force. The horizontal screw speed was adjusted during briquette production to maintain a roll torque of approximately 1800 newton-meters.

For conventional binder evaluations, briquettes were produced in two-kilogram batches at a target moisture content of 5 percent with 20 percent corn stover and either 80 percent coal (no binder), 77.5 percent coal (2.5 percent binder) or 75 percent coal (5 percent binder). Prior to briquette production, each wood-derived chemical was crushed and screened to a top size of one millimeter to facilitate mixing in powder form. The coal, corn stover and binding additives were mixed for five minutes in a Hobart A200 20-quart commercial mixer and directly co-briquetted in the Komarek B-100R. Immediately after formation, the briquettes were screened across a Sweco vibrating separator equipped with a 0.5-inch screen to remove excess fines. Finally, the briquettes were set out for 24 hours to facilitate curing of the binder prior to evaluations for water content, particle density, mechanical durability, crushing strength and water resistance. The results of these evaluations are discussed in Section 6.4.1.

For the preliminary briquette coating evaluations, a single six-kilogram batch of briquettes was produced with 20 percent corn stover and 80 percent coal at a target moisture content of five percent. The coal and corn stover were mixed for five minutes in a Hobart A200 20-quart commercial mixer and briquetted in the Komarek B-100R. As outlined above, these briquettes were also screened immediately after formation to remove excess fines and set out for 24 hours to maintain consistency in the experimental approach. For each chemical evaluated, coating of briquettes was conducted in two batches for two separate series of evaluations: (1) water uptake tests and (2) a series of sequential mechanical durability and water uptake tests. Each chemical was heated in a 250-milliliter glass beaker to 160 degrees Celsius in a laboratory oven operated at 200 degrees Celsius. Briquettes were submerged individually into the heated chemical for approximately two seconds and placed on a perforated platform inside the oven for ten minutes. Next, the perforated platform was removed from the oven, each briquette was flipped over and the platform was placed back into the oven for an additional five minutes. The purpose of placing the briquettes on the perforated platform inside the oven was to allow excess material to drip off the briquettes to reduce the applied chemical dosage. Finally, the coated briquettes were removed from the oven and set out for one hour to permit cooling of the applied chemical prior to evaluations for water resistance, mechanical durability and chemical dosage. Results of these evaluations are discussed in Section 6.4.2.

For the detailed coating evaluations, Emerald-sawdust (EM-SD) and Eagle Butte-corn stover (EB-CS) briquettes were produced in eight-kilogram batches with 70 percent coal and 30 percent biomass. The EM-SD and EB-CS briquettes were produced at target moisture contents of 2.20 and 18.50 percent, respectively. These moisture contents were selected using the optimization tools featured in the statistical models presented in Chapter 5. After production, the briquettes were split into two separate batches: one for coating and the other for directly testing without a coating. Six batches of 50 briquettes were coated with the G97 chemical following the same procedure described for the preliminary coating tests. After cooling for one hour, both the coated and uncoated briquettes were evaluated for tensile strength, crushing strength, elasticity, mechanical durability, attritability, friability, water content, particle density, water resistance and chemical dosage. Results of these evaluations are discussed in Section 6.4.3.

6.3.3 Briquette Characterization

6.3.3.1 Water Content

The water content of briquettes was determined by drying five briquettes for 24 hours at 105 degrees Celsius in a drying oven. The mass of water in the briquettes was calculated by subtracting the dry mass of the briquettes from the initial mass before drying. The water content was then calculated by:

$$w = m_w / m_s \qquad \text{(Eq. 6-1)}$$

where w is the water content, m_w is the mass of water and m_s is the dry mass of the briquettes. Water content was measured after the 24-hour curing period for the conventional binder tests and after the one hour cooling period for the coating tests. Water content of the feed material was measured prior to briquette production using an AND MF-50 moisture analyzer set at 105 degrees Celsius. Feed samples were dried until the change in mass was reduced to 0.05 percent per minute, at which point the displayed value was reported as the water content of the feed.

6.3.3.2 Particle Density

The particle density of briquettes was calculated by first measuring the initial (wet) density and then calculating the dry density (ρ_d) based on the measured water content by:

$$\rho_d = \rho_{wet} / (1 + w) \qquad \text{(Eq. 6-2)}$$

where ρ_{wet} is the calculated wet density and w is the calculated water content. A density determination rig was used to measure the apparent mass of briquettes in a solution of water and detergent. Wet density (ρ_{wet}) was then calculated by:

$$\rho_{wet} = (m_a/(m_a - m_b))\rho_w \quad \text{(Eq. 6-3)}$$

where m_a is the mass of the briquette in air, m_b is the apparent mass of the briquette in water and ρ_w is the density of the liquid. Wet density was measured after the 24-hour curing period for the conventional binder tests and after the one hour cooling period for the coating tests. For both cases, the procedure was repeated for 10 briquettes and the average of the 10 values was reported as the dry particle density.

6.3.3.3 Mechanical Durability

The mechanical durability of briquettes was measured by tumbling 20 briquettes for five minutes at 40 rotations per minute in a 12-inch PVC cylinder equipped with three 2-inch lifters. The briquettes were then removed from the cylinder and screened in a Ro-tap sieve shaker for 30 seconds over a 4.75-millimeter sieve. The mechanical durability (*MD*) of the briquettes was then calculated by:

$$MD = 100 \times \left(m_{final}/m_{initial}\right) \quad \text{(Eq. 6-4)}$$

where m_{final} is the mass of briquettes retained on the 4.75-millimeter sieve and $m_{initial}$ is the initial mass of the briquettes prior to durability testing.

6.3.3.4 Crushing Strength

The crushing strength of briquettes was determined using a Mark-10 M5-500 digital force gauge fitted with a four-inch diameter aluminum plate. The force gauge was mounted to a Mark-10 TSA750 manual test stand equipped with a one-inch diameter aluminum plunger that was used to apply force to the briquettes until failure. The force gauge was configured with a break detect feature which stops data acquisition once the applied force drops to 95 percent of the maximum force attained during each test. The crushing strength of each briquette was then reported as the maximum force attained during each test. To improve the accuracy of readings, an aluminum bar (51 x 8 x 8 millimeters) was placed upon the aluminum plate with each briquette then placed atop and parallel to the bar for testing. Evaluations were performed on 25 briquettes and the crushing strength was reported as the average of the 25 values.

6.3.3.5 Water Resistance

The water resistance of briquettes was determined using an apparatus designed to simulate precipitation that briquettes may encounter during storage and transportation. To calculate water resistance, five briquettes were subjected to a 15-second water spray at a flow rate of three gallons per minute from a height of 18 inches above the briquettes. Water resistance was reported as the water uptake of the briquettes that resulted from this spray test, with water uptake (u) calculated by:

$$u = \left(m_f - m_i\right)/m_i \qquad \text{(Eq. 6-5)}$$

where m_i is the initial mass of briquettes and m_f is the mass of briquettes after the water spray.

6.3.3.6 Chemical Dosage

For coating tests, the chemical dosage applied to the briquettes was determined by calculating the mass of briquettes before and after the application of the chemical coating. The mass of each chemical coating was calculated by subtracting the coated mass of the briquettes from the initial mass. The chemical dosage (d) was then calculated by:

$$d = m_c/m_b \qquad \text{(Eq. 6-6)}$$

where m_c is the mass of the chemical coating and m_b is the initial mass of the briquettes. Chemical dosage was measured immediately after the one hour cooling period.

6.3.3.7 Friability

The friability of briquettes was measured by dropping 20 briquettes twice from a height of six feet onto a steel plate using a modified shatter test device. The briquettes were then screened for 30 seconds in a Ro-tap sieve shaker over a 4.75-millimeter sieve. The friability (F) of the briquettes was then calculated by:

$$F = 100 \times \left(m_{final}/m_{initial}\right) \qquad \text{(Eq. 6-7)}$$

where m_{final} is the mass of briquettes retained on the 4.75-millimeter sieve and $m_{initial}$ is the initial mass of the briquettes prior to friability testing.

6.3.3.8 Attritability

The attritability of briquettes was measured by screening 20 briquettes for five minutes in a Ro-tap sieve shaker over a 4.75-millimeter sieve. The attritability (A) of the briquettes was then calculated by:

$$A = 100 \times (m_{final}/m_{initial}) \qquad \text{(Eq. 6-8)}$$

where m_{final} is the mass of briquettes retained on the 4.75-millimeter sieve and $m_{initial}$ is the initial mass of the briquettes prior to attritability testing.

6.3.3.9 Tensile Strength

To measure tensile strength, individual briquettes were crushed between two flat compression plates with the briquette standing tall (i.e. with the long axis of the briquette parallel to the axis of force application). This was accomplished using a Mark-10 M5-500 digital force gauge fitted with a four-inch diameter aluminum plate. The force gauge was mounted to a Mark-10 TSA750 manual test stand equipped with a one-inch diameter aluminum plunger that was used to apply force to the briquettes until failure. The force gauge was configured with a break detect feature which stops data acquisition once the applied force drops to 95 percent of the maximum force attained during each test. Tensile strength of each briquette was then designated as this maximum force. Evaluations were performed on 25 briquettes and the tensile strength was reported as the average of the 25 values.

6.3.3.10 Elasticity

To measure the elasticity of briquettes, the same equipment and procedure that was described for crushing strength evaluations was utilized. However, in this instance the test stand was fitted with a Mark-10 ESM001 digital travel display to record the displacement of briquettes while the load was applied by the plunger. This installation was required to determine the spring constant (*SC*) of the briquettes, which is calculated by:

$$SC = (F_2 - F_1)/(x_2 - x_1) \qquad \text{(Eq. 6-9)}$$

where F_2 is the maximum force applied during elastic deformation, F_1 is the minimum force applied during elastic deformation, x_2 is the displacement that corresponds with F_2, and x_1 is the displacement that corresponds with F_1. These values are obtained from the force versus displacement curve that is produced during data acquisition. The force gauge was configured to record two force and displacement data points per second with the break detect feature activated. Evaluations were performed on 25 briquettes and the elasticity was reported as the average calculated spring constant value for all 25 measurements.

6.4 Results and Discussion

6.4.1 Conventional Binder Evaluations

A series of conventional binder tests were conducted for the preliminary performance evaluation of six wood-derived chemicals in powder form when mixed with coal and biomass prior to briquette formation. For comparison, two additional sets of briquettes were produced with pregelatinized wheat starch and one additional batch was produced with no binder. For each chemical evaluated, briquettes were produced with a binder content of 2.5 percent and 5.0 percent. The evaluations performed for the conventional binder tests included water content, dry density, crushing strength, mechanical durability and water uptake. A detailed summary of the results of these evaluations are presented in Table 6-2. One observation from briquette production and evaluation was the poor performance of the G16 binder. Although the water content of the G16 briquettes was similar to others, the liquid state of the G16 binder shifted the location of optimum moisture for maximum compaction density and thus reduced the strength and durability of the briquettes.

Table 6-2. Summary of conventional binder evaluation results

Chemical Binder	Binder Content (%)	Water Content		Particle Density (g/cm^3)	Crushing Strength (lb_f)	Mechanical Durability (%)	Water Uptake (%)
		Feed	Briquettes				
No binder	0.0	0.051	0.027	1.16	295	92.5	15.8
Starch	2.5	0.053	0.032	1.15	362	95.4	19.6
Starch	5.0	0.050	0.034	1.16	406	96.0	21.7
G16	2.5	0.038	0.029	1.02	111	29.9	165.2
G16	5.0	0.038	0.028	1.01	61	26.3	190.6
G88	2.5	0.049	0.030	1.13	266	90.5	6.4
G88	5.0	0.045	0.027	1.13	244	90.2	7.0
G89	2.5	0.046	0.026	1.15	300	93.5	6.4
G89	5.0	0.050	0.026	1.15	304	93.8	5.9
G90	2.5	0.048	0.029	1.14	281	90.3	5.8
G90	5.0	0.049	0.023	1.14	276	88.7	3.7
G97	2.5	0.045	0.026	1.14	302	92.3	9.0
G97	5.0	0.044	0.027	1.14	336	91.4	5.8
G98	2.5	0.049	0.027	1.15	293	91.0	6.4
G98	5.0	0.044	0.027	1.12	337	90.7	5.4

Figure 6-3 shows the dry density values for each binder type and dosage. From this figure it is clear that the binderless briquettes had the greatest dry density (1.16 g/cm^3) and the addition of each binder led to a reduction in dry density. One possible explanation for this result is the reduction in average particle density that results from addition of binding additives with a lower density than coal. The only exception to this finding occurred with the addition of five percent starch, which also produced a dry density of 1.16 g/cm^3. For five of the seven binder types, the increase in binder content from 2.5 percent to 5.0 percent resulted in a reduction of the dry density of the briquettes. This further exemplifies the conclusion that the addition of a lower density wood-derived chemical will reduce the dry density of coal-biomass briquettes. Again, the only significant exception was the starch briquettes, which increased in density with an increase in binder content from 2.5 percent to 5.0 percent. Overall, the starch binder outperformed each of the wood-derived chemicals with respect to dry density. However, binderless briquetting with feed moisture optimization remains the best technique to maximize the dry density of coal-biomass briquettes.

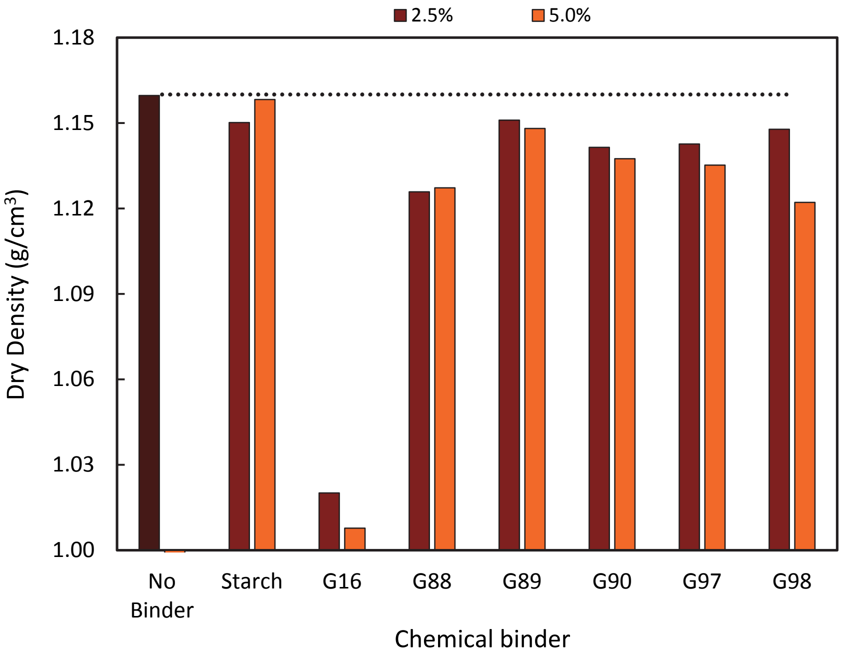


Figure 6-3. Dry density of briquettes with conventional binder application

The variations in briquette crushing strength that resulted from addition of each chemical binder are displayed in Figure 6-4. Several of the briquettes with added binder exhibited higher crushing strength than the binderless briquettes (295 lb$_f$), including those produced with starch (362, 406 lb$_f$), G89 (300, 304 lb$_f$), G97 (302, 336 lb$_f$) and G98 (293, 337 lb$_f$). The crushing strength of briquettes produced with the G16 chemical was significantly lower than each of the other batches (111, 61 lb$_f$), which again is thought to be the direct result of a shift in the location of optimum moisture for maximum compaction due to the liquid state of the chemical. The incremental addition of the wood-derived chemicals from 2.5 percent to 5.0 percent showed mixed results with respect to briquette crushing strength. Crushing strength of briquettes produced with three of the chemicals (i.e. G16, G88 and G90) decreased with a corresponding increase in binder content. Conversely, the crushing strength of briquettes produced with the other three wood-derived chemicals (i.e. G89, G97 and G98) increased with an increase in binder content. This shows that briquettes produced with binders that exceed the strength of their binderless counterpart at a low binder dosage will continue to increase in strength with an increase in binder content. Likewise, briquettes produced with binders that exhibit inferior strength than their binderless counterpart at low binder dosages will continue to decrease in strength with an increase in binder content. Overall, the starch binder outperformed each of the wood-derived chemicals with respect to crushing strength.

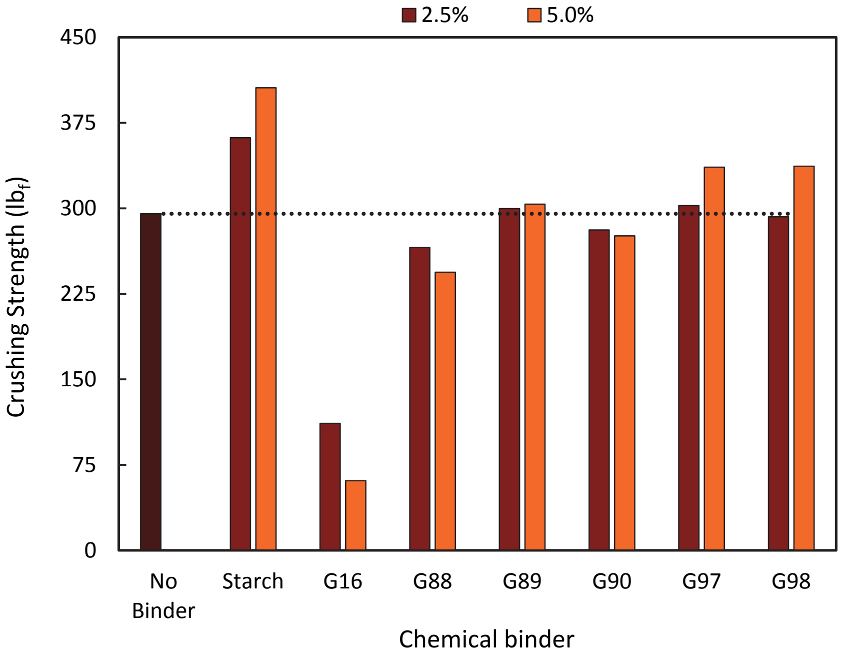


Figure 6-4. Crushing strength of briquettes with conventional binder application

The mechanical durability results for each chemical binder are displayed in Figure 6-5. Only the starch (95.4, 96.0%) and G89 (93.5, 93.8%) briquettes exhibited greater mechanical durability than the binderless briquettes (92.5%). Except for the G16 chemical, all of the other wood-derived chemicals produced briquettes with a mechanical durability slightly less than the binderless briquettes (88.7-92.3%). Similar to the crushing strength results, briquettes produced with binders that exceed the durability of their binderless counterpart at a low binder dosage continue to increase in durability with an increase in binder content. Likewise, briquettes produced with binders that exhibit inferior durability than their binderless counterpart at low binder dosages continue to decrease in durability with an increase in binder content. Overall, the starch binder outperformed each of the wood-derived chemicals with respect to mechanical durability.

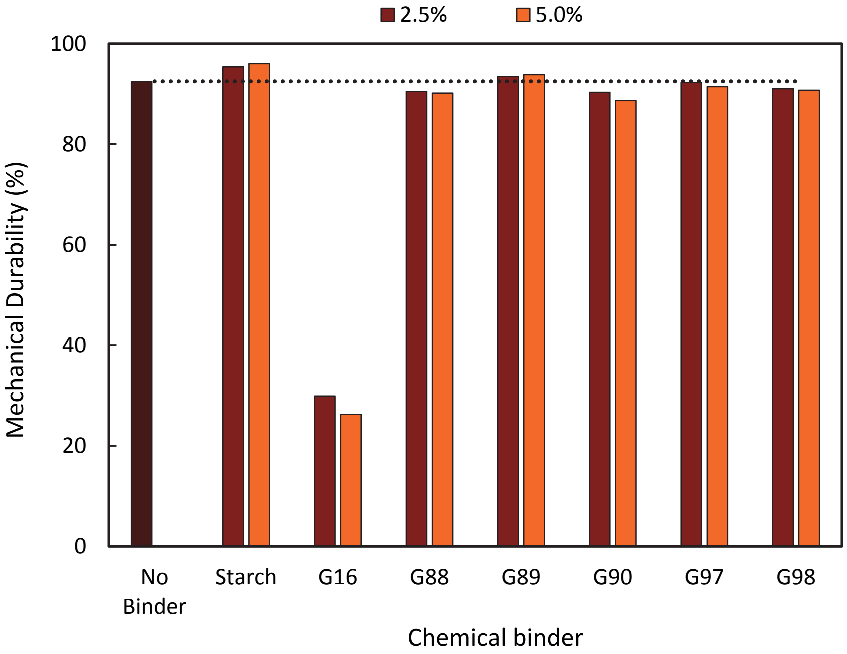


Figure 6-5. Mechanical durability of briquettes with conventional binder application

Figure 6-6 provides a visual representation of the water uptake results for binderless briquettes and those produced with each of the chemical binders. In this chart, a lower value is desirable as it corresponds to less water absorbed during the simulated rainfall period. The binderless briquettes absorbed less water (15.8%) than the starch briquettes (19.6, 21.7%) and the G16 briquettes (165.2, 190.6%). Conversely, briquettes produced with the other five wood-derived chemicals absorbed less water than the binderless briquettes, and thus improved the water resistance. The best performing wood-derived chemical was G90. This chemical produced briquettes with a water uptake of 5.8% and 3.7% at binder contents of 2.5 percent and 5.0 percent, respectively. This represents a 63% improvement in water resistance at 2.5 percent binder content and a 77% improvement in water resistance at a binder content of 5.0 percent. Although the briquettes produced with wood-derived chemicals were outperformed by the starch briquettes with respect to density, strength and durability, the significant improvement in water resistance achieved by the addition of G88, G89, G90, G97 and G98 presents a unique opportunity to improve coal-biomass briquette quality in the presence of water.

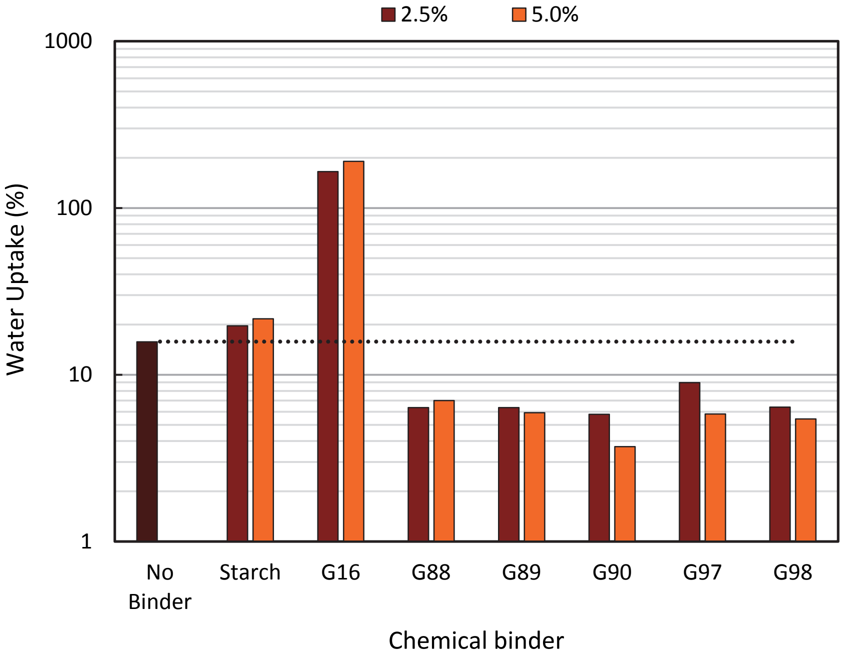


Figure 6-6. Water uptake of briquettes with conventional binder application

6.4.2 Preliminary Coating Evaluations

An additional series of tests were conducted to evaluate the performance of the five solid-state wood-derived chemicals as a coating agent applied to the exterior of coal-biomass briquettes. For comparison, additional tests were performed with no coating and with paraffin wax as the coating agent. For each type of chemical coating, two sets of evaluations were conducted: (1) chemical dosage and water uptake measurements for five briquettes, and (2) chemical dosage and a series of mechanical durability and water uptake measurements for 20 briquettes. The series of durability and water uptake tests included an initial mechanical durability test followed by water uptake evaluation of the plus 4.75-millimeter material, followed by another durability test, followed by another water uptake evaluation of the plus 4.75-millimeter material, followed by a final mechanical durability test. The results of these evaluations are included in Table 6-3. The weathered mechanical durability values listed in Table 6-3 represent the total durability of the briquettes after the series of water uptake and durability tests, as calculated by the product of each mechanical durability test result. Similarly, the weathered water uptake values listed in Table 6-3 represent the total water uptake of the briquettes after the series of water uptake and mechanical durability tests, as calculated by the product of the two water uptake test results.

Table 6-3. Summary of preliminary coating evaluation results

Chemical Coating	Set 1		Set 2				
	Chemical Dosage (%)	Water Uptake (%)	Chemical Dosage (%)	Mechanical Durability (%)	Weathered Mechanical Durability (%)	Water Uptake (%)	Weathered Water Uptake (%)
No coating	0.0	17.2	0.0	92.1	19.5	12.4	32.3
Paraffin wax	1.5	0.7	2.0	90.6	78.0	0.8	1.8
G88	6.8	1.3	9.9	98.8	96.3	0.6	1.2
G89	9.1	0.7	5.6	94.7	66.2	1.2	5.9
G90	9.0	0.9	8.8	97.1	93.0	0.4	1.0
G97	5.9	1.0	8.0	98.9	97.6	0.7	1.4
G98	5.8	1.0	6.5	98.3	96.8	0.7	1.7

The chemical dosage and water uptake results for the initial set of evaluations on five briquettes are displayed in Figure 6-7. From this figure, it is clearly shown that the briquettes with no coating exhibited the highest water uptake (17.2%). In contrast, the highest water uptake measured for the briquettes with a chemical coating was 1.3%, which occurred with the G88 coating. Each of the other water uptake vales were equal to or below 1.0%. The paraffin wax coating exhibited the greatest water resistance by limiting briquettes to a water uptake of 0.7%. This result was particularly notable given the lowest chemical dosage associated with the application of paraffin wax (1.5%). Although these results appear to be very promising, the wood-derived chemical dosage applied to the briquettes using this coating technique (5.8-9.1%) could be too costly for industrial applications, depending on the price of the chemicals. Nonetheless, coating briquettes with the wood-derived chemicals significantly improved briquette water resistance compared to no coating and conventional binder application. For example, the range of water uptake values for conventional binder application (5.0%) of G88, G89, G90, G97 and G98 was 3.7% to 7.0%. Conversely, the range of water uptake values for coating application of the same chemicals was 0.7% to 1.3%. However, the impact of water uptake on the mechanical integrity of briquettes requires further investigation.

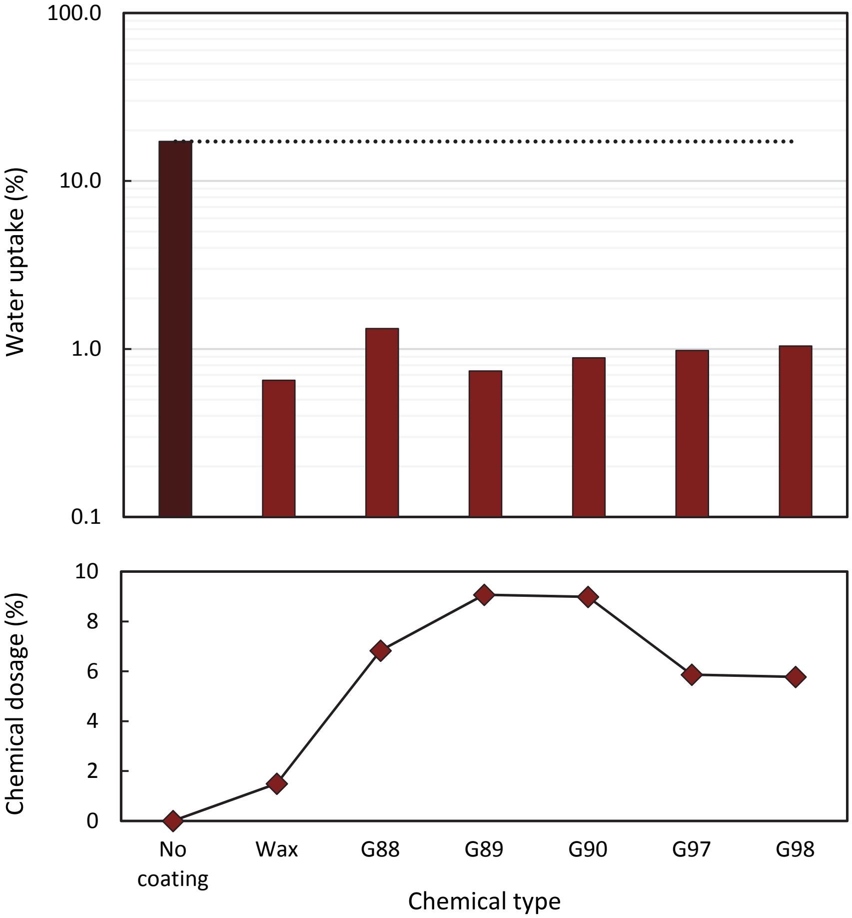


Figure 6-7. Water uptake of coated briquettes (Set 1)

The second set of coating evaluations were specifically designed to examine the impact of water uptake on the mechanical integrity of coal-biomass briquettes. Figure 6-8 shows the initial water uptake and the weathered water uptake values of briquettes with each type of chemical coating and without a coating. It is clearly shown that the initial (12.4%) and weathered (32.3%) water uptake of the briquettes with no coating are significantly higher than each of the coated briquette samples. All of the chemical coatings except G89 reduced the initial briquette water uptake below 1.0% and the weathered water uptake below 2.0%. The chemical coating with the greatest performance was G90, which improved the initial and weathered water resistance of the briquettes by 97%. As with the previous set of tests, the dosage of the paraffin wax was significantly lower than that of the wood-derived chemicals. This was likely due to the higher viscosity of the wood-derived chemicals at 160 degrees Celsius as compared to the paraffin wax.

The G89 briquettes had the lowest chemical dosage (5.6%) of the wood-derived chemical batches, whereas the G88 briquettes were found to have the highest dosage (9.9%).

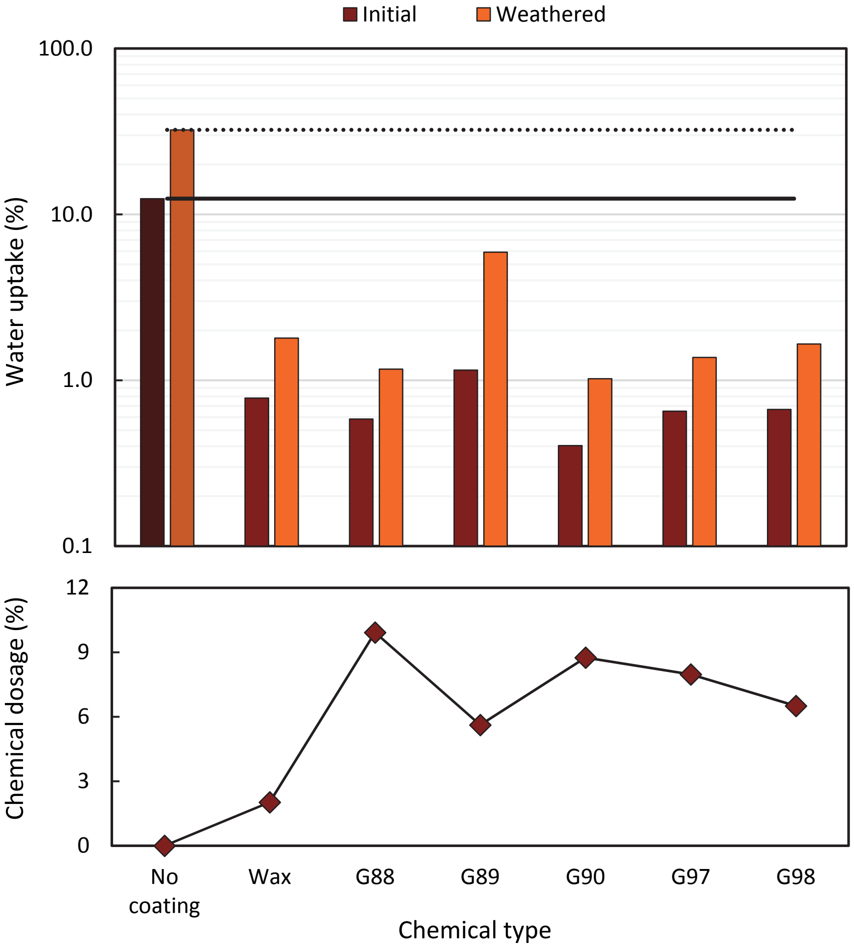


Figure 6-8. Water uptake of coated briquettes (Set 2)

Figure 6-9 shows the initial and weathered mechanical durability of the coated briquettes after the series of durability and water uptake evaluations. From this figure it is evident that the initial durability of briquettes with the wood-derived chemical coatings were greater than the durability of briquettes with no coating (92.1%) and the paraffin wax coating (90.6%). Briquettes coated with the G97 chemical exhibited the greatest initial mechanical durability (98.9%), followed closely by G88 (98.8%), G98 (98.3%), G90 (97.1%) and G89 (94.7%). The measured durability of each of these coated briquette samples are considered excellent (i.e. ≥95%). The weathered durability of the briquettes with no coating was 19.5%, which is considered very poor (i.e. <60%). However, the weathered durability of the coated briquettes showed significant improvement. For example, the weathered durability of briquettes coated with four of the wood-derived chemicals (G88, G90, G97 and G98) remained greater than the initial durability of the briquettes with no coating (i.e. >92.1%). The final durability of the G88 (96.3%), G97 (97.6%) and G98 (96.8%) briquettes remained classified as excellent, and therefore these chemicals are well suited for use as a coating agent to improve the integrity of coal-biomass briquettes in the presence of water.

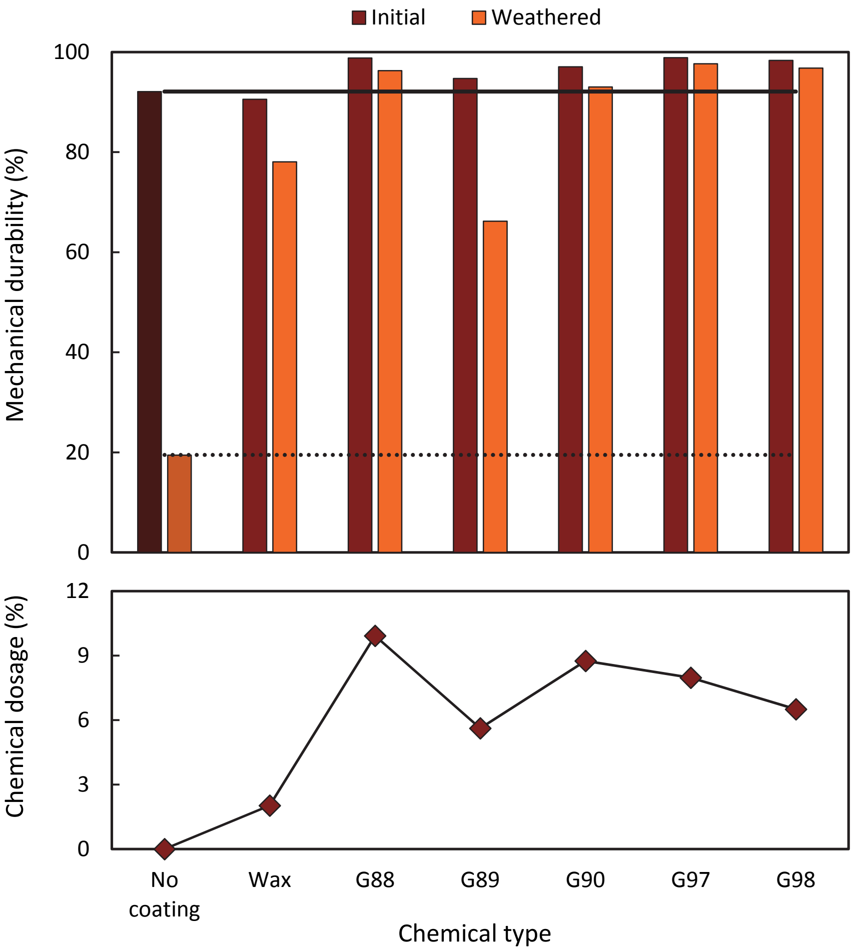


Figure 6-9. Mechanical durability of coated briquettes

To provide a greater appreciation for the results presented in Figure 6-8 and Figure 6-9, images of the actual briquette samples after the series of mechanical durability and water uptake evaluations are provided in Figure 6-10. Here it is clearly shown that the briquettes with no coating experienced a high degree of fragmentation during the evaluations (i.e. final durability = 19.5%). In contrast, briquettes coated with paraffin wax, G89 and G90 chemicals appear partially degraded, yet still much less degraded than the briquettes with no coating. Finally, briquettes coated with the G88, G97 and G98 chemicals appear fully intact, which corresponds with weathered mechanical durabilities of 96.3%, 97.6% and 96.8%, respectively. Due to the similar performance of G88, G97 and G98 with respect to mechanical durability and water uptake, the choice of the optimum chemical for coal-biomass briquette coating must be made with consideration to the market price of each chemical.

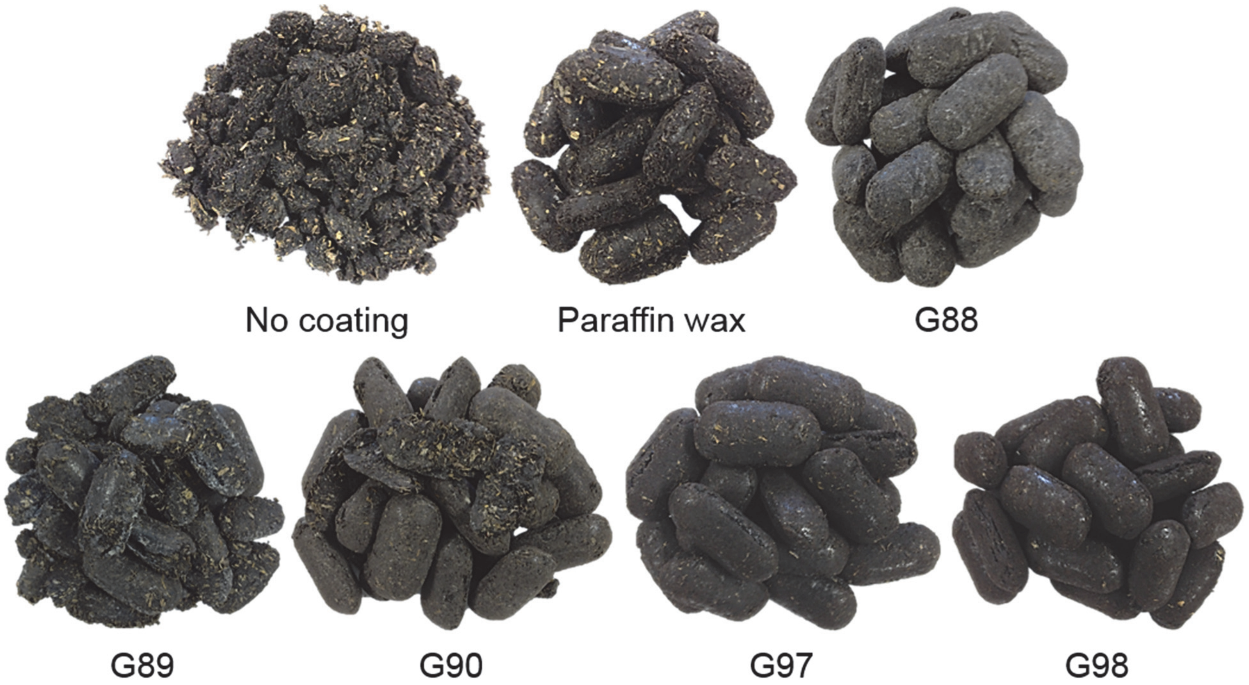


Figure 6-10. Briquette samples after durability and water uptake tests

6.4.3 Detailed Coating Evaluations

A series of detailed coating evaluations were performed to validate the performance of a selected wood-derived chemical coating and to measure several additional properties of the coated briquettes. The G88, G97 and G98 chemicals exhibited the best performance with respect to weathered mechanical durability and weathered water uptake. Through discussions with Georgia-Pacific, it was determined that the cost of the G97 chemical is approximately 30 percent less than the G88 chemical and approximately seven percent less than the G98 chemical. For this reason, the G97 chemical was selected for the detailed coating evaluations. These tests were performed with 30 percent biomass to determine the maximum achievable water resistance for briquettes with the greatest proportion of hygroscopic biomass material. The coal-biomass combinations selected for detailed evaluations were Emerald coal-sawdust (EM-SD) and Eagle Butte-corn stover (EB-CS), which were chosen to reflect the distribution of readily available coal and biomass resources in the United States (i.e. sawdust and bituminous coal are readily available in the east; corn stover and sub-bituminous coal are readily available in the west). To determine the impact of the G97 coating on the overall quality of coal-biomass briquettes, detailed evaluations were also performed on an uncoated portion of both types of briquettes. The results of these four series of detailed evaluations are presented in Table 6-4.

Table 6-4. Summary of detailed coating evaluation results

Briquette Property	**EM-SD**			**EB-CS**		
	No Coating	**G97 Coating**	**Change (%)**	**No Coating**	**G97 Coating**	**Change (%)**
Tensile strength (lb_f)	57.5	102.4	78.3	46.3	112.0	142.1
Crushing strength (lb_f)	357.4	312.9	-12.4	275.3	285.5	3.7
Spring constant (lb_f/in)	4646	3450	-25.7	2842	1804	-36.5
Mechanical durability (%)	92.8	97.7	5.3	91.1	97.6	7.2
Weathered mechanical durability (%)	39.4	89.4	126.9	7.7	94.7	1126.9
Attritability (%)	97.4	99.5	2.1	96.9	99.5	2.7
Friability (%)	97.1	99.3	2.3	98.4	99.5	1.1
Water content	0.018	0.022	21.0	0.163	0.131	-19.8
Particle density (g/cm^3)	1.13	1.11	-1.9	0.94	0.96	2.1
Water uptake (%)	8.3	1.0	-88.3	14.3	0.9	-93.7
Weathered water uptake (%)	20.4	1.5	-92.4	58.6	0.9	-98.4
Chemical dosage (%)	0.0	9.8	--	0.0	14.4	--

In addition to the results of each evaluation reported in Table 6-4, the percent change of each value is reported. This metric makes it easier to assess the impact of the G97 coating on each of the measured briquette properties. The tensile strength of the EM-SD briquettes and the EB-CS briquettes was significantly improved by the application of the chemical coating. Specifically, the tensile strength of the coated EM-SD briquettes increased by 78.3% to 102.4 lb_f and the tensile strength of the coated EB-CS briquetted increased by 142.1% to 112.0 lb_f. Another interesting result was that the tensile strength was higher for the uncoated EM-SD briquettes than the uncoated EB-CS briquettes, yet when the G97 coating was applied this finding was reversed. At this point, the fundamental cause of this occurrence is unknown.

The influence of the G97 coating on crushing strength showed mixed results. Specifically, the crushing strength of the coated EM-SD briquettes decreased by 12.4% to 312.9 lb_f. In contrast, the crushing strength of the coated EB-CS briquettes increased by 3.7% to 285.5 lb_f. Nonetheless, these crushing strength values are very high and indicative of extremely strong briquettes. Therefore, the reduced crushing strength value for the EM-SD briquettes is not particularly alarming. For both the coated and uncoated briquettes, the bituminous coal briquettes (EM-SD) exhibited higher crushing strengths than the sub-bituminous coal briquettes (EB-CS). This finding is in agreement with the statistical models discussed in Chapter 5.

The application of the G97 coating also resulted in a fairly significant decrease in the spring constant of the briquettes. Specifically, the spring constant of the coated EM-SD briquettes decreased by 25.7% to 3450 lb_f/in and the spring constant of the coated EB-CS briquettes decreased by 36.5% to 1804 lb_f/in. For both the coated and uncoated briquette evaluations, the EM-SD briquettes exhibited higher spring constant values than the EB-CS briquettes. This was most likely due to the difference in elasticity of the corn stover and sawdust. For example, corn stover has a much lower particle density than sawdust due to the internal pore structure of corn stalks. Therefore, raw corn stover can be compressed more easily than sawdust, which appears to also be the case when co-briquetted with coal.

A very promising result of these evaluations was the increase in mechanical durability that was measured for the coated briquettes. Specifically, the mechanical durability of the coated EM-SD briquettes increased by 5.3% to 97.7% and the mechanical durability of the EB-CS briquettes increased by 7.2% to 97.6%. Although this was a very encouraging result, a more important finding was the increase in weathered mechanical durability for the coated briquettes. The weathered mechanical durability of the coated EM-SD briquettes increased by 126.9% to 89.4% and the weathered mechanical durability of the coated EB-CS briquettes increased by 1126.9% to 94.7%. These weathered durability values are very good and indicate that these briquettes would remain a high-quality product in the presence of rain or other precipitation. These results validate the results of the preliminary coating evaluations.

Attritability and friability were also improved for bother briquette formulations by adding the G97 coating. For instance, attritability increased by 2.1% (EM-SD) and 2.7% (EB-CS) to 99.5% for both types of briquettes. This value is extremely high and indicates that attrition has a very minimal impact on the production of fine material for briquettes coated with the G97 chemical. A similar result was observed for briquette friability, wherein the measured values increased by 2.3% and 1.1% to 99.3% and 99.5% for the EM-SD and EB-CS briquettes, respectively. Similarly, this indicates that impact forces are not likely to significantly degrade the quality of coal-biomass briquettes coated with G97.

As expected, the G97 coating greatly improved the initial and weathered water resistance of both types of briquettes. Specifically, the initial and weathered water uptake of the coated EM-SD briquettes decreased by 88.3% and 92.4%, respectively. This equated to an initial water uptake of 1.0% and a weathered water uptake of 1.5%. Similarly, the initial and weathered water uptake of the coated EB-CS briquettes decreased by 93.7% and 98.4%, respectively. This equated to an initial and weathered water uptake of 0.9%. Both of these results further demonstrate the great potential for the G97 chemical to dramatically improve the water resistance of coal-biomass briquettes when applied as a coating to the exterior surface. In addition, these results further validate the results of the preliminary coating evaluations. Thus, it is likely that the other promising Georgia-Pacific wood-derived chemicals (i.e. G88, G98) would also exhibit very promising results in a series of validation tests.

Another interesting observation was the influence of the G97 coating on the particle density of the briquettes. Specifically, the particle density of the coated EM-SD briquettes decreased by 1.9% to 1.11 g/cm^3. Conversely, the particle density of the coated EB-CS briquettes increased by 2.1% to 0.96 g/cm^3. The reason for this occurrence is thought to be a direct result of the addition of the G97 chemical, which has a specific gravity of approximately 1.0. Therefore, it stands to reason that addition of this chemical to individual briquettes would increase the particle density of briquettes with an initial particle density less than 1.00 g/cm^3 and decrease the particle density of briquettes with an initial particle density greater than 1.00 g/cm^3. Furthermore, the change in particle density as a result of application of the G97 chemical was greater for the EB-CS briquettes (2.1%) than for the EM-SD briquettes (1.9%). This is likely a direct result of the higher chemical dosage measured for the EB-CS briquettes (14.4%) than the EM-SD briquettes (9.8%).

An unexpected and negative result of these tests was the increased chemical dosage measured for these two batches of briquettes compared to the chemical dosages measured for the preliminary coating evaluations. Since chemical dosage is directly linked to production cost, an increase in this value is particularly disconcerting. However, since this result is directly linked to the chemical application method employed for this study and the size of the pill-shaped briquettes produced, chemical dosage can certainly be reduced by improving the application method (i.e. spraying instead of dipping) and by increasing the ratio of briquette mass to surface area (i.e. using larger roll pockets). Based on the results of the preliminary coating evaluations and this detailed study, it appears that a decrease in chemical dosage would not necessarily result in decreased weathered mechanical durability and increased weathered water uptake. This assertion is only feasible if the thickness of the chemical coating is reduced by reducing the chemical dosage. In contrast, if the chemical dosage is reduced by not providing uniform coating to the entire surface of the briquettes, it is anticipated that weathered mechanical durability and weathered water uptake would suffer.

6.5 Summary and Conclusions

There is currently a growing interest in the development of economically feasible methods to sustain the physical and mechanical integrity of coal-biomass briquettes in the presence of water In light of this issue, a study was performed to evaluate the potential for several proprietary wood-derived chemicals to improve the water resistance of coal-biomass briquettes. Two methods for application of the chemicals were examined: (1) conventional binder application wherein chemicals were mixed with coal and biomass particles prior to briquette production, and (2) coating application wherein coal-biomass briquettes were dipped in heated chemicals to coat the exterior surface. Additional evaluations were performed without chemicals and with commonly used chemicals to establish the relative performance of each wood-derived chemical.

For the conventional binder application method, five of the six wood-derived chemicals significantly improved the water resistance of the coal-biomass briquettes. The best performing wood-derived chemical (G90) produced briquettes with a water uptake of 5.8% and 3.7% at binder contents of 2.5 percent and 5.0 percent, respectively. This represents a 63% and 77% improvement in water resistance as compared to the binderless briquettes. Although the briquettes produced with wood-derived chemicals were outperformed by the starch briquettes with respect to density, strength and durability, the significant improvement in water resistance from addition of the wood-derived chemicals presents a unique opportunity to improve coal-biomass briquette quality in the presence of water.

For the briquette coating technique, each of the wood-derived chemicals outperformed briquettes with no coating and four of the five chemicals outperformed briquettes with the paraffin wax coating. The wood-derived chemical with the greatest water resistance potential (G90) produced an initial briquette water uptake of 0.4% and a final water uptake of 1.0%. This represents a 97% improvement in water uptake for both initial and weathered water uptake. Briquettes coated with G97 exhibited the greatest initial (98.9%) and final (97.6%) mechanical durability. This represents a 7% increase in initial durability and a 401% increase in weathered durability. One concern with the results of the briquette coating evaluations is the high dosage (5-10%) of the wood-derived chemicals. This issue is thought to be a result of the dipping technique employed and the high viscosity of the heated chemicals.

The results of the detailed coating evaluations further exemplified the benefits of the G97 coating with respect to initial and weathered durability and water resistance. In addition, these evaluations provided insight to the influence of the G97 coating on other important properties of coal-biomass briquettes. These evaluations also provided evidence that the G97 coating can be successfully used to improve the durability and water resistance of briquettes comprised of different coal types (i.e. bituminous and sub-bituminous) and different biomass types (i.e. sawdust and corn stover). However, a major shortcoming of coating briquettes with wood-derived chemicals such as G97 is the high chemical dosage that was applied to the surface of the briquettes using the technique outlined in this study.

Therefore, briquette coating methods require further investigation to determine if the chemical dosage could be reduced by modifying the dipping technique or by implementing a hot spraying technique. The selection of the optimum wood-derived chemical for coal-biomass briquette coating applications depends primarily on the cost of each chemical and the desired level of briquette durability and water resistance. Therefore, it is recommended that the chemical coating type and application method be chosen independently for every unique coal-biomass briquette operation as a balance between desired quality and production cost.

6.6 References

Basu, P., Butler, J., & Leon, M. (2011). Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. *Renewable energy, 36*(1), 282-288.

Bates, A., Heng, S., & Perry, G. (1988). *Australian Patent No. 1988016577*. Wooden, ACT: Australian Patent Office.

Bratton, R., Luttrell, G., Kasindorf, H., McGraw, G., & McAllister, M. (2010). Evaluation of a novel fine coal briquetting process at GreenFields Coal Company. In R. Honaker (Ed.), *International coal preparation congress 2010 conference proceedings*. Littleton, CO: Society for Mining, Metallurgy, and Exploration.

EN 15150 (2011). *Solid biofuels − Determination of particle density*. Brussels, Belgium: European Committee for Standardization.

Fernando, R. (2009). *Co-gasification and indirect cofiring of coal and biomass*. London, England: IEA Clean Coal Centre.

Freitag, W. (1996). Principles of application. In D. Stoye & W. Freitag (Eds.), *Resins for coatings: Chemistry, properties and applications*, 40-44. Cincinnati, Ohio: Hanser/Gardner Publications.

Goss, W. (1938). *U.S Patent No. 2,114,377*. Washington, DC: U.S. Patent and Trademark Office.

Guigon, P., & Simon, O. (2003). Roll press design – influence of force feed systems on compaction. *Powder technology, 130*(1-3), 41-48.

Honaker, R., Parekh, B., Taulbee, D., & Tao, D. (2005). *Premium fuel production from mining and timber waste using advanced separation and pelletizing technologies*. Washington, DC: U.S. Department of Energy.

Lundwall, A. (1939). *U.S. Patent No. 2,155,500*. Washington, DC: U.S. Patent and Trademark Office.

Mills, J. U.S. Department of the Interior, United States Geological Survey. (1908). *Binders for coal briquets: Investigations made at the fuel-testing plant: St. Louis, Mo.* (Bulletin 343).

Motaung, S., Mangena, S., de Korte, G. (2007). Effects of coal composition and flotation reagents on the water resistance of binderless briquettes. *Coal preparation, 27*(4), 230-248.

Saglam, M., Yuksel, M., Yanik, J., Tutas, M., Karaduman, M., & Ustun, G. (1990). Production of water-resistant briquettes from Turkish lignites using sulphite liquor binders. *Fuel, 69*(1), 60-64.

Sami, M., Annamalai, K., & Wooldridge, M. (2001). Co-firing of coal and biomass fuel blends. *Progress in energy and combustion science, 27*(2), 171-214.

Shimasaki, K., Deguchi, T., Sugita, S., & Makino, E. (2003). *U.S. Patent No. 6,626,966*. Washington DC: U.S. Patent and Trademark Office.

Taulbee, D., Neathery, J., Patil, D., Sowder, N., O'Daniel, B., & Montross, M. (2010). Combustion of briquettes and fuels pellets prepared from blends of biomass and fine coal. In R. Honaker (Ed.), *International coal preparation congress 2010 conference proceedings*. Littleton, CO: Society for Mining, Metallurgy, and Exploration.

Taulbee, D., Patil, D., Honaker, R., & Parekh, B. (2009). Briquetting of coal fines and sawdust Part I: Binder and briquetting-parameters evaluations. *International journal of coal preparation and utilization, 29*(1), 1-22.

Trechock, J. (1973). *U.S. Patent No. 3,711,318*. Washington, DC: U.S. Patent and Trademark Office.

Wang, H., Zhu, S., Bai, Z., & Yang Y. (2011). Effect of heat treatment on water resistance of lignite briquettes. *Power and energy engineering conference (APPEEC)*, 2011 Asia-Pacific, 1-3.

Chapter 7

Conclusions and Recommendations

7.1 Summary of Research Activities

Co-utilization of biomass with coal in existing coal-fired facilities presents a unique opportunity to reduce greenhouse gas emissions and increase energy production from renewable resources. Significant interest in this opportunity has led to more than 150 coal-fired power stations across the world co-firing coal and biomass on a commercial or trial basis. These co-firing experiences have revealed a number of feedstock challenges that must be addressed to improve the potential for this growing technology. Recent studies suggest that many of these challenges can be mitigated by reconstituting coal-biomass mixtures into larger particles. Specifically, roll press briquetting has been investigated to produce homogeneous, free-flowing feedstocks that minimize handling and segregation problems often encountered with combustion and gasification systems. However, several technical and economic barriers require further investigation prior to industrial utilization of coal-biomass briquettes.

The research activities presented in this dissertation are intended to address the most critical technical challenges pertaining to coal-biomass briquette feedstocks. As with any product of an agglomeration process, the primary technical challenge regarding coal-biomass briquettes is achieving and maintaining a high level of quality from production to utilization. Several laboratory-scale research investigations were conducted to address this challenge, which included:

1. Identification, development and refinement of methods to characterize physical properties of coal-biomass briquettes;
2. Development of a methodology to identify the optimum water content of coal-biomass blends prior to briquette production;
3. Evaluation and optimization of feedstock variables, additive variables and roll press operating parameters in the production of coal-biomass briquettes from various coal and biomass types; and

4. Development and evaluation of methods to improve the water resistance of coal-biomass briquettes using proprietary wood-derived chemicals.

The study of briquette characterization methods included a detailed review of briquette properties to determine the most important properties for characterization of coal-biomass briquettes. The briquette properties that were identified as most significant are: (1) tensile strength, (2) crushing strength, (3) elasticity, (4) mechanical durability, (5) attritability, (6) friability, (7) water content, (8) particle density, (9) bulk density and (10) water resistance. Experimental evaluations were conducted to adapt, evaluate and refine established methods that appeared suitable for coal-biomass briquette evaluations. This was accomplished by measuring briquette properties at different test conditions to determine the most accurate and precise configuration of each test method. Additional work was conducted to develop novel characterization methods to quantify briquette properties when suitable established methods were not applicable or available.

The moisture optimization study was conducted to develop a new experimental approach to identify the optimum water content of coal-biomass briquettes. The Briquette Proctor Test was developed based on the Proctor Test for clay soils, in which briquettes are produced at different water contents using a hydraulic press to determine the point at which dry particle density reaches a maximum value. Briquette Proctor Tests were conducted over a range of water contents (0.01 to 0.25) for blends of sawdust and both bituminous and sub-bituminous coals. Further work was conducted to evaluate the influence of a similar range of water contents on the particle density, crushing strength and mechanical durability of briquettes produced with a roll press. The results of the hydraulic press briquette production and roll press briquette production were compared to determine the feasibility of using the Briquette Proctor Test to indicate optimum water contents for roll press briquette production. The results were also analyzed to determine the relationship between particle density and briquette quality (i.e. crushing strength and mechanical durability).

The evaluation and optimization of briquette production variables study was conducted to examine the most significant feedstock, additive and roll press variables in coal-biomass briquette production. For evaluation of feedstock variables, the effects of biomass content (10 to 30%), water content (0.02 to 0.20) and biomass top size (1.20 to 4.75 mm) on the quality (particle density, crushing strength and mechanical durability) of briquettes were studied. For evaluation of additive variables, the effects of binder content (0.0 to 5.0%) and cure time (0 to 7 days) on the quality of coal-biomass briquettes were investigated. For evaluation of roll press operating parameters, the effects of roll force (50 to 100 kN), roll torque (600 to 1800 N-m) and roll motor speed (300 to 900 rpm) on the quality of coal-biomass briquettes were studied. The results of these investigations were analyzed to develop mathematical models that can be used to predict the quality of coal-biomass briquettes. In addition, work was conducted to compare and contrast the quality of briquettes composed of four coal types and five biomass types. Finally, a comprehensive series of tests were conducted to characterize the physical properties, flow properties and gasification behavior of selected coal-biomass briquettes to verify the enhanced quality of co-briquetted feedstocks.

The water resistance study was conducted to evaluate the potential for several proprietary wood-derived chemicals to improve the water resistance of coal-biomass briquettes. Two methods for application of the chemicals were examined: (1) conventional binder application as a powder prior to briquette production and (2) briquette coating. For the conventional binder application method, the effects of binder content (0.0 to 5.0%) was evaluated for six wood-derived chemicals and pregelatinized wheat starch to determine the impact of each chemical on the water resistance, crushing strength and mechanical durability of briquettes. For the briquette coating method, the effects of coating individual briquettes with heated chemicals were evaluated for five wood-derived chemicals and paraffin wax to determine the impact of each coating on the water resistance and mechanical durability of briquettes. Additional work was conducted to fully characterize the coated briquettes and to compare the physical properties of coated and uncoated briquettes.

7.2 Original Contributions

As a result of the research presented in this dissertation, three original contributions have been made to the field of solid fuel processing technology:

1. *Novel Characterization Methods for Water Resistance, Attritability and Elasticity of Coal-Biomass Briquettes.* The methods developed to quantify each of these properties were independently developed and refined during the course of this research. These methods describe unique theoretically sound procedures and apparatuses to characterize coal-biomass briquettes.
2. *A Novel Low-Cost Method to Quickly Determine the Optimum Water Content of Coal-Biomass Briquettes.* The Briquette Proctor Test presents a unique approach to maximize the quality of coal-biomass briquettes by determining the optimum feedstock water

content. This test greatly reduces the time and materials required to locate the optimum water content, and thus provides a significant opportunity to reduce research and development costs.

3. *A Novel Post-Production Method to Improve the Water-Resistance of Coal-Biomass Briquettes using Wood-Derived Chemicals.* The coating of coal-biomass briquettes with heated wood-derived chemicals presents a significant opportunity to improve the water-resistance of coal-biomass briquettes. Water resistant coal-biomass briquettes could be transported and stored using existing coal infrastructure, which would minimize required capital expenditures upstream of the gasifier.

7.3 Final Conclusions

The following conclusions were drawn from the results of the research presented in this dissertation:

1. *Briquette Characterization Methods.* Crushing strength and mechanical durability are the most widely used indicators of the physical quality of coal-biomass briquettes, and thus both properties should be measured for all experimental and industrial briquette production operations.
2. *Optimization of Briquette Water Content.* The influence of water content of coal-biomass mixtures on the dry density of briquettes determined by the Briquette Proctor Test is very similar to the influence of water content on the dry density of compacted clay soils as determined by the standard Proctor Test. The optimum crushing strength and mechanical durability of coal-biomass briquettes can be determined by using the developed methodology for optimization of water content. Hydraulic press briquette production is representative of roll press briquette production, and thus the Briquette Proctor Test can be used to indicate the optimum water content of coal-biomass mixtures prior to roll press briquetting evaluations. The dry density of briquettes composed of bituminous coal and biomass exhibits a strong positive correlation with crushing strength and mechanical durability. An exhaustive experimental study of water content optimization for roll press briquetting coal-biomass mixtures can be streamlined by simply determining the water content that results in the highest dry density because maximum crushing strength and mechanical durability likely exist at or near this value as well.

3. *Comparison of Coal and Biomass Types.* Differences in the quality of coal-biomass briquettes composed of different types of bituminous coal with identical top sizes can be attributed to differences in the distribution modulus and ash content of the coals, where briquette quality increases with a corresponding increase in distribution modulus and decrease in ash content. Bituminous coals generally produce higher quality briquettes than sub-bituminous coals. Corn stover exhibits the best properties of the biomass types studied with regard to the crushing strength and mechanical durability of coal-biomass briquettes.
4. *Influence of Feedstock Variables.* Biomass content is the most statistically significant mixture variable with regard to the particle density of coal-biomass briquettes. For all types of coal and biomass evaluated, an increase in biomass content causes a direct reduction in particle density. Biomass content is the most statistically significant mixture variable with regard to the crushing strength of binderless coal-biomass briquettes. For all types of coal and biomass evaluated, an increase in biomass content causes a direct increase in crushing strength. Water content is the most statistically significant mixture variable with regard to the mechanical durability of binderless coal-biomass briquettes. For all types of coal and biomass evaluated, a clear optimum water content can be identified where mechanical durability reaches a maximum value. Biomass top size is not a statistically significant mixture variable with regard to the particle density, crushing strength and mechanical durability of coal-biomass briquettes.
5. *Influence of Additive Variables.* Starch content is a very statistically significant mixture variable with regard to the crushing strength and mechanical durability of coal-biomass briquettes. An increase in starch content causes a direct increase in crushing strength and mechanical durability. Cure time is a statistically significant process variable with regard to the crushing strength of coal-biomass briquettes. A period of 6 days is recommended to cure the briquettes for which this variable was studied.
6. *Influence of Roll Press Operating Parameters.* Roll torque is the most statistically significant roll press operating variable with regard to the particle density, crushing strength and mechanical durability of coal-biomass briquettes. An increase in roll torque causes a direct increase in particle density, crushing strength and mechanical durability. Roll force is a statistically significant roll press operating variable with regard to the particle density, crushing strength and mechanical durability of coal-biomass briquettes.

An increase in roll torque causes a direct increase in particle density, crushing strength and mechanical durability. Roll speed is a statistically significant roll press operating variable with regard to the particle density of coal-biomass briquettes. An increase in roll speed causes a direct reduction in particle density.

7. *Characteristics of Optimum Binderless Briquettes.* Binderless coal-biomass briquettes produced at optimized conditions exhibit very high crushing strength and mechanical durability values, which indicate that the briquettes would largely remain competent in the presence of forces encountered in handling, storage and transportation. Binderless coal-biomass briquettes produced at optimized conditions exhibit poor water resistance, which indicates that additional investigation of this matter is required. Binderless coal-biomass briquettes produced at optimized conditions exhibit excellent flow properties, which indicates that proper hopper design is straightforward. Binderless coal-biomass briquettes produced at optimized conditions exhibit excellent gasification behavior with regard to product gas composition and cold gas efficiency. This confirms that coal-biomass briquettes are exceptional gasification feedstocks for the co-production of power and synthetic fuels.
8. *Wood-Derived Chemicals to Improve Water Resistance.* Wood-derived chemicals added to coal-biomass mixtures prior to briquette production can improve the water resistance of coal-biomass briquettes by up to 77 percent at a binder content of five percent. Wood-derived chemicals applied to the exterior of coal-biomass briquettes as a coating can improve the water resistance of the briquettes by up to 97 percent and the weathered mechanical durability by up to 400 percent with a coating dosage of eight percent.

7.4 Recommendations for Further Research

Finally, further investigation is recommended in the following areas to improve the quality of coal-biomass briquettes and ultimately promote the co-utilization of coal and biomass feedstocks:

1. *Briquette Characterization Methods.* Although a general consensus has been reached regarding the most important physical properties of fuel briquettes, specific test methods to quantify these parameters are highly variable. It is common for researchers to independently develop assessment procedures appropriate to the nature of the particular

investigations performed at their laboratories. This makes it extremely difficult to compare the quality of briquettes produced and tested in separate laboratories. In support of this challenge, stakeholders in the fuel briquetting industry must work with organizations that develop and publish standard test methods (e.g. ASTM, CEN, ISO) to standardize common briquette characterization methods (e.g. crushing strength, mechanical durability). Additional investigation is also recommended for methods to characterize the effects of other weather conditions (i.e. humidity, freezing) on the quality of coal-biomass briquettes.

2. *Influence of Feedstock Variables.* Additional research is needed to determine the optimum particle-size distribution of coal and biomass feedstocks for briquette production. This variable is difficult to optimize since size-distributions are not defined by a single value, which makes manipulation and optimization of this variable difficult. Further investigation is also needed to determine the influence of surface and inherent moisture (in addition to total moisture) on the quality of briquettes composed of sub-bituminous coal and biomass.
3. *Influence of Roll Press Operating Parameters.* Further investigation is required to validate the optimized roll press production variables presented in this dissertation on a larger scale. Specifically, additional tests should be conducted using a pilot-scale roll press (e.g. 2 tons/hr) to determine the quality of briquettes produced at the optimum prescribed feedstock conditions and roll press operating conditions.
4. *Wood-Derived Chemicals to Improve Water Resistance.* Additional research is needed to improve the method used to coat coal-biomass briquettes with heated wood-derived chemicals. Improvement is needed to reduce the chemical dosage applied to individual briquettes to ultimately improve the economic feasibility of this technique. Further research is required to develop a continuous process for coating coal-biomass briquettes with heated wood-derived chemicals. The batch process described in this dissertation is not ideal for industrial applications and scaling the process to higher capacity would present challenges.
5. *Logistics, Sustainability and Economics.* Several additional studies should be conducted to investigate the market potential for coal-biomass briquettes. Specific investigation is required in the areas of logistics, biomass sustainability (i.e. life-cycle analysis), and economic feasibility to determine the potential role of coal-biomass briquettes in the global energy market. The results of this work would provide invaluable information for future energy policy decisions.

Appendix A. Experimental Data

A.1 Briquette Characterization Methods

A.1.1 Tensile Strength

Tensile Strength Test Configuration

Sample:	EM-CS
Client:	DOE
Coal:	Emerald - 80% - minus 1 mm
Biomass:	Corn stover - 20% - minus 3/16"
Date:	8/2/2013
Time	2:00:00 PM

Comments:	2032.00 g coal - 1.60% moist
	556.75 g corn stover - 11.35% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 N-m

Standard plunger - crush strength		Standard plunger - standing tall		Standard plunger - standing short	
Measurement number	Crushing strength	Measurement number	Recorded strength	Measurement number	Recorded strength
	lb_f		lb_f		lb_f
1	290.8	1	58.2	1	56.3
2	249.4	2	48.9	2	49.5
3	210.5	3	63.0	3	69.1
4	216.3	4	51.7	4	60.1
5	275.3	5	53.6	5	59.5
6	258.7	6	40.4	6	62.3
7	252.7	7	50.4	7	45.3
8	288.3	8	58.5	8	44.7
9	237.1	9	40.6	9	61.4
10	219.0	10	63.9	10	53.1
11	304.1	11	63.1	11	56.5
12	263.2	12	65.6	12	48.0
13	286.3	13	61.0	13	45.5
14	253.6	14	56.6	14	59.9
15	296.1	15	55.3	15	46.2
16	264.0	16	60.8	16	63.8
17	261.9	17	61.7	17	46.9
18	259.9	18	56.0	18	49.8
19	288.9	19	58.0	19	47.3
20	243.5	20	53.2	20	62.3
21	261.7	21	60.3	21	57.5
22	256.2	22	49.8	22	53.4
23	271.3	23	46.2	23	51.2
24	264.4	24	50.9	24	46.7
25	305.1	25	48.5	25	50.1
Average:	263.1	Average:	55.0	Average:	53.9
Std. Dev:	25.6	Std. Dev:	6.9	Std. Dev:	7.0
Std. Dev (%):	9.7	Std. Dev (%):	12.6	Std. Dev (%):	13.0

Tensile Strength Test Configuration

Sample:	EM-CS
Client:	DOE
Coal:	Emerald - 80% - minus 1 mm
Biomass:	Corn stover - 20% - minus 3/16"
Date:	8/2/2013
Time	2:00:00 PM

Comments:	2032.00 g coal - 1.60% moist
	556.75 g corn stover - 11.35% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 N-m

Split plunger - perpendicular		Split plunger - parallel		Point plunger	
Measurement number	Recorded strength	Measurement number	Recorded strength	Measurement number	Recorded strength
	lb_f		lb_f		lb_f
1	121.6	1	136.3	1	45.4
2	131.0	2	126.9	2	57.4
3	124.7	3	130.4	3	38.6
4	117.2	4	129.6	4	37.2
5	106.6	5	133.0	5	56.2
6	104.3	6	123.1	6	45.2
7	142.9	7	147.7	7	55.9
8	136.5	8	130.8	8	47.6
9	123.5	9	129.2	9	43.4
10	98.9	10	129.9	10	47.8
11	91.4	11	124.3	11	39.6
12	131.1	12	135.0	12	60.2
13	124.0	13	149.9	13	36.0
14	114.3	14	125.2	14	55.5
15	102.1	15	122.3	15	48.9
16	108.7	16	99.4	16	44.9
17	94.9	17	140.5	17	53.6
18	115.6	18	123.3	18	42.6
19	102.4	19	130.4	19	41.9
20	102.8	20	112.4	20	58.4
21	116.4	21	142.2	21	46.0
22	106.8	22	125.4	22	47.2
23	94.0	23	132.1	23	56.2
24	102.9	24	139.5	24	52.6
25	100.8	25	131.9	25	36.4
Average:	112.6	Average:	130.0	Average:	47.8
Std. Dev:	14.0	Std. Dev:	10.5	Std. Dev:	7.4
Std. Dev (%):	12.4	Std. Dev (%):	8.0	Std. Dev (%):	15.5

A.1.2 Crushing Strength

Crushing Strength Test Configuration	
Sample:	MR-SG
Client:	DOE
Coal:	McClure River - 80% - filter cake
Biomass:	Switchgrass - 20% - minus 3/16"
Date:	7/16/2012
Time	8:00:00 AM

Comments:	2022.00 g coal - 1.10% moist
	587.50 g switchgrass - 17.50% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 30 hz
	Roll torque: 1500 N-m

No bar method

Measurement Number	Recorded Crushing Strength Value (lb_f)
1	309.7
2	77.9
3	93.5
4	55.0
5	253.6
6	379.9
7	93.5
8	371.3
9	78.3
10	81.9
11	63.7
12	498.7
13	69.6
14	58.6
15	409.5
16	380.7
17	505.6
18	408.4
19	83.2
20	333.1
21	336.7
22	67.4
23	291.6
24	366.3
25	108.0
26	348.6
27	460.9
28	10.4
29	407.4
30	88.9
31	113.2
32	78.8
33	251.6
34	442.7
35	551.7
36	382.7
37	531.7
38	176.5
39	47.9
40	374.7
41	469.7
42	66.0
43	89.4
44	441.4
45	471.4
46	83.1
47	162.1
48	347.0
49	82.5
50	493.8
Average:	255.0
Std. Dev:	171.5
Std. Dev (%):	67.3

Modified bar method

Measuremen Number	Recorded Crushing Strength Value (lb_f)
1	91.4
2	121.2
3	107.3
4	108.8
5	138.6
6	50.0
7	109.3
8	85.1
9	155.3
10	106.8
11	158.7
12	122.2
13	128.1
14	155.6
15	69.3
16	19.7
17	165.4
18	93.5
19	232.8
20	94.8
21	162.0
22	158.4
23	124.6
24	78.5
25	159.9
26	122.6
27	91.4
28	170.8
29	128.6
30	184.6
31	60.6
32	91.5
33	154.4
34	109.5
35	116.5
36	96.2
37	134.2
38	175.9
39	80.2
40	52.8
41	85.2
42	68.6
43	81.0
44	109.3
45	94.6
46	86.1
47	120.1
48	141.9
49	64.5
50	87.9
Average:	114.1
Std. Dev:	40.6
Std. Dev (%):	35.6

A.1.3 Elasticity

Elasticity Test Configuration	
Sample:	EM-CS
Client:	DOE
Coal:	Emerald - 80% - minus 1 mm
Biomass:	Corn stover - 20% - minus 3/16"
Date:	8/13/2013
Time	3:00:00 PM

Comments:	
	2032.00 g coal - 1.60% moist
	556.75 g corn stover - 11.35% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 N-m

Hooke's Law ($F = -kx$) (until fracture)

Measurement number	Crushing strength	Briquette displacement	Spring constant
	lb_f	in	lb_f/in
1	251.5	0.0710	3542
2	205.0	0.0645	3178
3	291.7	0.0670	4354
4	291.0	0.0735	3959
5	249.7	0.0620	4027
6	268.9	0.0790	3404
7	240.2	0.0775	3099
8	261.9	0.0695	3768
9	261.8	0.0905	2893
10	279.3	0.0745	3749
11	226.9	0.0505	4493
12	270.6	0.0675	4009
13	285.7	0.0650	4395
14	242.5	0.0760	3191
15	296.4	0.0870	3407
16	230.9	0.0545	4237
17	258.2	0.0790	3268
18	261.9	0.0740	3539
19	249.4	0.0630	3959
20	280.6	0.0770	3644
21	250.3	0.0640	3911
22	245.0	0.0900	2722
23	291.6	0.0655	4452
24	337.0	0.0770	4377
25	243.1	0.0660	3683
Average:	262.8	0.0714	3730
Std. Dev:	27.6	0.0099	505
Std. Dev (%):	10.5	13.8	13.5

Hooke's Law ($F = -kx$) (linear portion only)

Measuremen number	Crushing force (1)	Briquette displacement (1)	Crushing force (2)	Briquette displacement (2)	Spring constant
	lb_f	in	lb_f	in	lb_f/in
1	217.4	0.0560	102.5	0.0265	3895
2	195.0	0.0430	106.7	0.0210	4535
3	221.3	0.0510	92.7	0.0170	4339
4	254.1	0.0510	135.3	0.0260	4982
5	190.5	0.0290	127.2	0.0150	6569
6	156.1	0.0470	71.1	0.0190	3321
7	225.7	0.0390	73.8	0.0100	5787
8	196.2	0.0490	135.4	0.0380	4004
9	244.0	0.0480	167.2	0.0300	5083
10	229.7	0.0440	108.9	0.0260	5220
11	197.9	0.0450	122.4	0.0290	4398
12	197.6	0.0540	147.8	0.0350	3659
13	200.1	0.0470	110.6	0.0160	4257
14	196.7	0.0430	128.4	0.0240	4574
15	211.3	0.0360	117.0	0.0180	5869
16	173.9	0.0350	49.7	0.0070	4969
17	178.1	0.0420	63.2	0.0120	4240
18	236.2	0.0440	101.0	0.0180	5368
19	227.3	0.0510	133.8	0.0290	4457
20	206.9	0.0450	120.5	0.0260	4598
21	223.7	0.0440	112.5	0.0220	5084
22	237.1	0.0510	118.3	0.0190	4649
23	227.8	0.0430	104.5	0.0150	5298
24	197.6	0.0500	81.4	0.0170	3952
25	211.9	0.0380	127.6	0.0220	5576
				Average:	4747
				Std. Dev:	755
				Std. Dev (%):	15.9

A.1.4 Mechanical Durability

Mechanical Durability Test Configuration

Sample:	MR-SG
Client:	DOE
Coal:	McClure River - 80% - filter cake
Biomass:	Switchgrass - 20% - minus 3/16"
Date:	7/16/2012
Time	8:00:00 AM

Comments:	2022.00 g coal - 1.10% moist
	587.50 g switchgrass - 17.50% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 30 hz
	Roll torque: 1500 N-m

Test 1

Number of Briquettes	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mechanical Durability (%)
1	9.36	5.55	59.3
2	18.66	11.57	62.0
4	36.35	19.95	54.9
8	74.00	46.29	62.6
16	147.87	87.27	59.0
32	302.79	175.06	57.8
64	592.73	344.11	58.1
128	1193.28	721.79	60.5
		Average:	59.3
		Std. Dev:	2.31
		Std. Dev (%):	3.90

Test 2

Number of Briquettes	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mechanical Durability (%)
1	9.71	5.56	57.3
2	18.65	9.41	50.5
4	37.20	20.47	55.0
8	74.55	39.47	52.9
16	149.57	82.93	55.4
32	290.09	153.78	53.0
64	595.79	328.59	55.2
128	1174.77	671.62	57.2
		Average:	54.6
		Std. Dev:	2.16
		Std. Dev (%):	3.96

Test 3

Number of Briquettes	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mechanical Durability (%)
1	9.31	4.73	50.8
2	17.74	9.06	51.1
4	37.36	20.81	55.7
8	73.73	37.57	51.0
16	147.59	75.74	51.3
32	296.33	142.76	48.2
64	592.68	305.86	51.6
128	1179.22	677.84	57.5
		Average:	52.1
		Std. Dev:	2.79
		Std. Dev (%):	5.35

Test 4

Number of Briquettes	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mechanical Durability (%)
15	136.09	65.30	48.0
20	182.80	86.67	47.4
25	239.33	112.66	47.1
30	272.25	131.87	48.4
35	315.66	148.45	47.0
40	355.01	174.41	49.1
45	409.49	196.34	47.9
50	463.89	224.30	48.4
55	498.32	241.52	48.5
60	556.08	279.28	50.2
65	607.65	305.25	50.2
		Average:	48.4
		Std. Dev:	1.05
		Std. Dev (%):	2.18

Mechanical Durability Test Configuration

Sample:	MR-SG
Client:	DOE
Coal:	McClure River - 80% - filter cake
Biomass:	Switchgrass - 20% - minus 3/16"
Date:	7/17/2012
Time	8:00:00 AM

Comments:	2022.00 g coal - 1.10% moist
	587.50 g switchgrass - 17.50% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 30 hz
	Roll torque: 1500 N-m
	Number of briquettes: 20

10 RPM

Screening Time (s)	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mechanical Durability (%)
20	193.54	185.05	95.6
40	191.89	178.39	93.0
80	193.11	168.79	87.4
160	192.22	153.19	79.7
320	192.16	129.69	67.5

20 RPM

Screening Time (s)	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mechanical Durability (%)
20	191.60	183.32	95.7
40	191.90	178.06	92.8
80	192.68	169.38	87.9
160	189.38	139.74	73.8
320	191.84	114.40	59.6

40 RPM

Screening Time (s)	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mechanical Durability (%)
20	192.94	183.00	94.8
40	192.17	177.89	92.6
80	191.37	168.82	88.2
160	192.37	152.63	79.3
320	193.69	126.73	65.4

60 RPM

Screening Time (s)	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mechanical Durability (%)
20	192.06	185.99	96.8
40	192.87	184.11	95.5
80	192.83	177.15	91.9
160	192.98	167.07	86.6
320	192.25	150.59	78.3

A.1.5 Attritability

Attritability Test Configuration

Sample:	MR-SG
Client:	DOE
Coal:	McClure River - 80% - filter cake
Biomass:	Switchgrass - 20% - minus 3/16"
Date:	6/8/2012
Time	8:00:00 AM

Comments:	2022.00 g coal - 1.10% moist
	587.50 g switchgrass - 17.50% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 30 hz
	Roll torque: 1500 N-m
	Screen size: 4.75 mm

5 briquettes

Screening Time (s)	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Attritability (%)
10	48.07	47.49	98.8
20	48.07	46.84	97.4
40	48.07	45.96	95.6
80	48.07	43.99	91.5
160	48.07	41.10	85.5
320	48.07	36.92	76.8

20 briquettes

Screening Time (s)	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Attritability (%)
10	192.89	189.21	98.1
20	192.89	186.50	96.7
40	192.89	181.65	94.2
80	192.89	173.01	89.7
160	192.89	160.69	83.3
320	192.89	144.95	75.1

10 briquettes

Screening Time (s)	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Attritability (%)
10	95.35	93.94	98.5
20	95.35	92.48	97.0
40	95.35	90.27	94.7
80	95.35	86.71	90.9
160	95.35	80.85	84.8
320	95.35	73.24	76.8

25 briquettes

Screening Time (s)	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Attritability (%)
10	239.62	234.45	97.8
20	239.62	230.50	96.2
40	239.62	223.92	93.4
80	239.62	212.75	88.8
160	239.62	197.83	82.6
320	239.62	177.28	74.0

15 briquettes

Screening Time (s)	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Attritability (%)
10	143.21	140.57	98.2
20	143.21	138.36	96.6
40	143.21	134.70	94.1
80	143.21	128.15	89.5
160	143.21	118.92	83.0
320	143.21	106.69	74.5

30 briquettes

Screening Time (s)	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Attritability (%)
10	287.26	280.64	97.7
20	287.26	275.56	95.9
40	287.26	267.56	93.1
80	287.26	254.48	88.6
160	287.26	235.34	81.9
320	287.26	211.85	73.7

Attritability Test Configuration

Sample:	MR-SG
Client:	DOE
Coal:	McClure River - 80% - filter cake
Biomass:	Switchgrass - 20% - minus 3/16"
Date:	6/8/2012
Time	1:00:00 PM

Comments:	2022.00 g coal - 1.10% moist
	587.50 g switchgrass - 17.50% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 30 hz
	Roll torque: 1500 N-m
	Screen size: 4.75 mm
	Screening time: 3 min

Number of Briquettes	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Attritability (%)
1	9.56	7.89	82.5
2	19.11	15.66	81.9
4	38.53	31.92	82.8
8	77.84	63.73	81.9
16	150.56	121.11	80.4
32	303.24	242.40	79.9
1	9.40	8.28	88.1
2	18.77	15.54	82.8
4	38.51	31.64	82.2
8	76.25	61.95	81.2
16	153.37	123.75	80.7
32	304.76	239.34	78.5
1	9.57	7.88	82.3
2	18.95	16.26	85.8
4	37.45	30.75	82.1
8	76.70	61.93	80.7
16	150.38	120.20	79.9
32	298.95	237.20	79.3

Number of Briquettes	Average Attritability (%)	Standard Deviation (%)
1	84.3	3.26
2	83.5	2.03
4	82.4	0.41
8	81.3	0.57
16	80.4	0.39
32	79.3	0.70

Attritability Test Configuration	
Sample:	MR-SG
Client:	DOE
Coal:	McClure River - 80% - filter cake
Biomass:	Switchgrass - 20% - minus 3/16"
Date:	6/8/2012
Time	3:00:00 PM

Comments:	
	2022.00 g coal - 1.10% moist
	587.50 g switchgrass - 17.50% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 30 hz
	Roll torque: 1500 N-m
	Screen size: 4.75 mm
	Screening time: 3 min
	Number of briquettes: 20

Screen Size (mm)	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Attritability (%)
6.70	90.53	79.36	87.7
4.75	91.64	81.22	88.6
3.35	88.91	79.42	89.3
2.36	91.28	82.12	90.0
1.70	90.45	81.74	90.4
1.18	90.90	82.79	91.1
0.841	90.93	84.41	92.8
0.590	91.97	86.78	94.4
0.425	91.07	86.70	95.2
0.212	91.53	88.66	96.9

A.1.6 Friability

Friability Test Configuration	
Sample:	MR-SG
Client:	DOE
Coal:	McClure River - 80% - filter cake
Biomass:	Switchgrass - 20% - minus 3/16"
Date:	7/22/2012
Time	8:00:00 AM

Comments:	
	2022.00 g coal - 1.10% moist
	587.50 g switchgrass - 17.50% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 30 hz
	Roll torque: 1500 N-m
	Screen over 4.75 mm sieve

4 feet drop height

Number of Briquettes	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Friability (%)
10	94.38	92.00	97.5
20	191.65	185.02	96.5
40	384.50	370.80	96.4
80	764.84	739.33	96.7
		Average:	96.8
		Std. Dev:	0.41
		Std. Dev (%):	0.42

8.4 feet drop height

Number of Briquettes	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Friability (%)
10	96.93	91.78	94.7
20	194.47	180.11	92.6
40	384.85	349.45	90.8
80	766.65	716.43	93.4
		Average:	92.9
		Std. Dev:	1.41
		Std. Dev (%):	1.52

6 feet drop height

Number of Briquettes	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Friability (%)
10	96.81	92.51	95.6
20	194.43	185.44	95.4
40	395.90	376.24	95.0
80	764.48	731.53	95.7
		Average:	95.4
		Std. Dev:	0.25
		Std. Dev (%):	0.26

A.1.7 Water Content

Water Content Test Configuration	
Sample:	EM-CS
Client:	DOE
Coal:	Emerald - 80% - minus 1 mm
Biomass:	Corn stover - 20% - minus 3/16"
Date:	3/13/2013
Time	1:00:00 PM

Comments:	
	2032.00 g coal - 1.60% moist
	556.75 g corn stover - 11.35% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 N-m

Measurement Number	Initial	24 hours			26 hours			Change in
	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content (x 10^2)	Dry Mass (g)	Water Mass (g)	Water Content (x 10^2)	Water Content (%/hr)
1	9.844	9.463	0.381	4.03	9.462	0.382	4.04	0.14
2	9.651	9.299	0.352	3.79	9.298	0.353	3.80	0.15
3	9.771	9.470	0.301	3.18	9.469	0.302	3.19	0.17
4	9.418	9.055	0.363	4.01	9.054	0.364	4.02	0.14
5	9.595	9.226	0.369	4.00	9.224	0.371	4.02	0.28
6	9.572	9.213	0.359	3.90	9.212	0.360	3.91	0.14
Average:				3.82			3.83	0.17
Std. Dev:				0.30			0.30	0.05
Std. Dev (%):				7.78			7.79	29.75

A.1.8 Particle Density

Particle Density Test Configuration	
Sample:	EM-CS
Client:	DOE
Coal:	Emerald - 80% - minus 1 mm
Biomass:	Corn stover - 20% - minus 3/16"
Date:	2/10/2013
Time	12:00:00 PM

Comments:	
	2032.00 g coal - 1.60% moist
	556.75 g corn stover - 11.35% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 N-m
	Detergent = Triton X-100 @ 1.5 g/l
	Minwax Helmsman Spar Urethane
	--> Clear Satin, Aerosol, SG = 0.72

Water Tests w/o Detergent

Measurement #	Mass in Air (g)	Mass in Water (g)	Particle Density (g/cm^3)
1	9.54	1.00	1.12
2	9.52	0.91	1.11
3	9.50	0.92	1.11
4	9.55	0.97	1.11
5	9.36	0.74	1.09
6	9.19	0.77	1.09
7	9.40	0.89	1.10
8	9.53	0.89	1.10
9	9.25	0.97	1.12
10	9.54	0.97	1.11
11	9.41	0.84	1.10
12	9.66	0.89	1.10
		Average:	1.10
		St. Dev:	0.01
		St. Dev (%):	0.88

Water Tests w/ Detergent

Measurement #	Mass in Air (g)	Mass in Water (g)	Particle Density (g/cm^3)
1	9.31	1.05	1.13
2	9.33	1.11	1.14
3	9.57	1.13	1.13
4	9.67	1.23	1.15
5	9.53	1.12	1.13
6	9.49	1.14	1.14
7	9.34	0.96	1.11
8	9.20	0.73	1.09
9	9.33	0.93	1.11
10	9.55	1.14	1.14
11	9.46	1.08	1.13
12	9.65	1.26	1.15
		Average:	1.13
		St. Dev:	0.01
		St. Dev (%):	0.85

Particle Density Test Configuration

Sample:	EM-CS
Client:	DOE
Coal:	Emerald - 80% - minus 1 mm
Biomass:	Corn stover - 20% - minus 3/16"
Date:	2/10/2013
Time	12:00:00 PM

Comments:	2032.00 g coal - 1.60% moist
	556.75 g corn stover - 11.35% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 N-m
	Detergent = Triton X-100 @ 1.5 g/l
	Minwax Helmsman Spar Urethane
	--> Clear Satin, Aerosol, SG = 0.72

Water Tests w/ Urethane & Detergent

Measurement #	Pellet Mass in Air (g)	llet + Uretha Mass in Air (g)	ellet + Urethan Mass in Water (g)	Urethane Mass in Air (g)	Urethane Volume (cm^3)	Pellet + Urethane Density (g/cm^3)	Pellet + Urethane Volume (cm^3)	Pellet Volume (cm^3)	Pellet Density (g/cm^3)
1	9.20	9.40	0.86	0.20	0.28	1.10	8.54	8.26	1.11
2	9.43	9.68	0.96	0.25	0.35	1.11	8.72	8.37	1.13
3	9.39	9.61	0.99	0.22	0.31	1.11	8.62	8.31	1.13
4	9.36	9.55	1.08	0.19	0.26	1.13	8.47	8.21	1.14
5	9.73	9.94	1.09	0.21	0.29	1.12	8.85	8.56	1.14
6	9.34	9.56	0.92	0.22	0.31	1.11	8.64	8.33	1.12
7	9.39	9.61	0.93	0.22	0.31	1.11	8.68	8.37	1.12
8	9.49	9.71	0.97	0.22	0.31	1.11	8.74	8.43	1.13
9	9.49	9.72	0.97	0.23	0.32	1.11	8.75	8.43	1.13
10	9.38	9.57	0.95	0.19	0.26	1.11	8.62	8.36	1.12
11	9.29	9.46	1.00	0.17	0.24	1.12	8.46	8.22	1.13
12	9.79	10.01	1.16	0.22	0.31	1.13	8.85	8.54	1.15
								Average:	1.13
								St. Dev:	0.01
								St. Dev (%):	0.81

Particle Density Test Configuration

Sample:	EM-CS
Client:	DOE
Coal:	Emerald - 80% - minus 1 mm
Biomass:	Corn stover - 20% - minus 3/16"
Date:	2/10/2013
Time	12:00:00 PM

Comments:	2032.00 g coal - 1.60% moist
	556.75 g corn stover - 11.35% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 N-m
	Detergent = Triton X-100 @ 1.5 g/l
	Minwax Helmsman Spar Urethane
	--> Clear Satin, Aerosol, SG = 0.72

Water Tests w/ Urethane

Measurement #	Pellet Mass in Air (g)	llet + Uretha Mass in Air (g)	ellet + Urethan Mass in Water (g)	Urethane Mass in Air (g)	Urethane Volume (cm^3)	Pellet + Urethane Density (g/cm^3)	Pellet + Urethane Volume (cm^3)	Pellet Volume (cm^3)	Pellet Density (g/cm^3)
1	9.44	9.61	1.05	0.17	0.24	1.12	8.56	8.32	1.13
2	9.59	9.83	0.97	0.24	0.33	1.11	8.86	8.53	1.12
3	9.56	9.83	0.88	0.27	0.37	1.10	8.95	8.58	1.11
4	9.50	9.74	0.95	0.24	0.33	1.11	8.79	8.46	1.12
5	9.42	9.69	0.89	0.27	0.37	1.10	8.80	8.43	1.12
6	9.65	9.85	0.88	0.20	0.28	1.10	8.97	8.69	1.11
7	9.53	9.75	0.97	0.22	0.31	1.11	8.78	8.47	1.12
8	9.33	9.58	0.85	0.25	0.35	1.10	8.73	8.38	1.11
9	9.50	9.71	0.95	0.21	0.29	1.11	8.76	8.47	1.12
10	9.43	9.67	0.90	0.24	0.33	1.10	8.77	8.44	1.12
11	9.63	9.89	0.95	0.26	0.36	1.11	8.94	8.58	1.12
12	9.23	9.44	0.88	0.21	0.29	1.10	8.56	8.27	1.12
								Average:	1.12
								St. Dev:	0.01
								St. Dev (%):	0.57

A.1.9 Bulk Density

Bulk Density Test Configuration	
Sample:	EM-CS
Client:	DOE
Coal:	Emerald - 80% - minus 1 mm
Biomass:	Corn stover - 20% - minus 3/16"
Date:	8/5/2013
Time	2:00:00 PM

Comments:	
	2032.00 g coal - 1.60% moist
	556.75 g corn stover - 11.35% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 N-m
	Feed water content = 0.036,0.037
	Pour from 2' above bottom of box
	Use straight edge to remove excess

0.24 ft^3 = 421.88 in^3 = 6913.29 cm^3

Test number	Empty box mass (g)	Filled box mass (g)	Bulk density (g/cm^3)	Bulk density (lb/ft^3)
1	1814.5	6307.5	0.65	40.57
2	1814.5	6258.0	0.64	40.13
3	1814.5	6321.5	0.65	40.70
4	1814.5	6312.5	0.65	40.62
5	1814.5	6286.5	0.65	40.38
6	1814.5	6292.5	0.65	40.44
7	1814.5	6269.5	0.64	40.23
8	1814.5	6304.0	0.65	40.54
		Average:	0.65	40.45
		Std. Dev:	0.00	0.20
		Std. Dev (%):	0.49	0.49

Compressibility

Consolidation weight (lb)	Consolidation pressure (lb/ft^2)	Empty box mass (g)	Filled box mass (g)	Bulk density (g/cm^3)	Bulk density (lb/ft^3)
0.00	0.00	1825.0	6319.0	0.65	40.58
13.55	34.68	1825.0	6387.5	0.66	41.20
23.55	60.28	1825.0	6438.0	0.67	41.66
33.55	85.88	1825.0	6404.0	0.66	41.35
43.55	111.48	1825.0	6463.5	0.67	41.89
50.55	129.40	1825.0	6476.0	0.67	42.00
			Average:	0.66	41.45
			Std. Dev:	0.01	0.52
			Std. Dev (%):	1.26	1.26

0.50 ft^3 = 857.38 in^3 = 14049.86 cm^3

Test number	Empty box mass (g)	Filled box mass (g)	Bulk density (g/cm^3)	Bulk density (lb/ft^3)
1	2741.0	11811.5	0.65	40.30
2	2741.5	11938.5	0.65	40.87
3	2742.0	11961.5	0.66	40.97
4	2742.0	11864.5	0.65	40.53
5	2742.5	11963.0	0.66	40.97
6	2743.0	11983.0	0.66	41.06
		Average:	0.65	40.78
		Std. Dev:	0.00	0.30
		Std. Dev (%):	0.73	0.73

1.00 ft^3 = 1728 in^3 = 28316.85 cm^3

Test number	Empty box mass (g)	Filled box mass (g)	Bulk density (g/cm^3)	Bulk density (lb/ft^3)
1	4250.0	22784.5	0.65	40.86
2	4250.0	22704.0	0.65	40.68
3	4250.5	22811.5	0.66	40.92
4	4250.5	22791.0	0.65	40.87
5	4250.5	22727.0	0.65	40.73
6	4251.0	22821.5	0.66	40.94
		Average:	0.65	40.84
		Std. Dev:	0.00	0.10
		Std. Dev (%):	0.25	0.25

A.1.10 Water Resistance

Water Uptake Test	
Sample:	EM-CS
Client:	DOE
Coal:	Emerald - 80% - minus 1 mm
Biomass:	Corn stover - 20% - minus 3/16"
Date:	5/27/2013
Time	2:00:00 PM

Comments	
	2032.00 g coal - 1.60% moist
	556.75 g corn stover - 11.35% moist
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 N-m

15 sec @ 3 gpm

Number of briquettes tested	Dry mass (g)	Wet mass (g)	Water mass (g)	Water uptake (%)
5	48.41	59.48	11.07	22.87
10	93.60	114.00	20.40	21.79
20	189.77	230.92	41.15	21.68
40	379.14	465.91	86.77	22.89
			Average:	22.31
			Std. Dev:	0.66
			Std. Dev (%):	2.95

5 briquettes @ 3 gpm

Spray duration (sec)	Dry mass (g)	Wet mass (g)	Water mass (g)	Water uptake (%)
5	47.66	57.89	10.23	21.46
15	47.12	59.94	12.82	27.21
30	47.94	63.31	15.37	32.06
60	47.84	64.27	16.43	34.34
120	48.96	70.78	21.82	44.57
			Average:	31.93
			Std. Dev:	8.62
			Std. Dev (%	27.00

5 briquettes @ 15 sec

Spray rate (gpm)	Dry mass (g)	Wet mass (g)	Water mass (g)	Water uptake (%)
1	48.75	57.47	8.72	17.89
2	46.70	54.86	8.16	17.47
3	46.23	55.40	9.17	19.84
4	47.55	56.10	8.55	17.98
5	46.25	57.57	11.32	24.48
			Average:	19.53
			Std. Dev:	2.91
			Std. Dev (%):	14.90

A.2 Moisture Optimization in Briquette Production

A.2.1 Hydraulic Press Moisture Optimization

Modified Proctor Test

Sample:	TC-SD-XX
Client:	DOE
Coal:	Toms Creek - 80%
Biomass:	Cabinet Sawdust - 20%
Size:	Minus 1 mm TC
Date:	1/30/2013
Time	1:30:00 PM

Comment:	Die diameter = 1.125 inch
	Pellet dry mass target - 15 g
	Water content target - varies
	Pressure target - 20,000 lb
	TC mass - 12.08 g
	SD mass - 3.00 g
	Water mass - varies
	Dry time - 24 hrs
	Time before weighing - 3 min

Tests

Target Water Content	Wet Mass (g)	Dry Mass (g)	Mass in Air (g)	Mass in Water (g)	Water Mass (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)	Water Content --
0.01	15.08	14.93	15.11	0.79	0.15	1.06	1.045	0.010
0.02	15.20	14.88	15.20	1.28	0.32	1.09	1.069	0.022
0.03	15.41	15.02	15.41	1.70	0.39	1.12	1.096	0.026
0.04	15.51	14.96	15.43	1.94	0.55	1.14	1.103	0.037
0.05	15.62	14.99	15.59	1.88	0.63	1.14	1.091	0.042
0.06	15.70	14.88	15.74	2.01	0.82	1.15	1.087	0.055
0.08	16.01	14.93	16.01	1.71	1.08	1.12	1.044	0.072
0.10	16.22	14.89	16.23	1.34	1.33	1.09	1.001	0.089
0.15	17.02	15.02	16.94	0.75	2.00	1.05	0.923	0.133

Modified Proctor Test

Sample:	MR-SD-XX
Client:	DOE
Coal:	McClure River - 80%
Biomass:	Cabinet Sawdust - 20%
Size:	Minus 1 mm MR
Date:	3/28/2013
Time	12:00:00 PM

Comment:	Die diameter = 1.125 inch
	Pellet dry mass target - 15 g
	Water content target - varies
	Pressure target - 20,000 lb
	MR mass - 12.11 g
	SD mass - 3.00 g
	Water mass - varies
	Dry time - 24 hrs
	Time before weighing (dry) - 3 min

Tests

Target Water Content	Wet Mass (g)	Dry Mass (g)	Mass in Air (g)	Mass in Water (g)	Water Mass (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)	Water Content --
0.01	15.01	14.84	14.98	0.13	0.17	1.01	0.997	0.011
0.02	15.17	14.90	15.15	0.88	0.27	1.06	1.043	0.018
0.03	15.29	14.92	15.30	1.07	0.37	1.08	1.049	0.025
0.04	15.41	14.92	15.41	1.42	0.49	1.10	1.066	0.033
0.05	15.49	14.91	15.57	1.50	0.58	1.11	1.065	0.039
0.06	15.66	14.92	15.67	1.46	0.74	1.10	1.051	0.050
0.08	15.88	14.94	15.97	1.27	0.94	1.09	1.022	0.063
0.10	16.16	14.94	16.23	0.95	1.22	1.06	0.982	0.082
0.15	16.80	14.93	16.91	0.47	1.87	1.03	0.914	0.125

Modified Proctor Test

Sample:	EM-SD-XX
Client:	DOE
Coal:	Emerald - 80%
Biomass:	Cabinet Sawdust - 20%
Size:	Minus 1 mm EM
Date:	4/2/2013
Time	12:00:00 PM

Comment:	Die diameter = 1.125 inch
	Pellet dry mass target - 15 g
	Water content target - varies
	Pressure target - 20,000 lb
	EM mass - 12.14 g
	SD mass - 3.00 g
	Water mass - varies
	Dry time - 24 hrs
	Time before weighing (dry) - 3 min

Tests

Target Water Content	Wet Mass (g)	Dry Mass (g)	Mass in Air (g)	Mass in Water (g)	Water Mass (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)	Water Content --
0.01	14.87	14.71	14.96	0.11	0.16	1.01	0.997	0.011
0.02	15.16	14.89	15.13	0.74	0.27	1.05	1.033	0.018
0.03	15.22	14.85	15.28	1.22	0.37	1.09	1.060	0.025
0.04	15.37	14.88	15.44	1.33	0.49	1.09	1.059	0.033
0.05	15.53	14.89	15.58	1.31	0.64	1.09	1.047	0.043
0.06	15.65	14.92	15.71	1.32	0.73	1.09	1.041	0.049
0.08	15.94	14.93	15.95	1.32	1.01	1.09	1.021	0.068
0.10	16.17	14.93	16.21	0.65	1.24	1.04	0.962	0.083
0.15	16.86	14.94	16.92	0.28	1.92	1.02	0.901	0.129

Modified Proctor Test

Sample:	EB-SD-XX
Client:	DOE
Coal:	Eagle Butte - 80%
Biomass:	Cabinet Sawdust - 20%
Size:	Minus 1 mm EB
Date:	6/24/2013
Time	11:00:00 AM

Comment:	Die diameter = 1.125 inch
	Pellet dry mass target - 15 g
	Water content target - varies
	Pressure target - 20,000 lb
	EB mass - 12.14 g
	SD mass - 3.00 g
	Water mass - varies
	Dry time - 24 hrs
	Time before weighing (dry) - 3 min

Tests

Target Water Content	Wet Mass (g)	Dry Mass (g)	Mass in Air (g)	Mass in Water (g)	Water Mass (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)	Water Content --
0.02	15.25	14.97	15.21	-2.12	0.28	0.88	0.862	0.019
0.04	15.48	14.93	15.51	-1.00	0.55	0.94	0.906	0.037
0.06	15.81	14.96	15.83	-0.46	0.85	0.97	0.920	0.057
0.08	16.11	14.92	16.08	-0.12	1.19	0.99	0.919	0.080
0.10	16.36	14.94	16.40	0.02	1.42	1.00	0.914	0.095
0.12	16.62	14.96	16.65	0.39	1.66	1.02	0.922	0.111
0.15	17.12	14.94	17.11	0.89	2.18	1.05	0.921	0.146
0.20	17.83	14.99	17.77	0.86	2.84	1.05	0.883	0.189
0.25	18.58	15.01	18.60	0.22	3.57	1.01	0.818	0.238

A.2.2 Roll Press Moisture Optimization

Moisture Optimization Test

Sample:	MO-TC-0.7
Client:	DOE
Coal:	Toms Creek - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	0.7%
Date:	2/25/2013
Time	2:00:00 PM

Comments:	1600.00 g coal
	420.00 g sawdust
	14.05 g water (target 14.00 g)
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 900-1200 ft-lb
	Screw speed: 16-19 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	77.45	76.86	0.59	0.008
1	9.14	9.08	0.06	0.007
2	8.96	8.91	0.05	0.006
3	8.94	8.90	0.04	0.004
4	8.98	8.93	0.05	0.006
5	9.02	8.97	0.05	0.006
			Average:	**0.006**
			St. Dev:	**0.001**
			St. Dev (%):	**13.407**
1	8.69	8.62	0.07	0.008
2	9.21	9.16	0.05	0.005
3	8.89	8.84	0.05	0.006
4	8.83	8.77	0.06	0.007
5	9.19	9.13	0.06	0.007
			Average:	**0.007**
			St. Dev:	**0.001**
			St. Dev (%):	**16.317**
Durability 1	154.22	153.26	0.96	0.006
Durability 2	154.99	154.02	0.97	0.006
			Average:	**0.006**
			St. Dev:	**0.000**
			St. Dev (%):	**0.383**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	180.80	154.20	85.29
2	180.99	154.93	85.60
		Average:	**85.44**
		St. Dev:	**0.22**
		St. Dev (%):	**0.26**

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	127.9
2	122.6
3	156.2
4	182.2
5	147.9
6	141.4
7	149.3
8	138.6
9	116.9
10	147.1
11	157.4
12	133.9
13	144.0
14	161.9
15	144.3
16	139.5
17	154.8
18	189.4
19	165.9
20	158.3
21	157.1
22	110.8
23	145.2
24	144.5
25	144.3
26	137.0
27	114.5
28	129.4
29	141.0
30	133.2
31	161.4
32	136.8
33	136.5
34	158.5
35	141.2
36	141.6
37	144.7
38	154.8
39	141.9
40	155.9
Average:	**145.2**
St. Dev:	**16.0**
St. Dev (%):	**11.0**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.21	0.98	1.12	1.11
2	9.16	1.03	1.13	1.12
3	8.75	0.99	1.13	1.12
4	9.07	1.05	1.13	1.12
5	9.05	0.68	1.08	1.08
6	8.93	0.27	1.03	1.03
7	9.18	0.93	1.11	1.11
8	9.06	1.07	1.13	1.13
9	9.10	0.35	1.04	1.03
10	9.04	0.83	1.10	1.09
			Average:	**1.09**
			St. Dev:	**0.04**
			St. Dev (%):	**3.43**
1	9.20	0.51	1.06	1.05
2	9.29	1.19	1.15	1.14
3	9.17	0.87	1.10	1.10
4	9.03	1.07	1.13	1.13
5	9.25	0.99	1.12	1.11
6	9.13	1.09	1.14	1.13
7	9.22	1.16	1.14	1.14
8	8.98	0.76	1.09	1.09
9	8.99	1.05	1.13	1.12
10	8.94	1.10	1.14	1.13
			Average:	**1.11**
			St. Dev:	**0.03**
			St. Dev (%):	**2.50**

Moisture Optimization Test

Sample:	MO-TC-1.5
Client:	DOE
Coal:	Toms Creek - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	1.5%
Date:	2/27/2013
Time	10:00:00 AM

Comments:	1600.00 g coal
	420.00 g sawdust
	30.04 g water (target 30.00 g)
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 900-1300 ft-lb
	Screw speed: 15-18 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	73.02	71.88	1.14	0.016
1	9.49	9.37	0.12	0.013
2	9.01	8.87	0.14	0.016
3	9.12	8.97	0.15	0.017
4	9.65	9.51	0.14	0.015
5	9.27	9.14	0.13	0.014
			Average:	**0.015**
			St. Dev:	**0.001**
			St. Dev (%):	**10.078**
1	9.22	9.10	0.12	0.013
2	9.27	9.15	0.12	0.013
3	9.49	9.37	0.12	0.013
4	9.50	9.38	0.12	0.013
5	9.42	9.31	0.11	0.012
			Average:	**0.013**
			St. Dev:	**0.001**
			St. Dev (%):	**4.303**
Durability 1	171.06	168.63	2.43	0.014
Durability 2	170.08	167.52	2.56	0.015
			Average:	**0.015**
			St. Dev:	**0.001**
			St. Dev (%):	**4.151**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	186.01	171.06	91.96
2	185.28	170.13	91.82
		Average:	**91.89**
		St. Dev:	**0.10**
		St. Dev (%):	**0.11**

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	209.7
2	162.4
3	222.5
4	183.3
5	185.4
6	167.0
7	158.2
8	152.2
9	176.1
10	172.1
11	163.9
12	177.5
13	183.4
14	178.8
15	159.6
16	214.8
17	195.4
18	168.4
19	206.5
20	180.6
21	182.1
22	176.9
23	193.7
24	176.2
25	170.3
26	196.1
27	180.9
28	185.1
29	166.8
30	207.6
31	189.7
32	159.0
33	167.9
34	149.2
35	192.1
36	187.0
37	152.6
38	192.8
39	170.2
40	176.9
41	211.7
Average:	**180.6**
St. Dev:	**17.9**
St. Dev (%):	**9.9**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.29	1.36	1.17	1.15
2	9.39	1.28	1.16	1.14
3	9.37	1.45	1.18	1.17
4	9.52	1.27	1.15	1.14
5	9.47	1.52	1.19	1.17
6	9.42	1.39	1.17	1.16
7	9.05	0.79	1.10	1.08
8	9.41	1.46	1.18	1.17
9	9.13	0.69	1.08	1.07
10	9.53	1.33	1.16	1.15
			Average:	**1.14**
			St. Dev:	**0.04**
			St. Dev (%):	**3.22**
1	9.01	0.95	1.12	1.10
2	9.22	1.46	1.19	1.17
3	9.56	1.27	1.15	1.14
4	9.44	1.25	1.15	1.14
5	9.61	1.19	1.14	1.13
6	9.39	1.23	1.15	1.14
7	9.28	1.45	1.19	1.17
8	9.08	1.43	1.19	1.17
9	9.17	1.23	1.15	1.14
10	9.14	1.01	1.12	1.11
			Average:	**1.14**
			St. Dev:	**0.02**
			St. Dev (%):	**2.15**

Moisture Optimization Test

Sample:	MO-TC-2.2
Client:	DOE
Coal:	Toms Creek - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	2.2%
Date:	2/21/2013
Time	12:00:00 PM

Comments:	1616.48 g coal
	421.80 g sawdust
	5.72 g water (target 5.82 g)
	Force: 100 kN
	Roll speed: 450 rpm -- 15 hz
	Roll torque: 1000-1200 ft-lb
	Screw speed: 14-17 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	62.19	60.82	1.37	0.023
1	9.20	9.02	0.18	0.020
2	8.96	8.78	0.18	0.021
3	9.35	9.17	0.18	0.020
4	9.49	9.31	0.18	0.019
5	9.29	9.11	0.18	0.020
			Average:	**0.020**
			St. Dev:	**0.000**
			St. Dev (%):	**2.194**
1	8.99	8.86	0.13	0.015
2	8.86	8.72	0.14	0.016
3	9.33	9.19	0.14	0.015
4	8.73	8.58	0.15	0.017
5	9.38	9.24	0.14	0.015
			Average:	**0.016**
			St. Dev:	**0.001**
			St. Dev (%):	**7.023**
Durability 1	173.23	170.01	3.22	0.019
Durability 2	173.90	170.63	3.27	0.019
			Average:	**0.019**
			St. Dev:	**0.000**
			St. Dev (%):	**0.832**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.46	1.84	1.24	1.22
2	9.44	1.62	1.21	1.18
3	8.93	0.99	1.12	1.10
4	9.04	1.38	1.18	1.16
5	9.52	1.59	1.20	1.18
			Average:	**1.17**
			St. Dev:	**0.04**
			St. Dev (%):	**3.62**
1	9.07	1.56	1.21	1.19
2	9.45	1.44	1.18	1.16
3	8.68	1.29	1.17	1.16
4	9.06	1.44	1.19	1.17
5	9.47	1.52	1.19	1.17
6	9.76	0.77	1.09	1.07
7	9.21	1.12	1.14	1.12
8	9.26	1.21	1.15	1.13
9	9.15	1.26	1.16	1.14
10	9.41	1.25	1.15	1.14
11	9.34	1.61	1.21	1.19
12	8.71	0.78	1.10	1.08
			Average:	**1.14**
			St. Dev:	**0.04**
			St. Dev (%):	**3.38**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	186.32	173.32	93.02
2	187.32	173.97	92.87
		Average:	**92.95**
		St. Dev:	**0.11**
		St. Dev (%):	**0.11**

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	237.4
2	212.2
3	229.8
4	230.4
5	172.0
6	191.5
7	201.4
8	228.4
9	195.7
10	179.6
11	254.2
12	186.9
13	266.3
14	208.0
15	212.4
16	208.3
17	218.4
18	233.2
19	217.1
20	236.6
21	215.9
22	207.6
23	218.7
24	211.1
25	200.4
26	239.0
27	229.4
28	255.1
29	221.5
30	209.7
31	236.3
32	235.4
33	219.3
34	218.6
35	221.6
36	225.8
37	211.2
38	253.0
39	224.6
40	240.0
41	229.1
42	220.2
43	242.7
44	204.7
45	217.4
46	200.9
47	238.6
48	218.2
49	227.4
50	147.9
Average:	**219.2**
St. Dev:	**21.6**
St. Dev (%):	**9.9**

Moisture Optimization Test

Sample:	MO-TC-3.7
Client:	DOE
Coal:	Toms Creek - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	3.7%
Date:	2/22/2013
Time	12:00:00 PM

Comments:
1616.48 g coal
421.80 g sawdust
35.93 g water (target 35.72 g)
Force: 100 kN
Roll speed: 450 rpm -- 15 hz
Roll torque: 1000-1500 ft-lb
Screw speed: 14-17 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	63.17	60.79	2.38	0.039
1	9.73	9.42	0.31	0.033
2	9.23	8.95	0.28	0.031
3	9.38	9.07	0.31	0.034
4	9.38	9.10	0.28	0.031
5	9.25	8.96	0.29	0.032
			Average:	**0.032**
			St. Dev:	**0.001**
			St. Dev (%):	**4.176**
1	9.64	9.41	0.23	0.024
2	9.43	9.20	0.23	0.025
3	9.54	9.28	0.26	0.028
4	9.38	9.16	0.22	0.024
5	9.50	9.27	0.23	0.025
			Average:	**0.025**
			St. Dev:	**0.002**
			St. Dev (%):	**6.286**
Durability 1	176.18	171.08	5.10	0.030
Durability 2	174.55	169.64	4.91	0.029
			Average:	**0.029**
			St. Dev:	**0.001**
			St. Dev (%):	**2.087**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.39	1.59	1.20	1.17
2	9.71	1.73	1.22	1.18
3	9.39	1.18	1.14	1.11
4	9.82	1.28	1.15	1.11
5	9.56	1.77	1.23	1.19
6	9.44	1.53	1.19	1.16
7	9.37	0.97	1.12	1.08
8	9.50	1.28	1.16	1.12
9	9.31	1.14	1.14	1.10
10	9.29	1.22	1.15	1.12
			Average:	**1.13**
			St. Dev:	**0.04**
			St. Dev (%):	**3.21**
1	9.35	1.49	1.19	1.16
2	9.78	1.22	1.14	1.11
3	9.43	1.31	1.16	1.13
4	9.26	1.39	1.18	1.15
5	9.79	1.52	1.18	1.15
6	9.52	1.36	1.17	1.14
7	9.46	1.35	1.17	1.14
8	9.48	1.38	1.17	1.14
9	9.49	1.45	1.18	1.15
10	9.32	1.47	1.19	1.16
			Average:	**1.14**
			St. Dev:	**0.01**
			St. Dev (%):	**1.21**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.63	175.97	92.80
2	188.93	174.28	92.25
		Average:	**92.52**
		St. Dev:	**0.39**
		St. Dev (%):	**0.42**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	244.5
2	233.4
3	186.0
4	200.1
5	144.5
6	194.8
7	232.3
8	230.7
9	243.0
10	203.9
11	232.4
12	203.3
13	243.4
14	187.2
15	225.9
16	209.0
17	242.6
18	180.1
19	241.0
20	205.6
21	250.8
22	249.3
23	193.1
24	212.9
25	194.4
26	214.3
27	216.2
28	219.4
29	242.3
30	220.3
31	244.1
32	210.1
33	161.4
34	149.0
35	205.7
36	211.0
37	192.3
38	148.3
39	201.8
40	208.6
41	208.6
42	231.7
43	198.3
Average:	**210.9**
St. Dev:	**27.4**
St. Dev (%):	**13.0**

Moisture Optimization Test

Sample:	MO-TC-5.2
Client:	DOE
Coal:	Toms Creek - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	5.2%
Date:	2/26/2013
Time	11:00:00 AM

Comments:
1616.48 g coal
421.80 g sawdust
65.77 g water (target 65.72 g)
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 900-1300 ft-lb
Screw speed: 15-17 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	57.01	54.35	2.66	0.049
1	9.70	9.30	0.40	0.043
2	9.35	8.96	0.39	0.044
3	9.57	9.18	0.39	0.042
4	9.53	9.12	0.41	0.045
5	9.47	9.06	0.41	0.045
			Average:	**0.044**
			St. Dev:	**0.001**
			St. Dev (%):	**2.763**
1	9.56	9.25	0.31	0.034
2	9.25	8.98	0.27	0.030
3	9.35	9.06	0.29	0.032
4	9.01	8.71	0.30	0.034
5	9.44	9.15	0.29	0.032
			Average:	**0.032**
			St. Dev:	**0.002**
			St. Dev (%):	**5.241**
Durability 1	166.65	160.02	6.63	0.041
Durability 2	167.01	160.43	6.58	0.041
			Average:	**0.041**
			St. Dev:	**0.000**
			St. Dev (%):	**0.716**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.54	1.06	1.13	1.08
2	9.55	1.68	1.21	1.16
3	9.30	1.32	1.17	1.12
4	9.54	1.67	1.21	1.16
5	9.45	1.25	1.15	1.10
6	9.53	1.19	1.14	1.09
7	9.66	1.63	1.20	1.15
8	9.67	1.44	1.17	1.13
9	9.86	0.69	1.08	1.03
10	9.85	1.38	1.16	1.11
			Average:	**1.11**
			St. Dev:	**0.04**
			St. Dev (%):	**3.67**
1	9.43	1.59	1.20	1.17
2	9.62	1.42	1.17	1.14
3	9.34	1.60	1.21	1.17
4	9.49	0.84	1.10	1.06
5	9.37	1.27	1.16	1.12
6	9.22	1.37	1.17	1.14
7	9.78	1.41	1.17	1.13
8	9.42	1.14	1.14	1.10
9	9.25	0.83	1.10	1.06
10	9.81	1.53	1.18	1.15
			Average:	**1.12**
			St. Dev:	**0.04**
			St. Dev (%):	**3.32**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.70	166.73	87.89
2	188.87	167.09	88.47
		Average:	**88.18**
		St. Dev:	**0.41**
		St. Dev (%):	**0.46**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	171.0
2	179.9
3	192.8
4	181.9
5	177.4
6	167.8
7	183.0
8	153.7
9	166.8
10	171.0
11	165.7
12	159.8
13	184.5
14	168.0
15	197.0
16	192.6
17	193.2
18	198.6
19	185.3
20	168.9
21	188.6
22	182.8
23	176.5
24	181.3
25	175.4
26	186.5
27	184.0
28	150.0
29	162.5
30	178.4
31	178.4
32	180.5
33	137.9
34	187.7
35	161.0
36	202.0
37	200.7
38	210.8
39	166.2
40	146.3
41	224.2
42	193.6
43	169.7
44	182.4
45	178.7
46	201.8
47	168.2
48	203.2
49	207.7
50	149.0
Average:	**179.5**
St. Dev:	**17.6**
St. Dev (%):	**9.8**

Moisture Optimization Test

Sample:	MO-TC-6.7
Client:	DOE
Coal:	Toms Creek - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	6.7%
Date:	2/28/2013
Time	1:00:00 PM

Comments:
1616.48 g coal
421.80 g sawdust
95.83 g water (target 95.72 g)
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 1000-1300 ft-lb
Screw speed: 15-12 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	57.74	54.06	3.68	0.068
1	9.55	9.04	0.51	0.056
2	9.59	9.07	0.52	0.057
3	9.39	8.91	0.48	0.054
4	9.54	9.06	0.48	0.053
5	9.53	9.00	0.53	0.059
			Average:	**0.056**
			St. Dev:	**0.002**
			St. Dev (%):	**4.372**
1	9.34	8.91	0.43	0.048
2	9.38	8.96	0.42	0.047
3	9.32	8.93	0.39	0.044
4	9.38	8.99	0.39	0.043
5	9.32	8.94	0.38	0.043
			Average:	**0.045**
			St. Dev:	**0.002**
			St. Dev (%):	**5.533**
Durability 1	145.46	138.24	7.22	0.052
Durability 2	144.98	138.16	6.82	0.049
			Average:	**0.051**
			St. Dev:	**0.002**
			St. Dev (%):	**3.988**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.50	0.68	1.08	1.02
2	9.34	1.33	1.17	1.10
3	9.62	1.35	1.16	1.10
4	9.46	1.28	1.16	1.10
5	9.52	1.36	1.17	1.10
6	9.43	1.47	1.18	1.12
7	9.42	1.00	1.12	1.06
8	9.45	1.53	1.19	1.13
9	9.61	1.42	1.17	1.11
10	9.40	1.38	1.17	1.11
			Average:	**1.10**
			St. Dev:	**0.03**
			St. Dev (%):	**2.97**
1	9.26	1.40	1.18	1.13
2	9.17	0.81	1.10	1.05
3	9.40	1.49	1.19	1.14
4	9.60	1.45	1.18	1.13
5	9.43	1.36	1.17	1.12
6	9.44	1.19	1.14	1.10
7	9.40	1.26	1.15	1.11
8	9.45	1.32	1.16	1.11
9	9.39	1.26	1.15	1.11
10	9.40	1.17	1.14	1.09
			Average:	**1.11**
			St. Dev:	**0.02**
			St. Dev (%):	**2.24**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.20	145.71	77.01
2	188.83	145.06	76.82
		Average:	**76.92**
		St. Dev:	**0.14**
		St. Dev (%):	**0.18**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	102.2
2	79.1
3	110.2
4	91.6
5	112.5
6	96.1
7	93.3
8	109.0
9	98.3
10	111.3
11	120.5
12	105.4
13	120.4
14	132.8
15	100.8
16	111.9
17	49.0
18	132.0
19	96.5
20	76.5
21	113.4
22	107.1
23	107.4
24	125.5
25	143.3
26	90.9
27	124.6
28	95.8
29	131.9
30	115.6
31	78.4
32	125.0
33	129.6
34	92.8
35	116.2
36	117.2
37	133.5
38	78.0
39	122.4
40	135.7
41	120.9
42	127.6
43	136.7
44	105.5
45	105.7
46	94.0
47	119.6
48	99.9
49	102.5
50	92.0
Average:	**108.8**
St. Dev:	**18.8**
St. Dev (%):	**17.3**

Moisture Optimization Test

Sample:	MO-TC-8.2
Client:	DOE
Coal:	Toms Creek - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	8.2%
Date:	2/28/2013
Time	10:00:00 AM

Comments:
1616.48 g coal
421.80 g sawdust
125.86 g water (target 125.72 g)
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 900-1300 ft-lb
Screw speed: 15-20 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	61.30	56.61	4.69	0.083
1	9.27	8.66	0.61	0.070
2	9.25	8.66	0.59	0.068
3	9.18	8.47	0.71	0.084
4	9.72	9.10	0.62	0.068
5	9.17	8.52	0.65	0.076
			Average:	**0.073**
			St. Dev:	**0.007**
			St. Dev (%):	**9.178**
1	9.24	8.83	0.41	0.046
2	9.30	8.84	0.46	0.052
3	9.17	8.73	0.44	0.050
4	9.28	8.78	0.50	0.057
5	9.18	8.71	0.47	0.054
			Average:	**0.052**
			St. Dev:	**0.004**
			St. Dev (%):	**7.570**
Durability 1	117.89	111.08	6.81	0.061
Durability 2	116.27	110.04	6.23	0.057
			Average:	**0.059**
			St. Dev:	**0.003**
			St. Dev (%):	**5.626**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.28	0.93	1.11	1.04
2	9.34	1.03	1.12	1.05
3	9.47	1.22	1.15	1.07
4	9.19	1.12	1.14	1.06
5	9.69	1.39	1.17	1.09
6	9.20	1.12	1.14	1.06
7	9.19	1.17	1.15	1.07
8	9.40	1.17	1.14	1.06
9	9.41	0.93	1.11	1.03
10	9.11	1.15	1.14	1.07
			Average:	**1.06**
			St. Dev:	**0.02**
			St. Dev (%):	**1.55**
1	8.93	0.74	1.09	1.04
2	9.24	1.03	1.13	1.07
3	9.21	0.83	1.10	1.04
4	9.09	0.79	1.10	1.04
5	9.20	0.89	1.11	1.05
6	9.34	1.19	1.15	1.09
7	9.12	1.06	1.13	1.08
8	9.19	0.72	1.09	1.03
9	9.12	1.27	1.16	1.10
10	9.14	1.17	1.15	1.09
			Average:	**1.06**
			St. Dev:	**0.03**
			St. Dev (%):	**2.42**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	185.85	118.04	63.51
2	185.40	116.34	62.75
		Average:	**63.13**
		St. Dev:	**0.54**
		St. Dev (%):	**0.85**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	60.1
2	62.8
3	69.7
4	60.0
5	58.4
6	56.4
7	43.0
8	69.2
9	58.3
10	59.7
11	55.3
12	57.5
13	61.8
14	80.4
15	61.8
16	53.5
17	74.4
18	65.4
19	74.0
20	60.9
21	62.0
22	78.6
23	61.1
24	68.5
25	37.8
26	61.4
27	54.7
28	56.0
29	54.7
30	54.2
31	64.9
32	43.0
33	65.9
34	65.4
35	66.3
36	70.9
37	57.5
38	62.0
39	73.6
40	58.4
41	60.2
42	51.4
43	49.7
44	67.9
45	65.1
46	36.6
47	58.4
48	55.2
49	59.5
50	57.2
Average:	**60.4**
St. Dev:	**9.1**
St. Dev (%):	**15.0**

Moisture Optimization Test

Sample:	MO-MR-0.7
Client:	DOE
Coal:	McClure River - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	0.7%
Date:	4/12/2013
Time	10:00:00 AM

Comments:	1600.00 g coal
	400.00 g sawdust
	14.00 g water (target 14.00 g)
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1000-1200 ft-lb
	Screw speed: 15-18 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	41.40	40.95	0.45	0.011
1	8.87	8.78	0.09	0.010
2	8.96	8.88	0.08	0.009
3	9.07	9.00	0.07	0.008
4	9.01	8.94	0.07	0.008
5	9.05	8.97	0.08	0.009
			Average:	**0.009**
			St. Dev:	**0.001**
			St. Dev (%):	**11.615**
1	9.00	8.88	0.12	0.014
2	9.11	8.99	0.12	0.013
3	9.11	8.99	0.12	0.013
4	8.90	8.79	0.11	0.013
5	9.05	8.95	0.10	0.011
			Average:	**0.013**
			St. Dev:	**0.001**
			St. Dev (%):	**7.663**
Durability 1	168.81	166.63	2.18	0.013
Durability 2	168.98	166.80	2.18	0.013
			Average:	**0.013**
			St. Dev:	**0.000**
			St. Dev (%):	**0.072**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.07	1.21	1.15	1.14
2	9.36	1.25	1.15	1.14
3	8.91	1.07	1.14	1.13
4	9.35	1.24	1.15	1.14
5	8.94	0.92	1.11	1.11
6	9.07	1.16	1.15	1.14
7	8.98	1.12	1.14	1.13
8	8.92	0.91	1.11	1.10
9	9.03	1.14	1.14	1.13
10	8.70	0.78	1.10	1.09
			Average:	**1.13**
			St. Dev:	**0.02**
			St. Dev (%):	**1.74**
1	8.95	1.00	1.13	1.11
2	8.85	1.12	1.14	1.13
3	8.96	0.89	1.11	1.10
4	8.97	0.95	1.12	1.10
5	9.11	1.19	1.15	1.14
6	9.26	1.18	1.15	1.13
7	9.03	0.98	1.12	1.11
8	8.96	1.13	1.14	1.13
9	9.06	1.13	1.14	1.13
10	9.14	1.10	1.14	1.12
			Average:	**1.12**
			St. Dev:	**0.01**
			St. Dev (%):	**1.22**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	181.03	168.84	93.27
2	180.93	169.03	93.42
		Average:	**93.34**
		St. Dev:	**0.11**
		St. Dev (%):	**0.12**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	181.1
2	180.8
3	164.6
4	181.8
5	192.9
6	190.8
7	215.3
8	207.1
9	229.3
10	176.4
11	156.8
12	185.2
13	161.2
14	190.8
15	188.8
16	195.6
17	162.0
18	175.0
19	194.0
20	172.5
21	200.9
22	194.4
23	182.5
24	171.8
25	209.6
26	155.9
27	177.9
28	213.5
29	220.7
30	197.0
31	213.0
32	180.1
33	205.1
34	198.7
35	180.4
36	192.4
37	211.0
38	203.1
39	195.5
40	200.2
41	174.5
42	191.6
43	193.6
44	215.7
45	203.3
46	176.5
47	205.4
48	169.6
49	189.9
50	170.7
Average:	**189.9**
St. Dev:	**17.3**
St. Dev (%):	**9.1**

Moisture Optimization Test

Sample:	MO-MR-1.5
Client:	DOE
Coal:	McClure River - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	1.5%
Date:	4/8/2013
Time	1:00:00 PM

Comments:

1600.00 g coal
421.80 g sawdust
8.19 g water (target 8.20 g)
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 1000-1300 ft-lb
Screw speed: 15-18 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	57.19	56.29	0.90	0.016
1	9.25	9.13	0.12	0.013
2	9.36	9.23	0.13	0.014
3	8.82	8.70	0.12	0.014
4	9.00	8.88	0.12	0.014
5	8.90	8.78	0.12	0.014
			Average:	**0.014**
			St. Dev:	**0.000**
			St. Dev (%):	**2.551**
1	8.75	8.62	0.13	0.015
2	8.83	8.71	0.12	0.014
3	9.12	9.00	0.12	0.013
4	9.16	9.04	0.12	0.013
5	9.03	8.92	0.11	0.012
			Average:	**0.014**
			St. Dev:	**0.001**
			St. Dev (%):	**7.377**
Durability 1	171.68	169.24	2.44	0.014
Durability 2	169.33	166.87	2.46	0.015
			Average:	**0.015**
			St. Dev:	**0.000**
			St. Dev (%):	**1.574**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.42	1.41	1.18	1.16
2	9.00	1.17	1.15	1.13
3	9.11	0.99	1.12	1.11
4	9.28	1.31	1.16	1.15
5	9.00	1.24	1.16	1.14
6	9.10	1.32	1.17	1.15
7	9.11	1.08	1.13	1.12
8	8.91	0.99	1.13	1.11
9	9.11	1.23	1.16	1.14
10	9.15	1.27	1.16	1.15
			Average:	**1.14**
			St. Dev:	**0.02**
			St. Dev (%):	**1.62**
1	8.96	0.96	1.12	1.11
2	8.93	1.19	1.15	1.14
3	9.09	1.22	1.16	1.14
4	9.36	1.09	1.13	1.12
5	8.97	0.88	1.11	1.09
6	9.40	1.30	1.16	1.14
7	9.30	1.04	1.13	1.11
8	8.96	1.07	1.14	1.12
9	9.03	0.73	1.09	1.07
10	9.05	1.13	1.14	1.13
			Average:	**1.12**
			St. Dev:	**0.02**
			St. Dev (%):	**2.00**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	181.99	171.79	94.40
2	179.63	169.40	94.30
		Average:	**94.35**
		St. Dev:	**0.06**
		St. Dev (%):	**0.07**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	154.3
2	193.2
3	176.0
4	155.3
5	208.8
6	217.8
7	181.8
8	193.9
9	192.1
10	186.9
11	217.5
12	164.8
13	156.3
14	197.6
15	142.4
16	172.7
17	222.8
18	156.1
19	248.8
20	168.9
21	199.0
22	201.5
23	227.6
24	226.8
25	156.8
26	139.9
27	171.6
28	201.0
29	154.2
30	157.4
31	149.0
32	186.8
33	216.7
34	211.9
35	237.2
36	236.8
37	179.6
38	247.3
39	237.8
40	204.3
41	233.5
42	182.7
Average:	**192.1**
St. Dev:	**31.1**
St. Dev (%):	**16.2**

Moisture Optimization Test

Sample:	MO-MR-2.2
Client:	DOE
Coal:	McClure River - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	2.2%
Date:	3/18/2013
Time	1:00:00 PM

Comments:	1614.88 g coal
	421.80 g sawdust
	g water (target 7.32 g)
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 900-1200 N-m
	Screw speed: 16-19 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	47.10	46.08	1.02	0.022
1	9.09	8.93	0.16	0.018
2	8.99	8.83	0.16	0.018
3	9.06	8.91	0.15	0.017
4	8.85	8.71	0.14	0.016
5	9.05	8.89	0.16	0.018
			Average:	**0.017**
			St. Dev:	**0.001**
			St. Dev (%):	**5.161**
1	8.97	8.83	0.14	0.016
2	9.03	8.89	0.14	0.016
3	9.07	8.93	0.14	0.016
4	9.10	8.95	0.15	0.017
5	9.15	9.01	0.14	0.016
			Average:	**0.016**
			St. Dev:	**0.000**
			St. Dev (%):	**3.051**
Durability 1	171.96	169.08	2.88	0.017
Durability 2	172.92	169.91	3.01	0.018
			Average:	**0.017**
			St. Dev:	**0.000**
			St. Dev (%):	**2.775**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.87	1.33	1.18	1.16
2	9.18	1.34	1.17	1.15
3	8.78	1.29	1.17	1.15
4	8.77	1.23	1.16	1.14
5	8.98	1.30	1.17	1.15
6	8.89	1.22	1.16	1.14
7	9.35	1.49	1.19	1.17
8	9.07	1.37	1.18	1.16
9	9.26	1.32	1.17	1.15
10	8.98	1.29	1.17	1.15
			Average:	**1.15**
			St. Dev:	**0.01**
			St. Dev (%):	**0.73**
1	9.45	1.47	1.18	1.17
2	9.19	1.40	1.18	1.16
3	8.92	1.25	1.16	1.14
4	9.48	1.44	1.18	1.16
5	9.27	1.22	1.15	1.13
6	9.17	1.16	1.14	1.13
7	9.47	1.28	1.16	1.14
8	9.20	1.12	1.14	1.12
9	9.13	1.31	1.17	1.15
10	9.19	1.38	1.18	1.16
			Average:	**1.15**
			St. Dev:	**0.02**
			St. Dev (%):	**1.37**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	180.75	172.02	95.17
2	181.87	172.97	95.11
		Average:	**95.14**
		St. Dev:	**0.05**
		St. Dev (%):	**0.05**

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	261.9
2	281.0
3	273.5
4	283.2
5	270.4
6	313.9
7	294.1
8	285.4
9	275.1
10	273.2
11	284.7
12	285.8
13	279.2
14	281.2
15	281.5
16	287.8
17	304.9
18	306.9
19	272.5
20	283.3
21	214.6
22	210.6
23	248.5
24	228.2
25	271.3
26	268.9
27	286.3
28	224.6
29	227.1
30	241.0
31	258.4
32	233.9
33	216.3
34	292.4
35	272.7
36	230.9
37	296.4
38	295.0
39	273.0
40	291.9
41	291.4
42	261.6
Average:	**269.4**
St. Dev:	**26.8**
St. Dev (%):	**10.0**

Moisture Optimization Test

Sample:	MO-MR-3.7
Client:	DOE
Coal:	McClure River - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	3.7%
Date:	4/5/2013
Time	11:00:00 AM

Comments:
1614.88 g coal
421.80 g sawdust
37.34 g water (target 37.32 g)
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 900-1300 ft-lb
Screw speed: 14-17 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	42.87	41.29	1.58	0.038
1	9.38	9.11	0.27	0.030
2	9.33	9.08	0.25	0.028
3	9.36	9.10	0.26	0.029
4	9.57	9.30	0.27	0.029
5	9.18	8.92	0.26	0.029
			Average:	**0.029**
			St. Dev:	**0.001**
			St. Dev (%):	**2.765**
1	9.43	9.18	0.25	0.027
2	9.89	9.62	0.27	0.028
3	9.30	9.05	0.25	0.028
4	9.82	9.55	0.27	0.028
5	9.16	8.91	0.25	0.028
			Average:	**0.028**
			St. Dev:	**0.000**
			St. Dev (%):	**1.502**
Durability 1	174.67	169.74	4.93	0.029
Durability 2	175.99	171.08	4.91	0.029
			Average:	**0.029**
			St. Dev:	**0.000**
			St. Dev (%):	**0.843**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.35	1.43	1.18	1.15
2	9.27	1.30	1.16	1.13
3	9.40	1.28	1.16	1.13
4	9.59	1.29	1.16	1.12
5	9.24	1.24	1.16	1.12
6	9.47	0.97	1.11	1.08
7	9.18	1.25	1.16	1.13
8	9.09	1.15	1.14	1.11
9	9.44	1.18	1.14	1.11
10	9.32	1.33	1.17	1.13
			Average:	**1.12**
			St. Dev:	**0.02**
			St. Dev (%):	**1.52**
1	9.16	1.19	1.15	1.12
2	9.36	1.39	1.17	1.14
3	9.25	0.93	1.11	1.08
4	9.27	1.34	1.17	1.14
5	9.32	1.25	1.15	1.12
6	9.47	1.07	1.13	1.10
7	9.56	1.42	1.17	1.14
8	9.09	1.14	1.14	1.11
9	9.23	1.29	1.16	1.13
10	9.32	1.30	1.16	1.13
			Average:	**1.12**
			St. Dev:	**0.02**
			St. Dev (%):	**1.78**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	185.88	174.72	94.00
2	186.20	176.03	94.54
		Average:	**94.27**
		St. Dev:	**0.38**
		St. Dev (%):	**0.41**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	245.9
2	243.9
3	268.4
4	310.4
5	271.5
6	259.5
7	230.3
8	242.7
9	246.9
10	230.6
11	247.4
12	205.4
13	235.6
14	226.7
15	242.7
16	233.9
17	257.4
18	228.4
19	245.9
20	233.1
21	227.6
22	271.5
23	277.7
24	218.8
25	247.1
26	245.3
27	230.8
28	258.4
29	254.9
30	237.2
31	232.5
32	249.3
33	224.7
34	248.2
35	265.4
36	263.3
37	240.5
38	293.5
39	242.9
40	252.1
41	234.3
42	281.9
43	204.2
44	262.4
45	251.9
46	331.9
47	229.1
48	322.2
49	286.7
50	306.4
Average:	**252.0**
St. Dev:	**27.2**
St. Dev (%):	**10.8**

Moisture Optimization Test

Sample:	MO-MR-5.2
Client:	DOE
Coal:	McClure River - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	5.2%
Date:	4/5/2013
Time	2:00:00 PM

Comments:
1614.88 g coal
421.80 g sawdust
67.33 g water (target 67.32 g)
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 900-1400 ft-lb
Screw speed: 14-18 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	40.34	38.61	1.73	0.045
1	9.24	8.87	0.37	0.042
2	9.51	9.13	0.38	0.042
3	9.38	9.04	0.34	0.038
4	9.63	9.26	0.37	0.040
5	9.69	9.36	0.33	0.035
			Average:	**0.039**
			St. Dev:	**0.003**
			St. Dev (%):	**7.076**
1	9.30	8.98	0.32	0.036
2	9.37	9.07	0.30	0.033
3	9.33	9.03	0.30	0.033
4	9.27	8.97	0.30	0.033
5	9.13	8.83	0.30	0.034
			Average:	**0.034**
			St. Dev:	**0.001**
			St. Dev (%):	**3.081**
Durability 1	169.26	163.37	5.89	0.036
Durability 2	165.90	160.25	5.65	0.035
			Average:	**0.036**
			St. Dev:	**0.001**
			St. Dev (%):	**1.578**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.18	1.22	1.15	1.11
2	9.46	1.29	1.16	1.11
3	9.31	1.29	1.16	1.12
4	9.25	1.03	1.13	1.08
5	9.50	1.23	1.15	1.11
6	9.23	0.95	1.11	1.07
7	9.06	1.09	1.14	1.09
8	9.36	1.30	1.16	1.12
9	9.58	1.16	1.14	1.09
10	9.40	1.31	1.16	1.12
			Average:	**1.10**
			St. Dev:	**0.02**
			St. Dev (%):	**1.45**
1	9.50	1.35	1.17	1.13
2	9.25	1.16	1.14	1.11
3	9.29	1.22	1.15	1.11
4	9.14	1.19	1.15	1.11
5	9.29	0.99	1.12	1.08
6	9.28	0.88	1.10	1.07
7	9.33	0.96	1.11	1.08
8	9.30	1.06	1.13	1.09
9	9.16	1.07	1.13	1.10
10	9.28	0.89	1.11	1.07
			Average:	**1.09**
			St. Dev:	**0.02**
			St. Dev (%):	**1.82**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.90	169.38	90.14
2	185.79	166.02	89.36
		Average:	**89.75**
		St. Dev:	**0.55**
		St. Dev (%):	**0.62**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	195.3
2	172.6
3	194.8
4	193.7
5	226.1
6	231.6
7	187.4
8	168.8
9	164.8
10	214.8
11	177.5
12	198.2
13	251.8
14	188.2
15	193.1
16	190.4
17	214.6
18	158.5
19	269.0
20	197.8
21	221.9
22	168.7
23	210.4
24	199.4
25	213.5
26	204.5
27	182.5
28	139.4
29	196.1
30	214.9
31	187.2
32	260.6
33	197.8
34	234.1
35	151.9
36	218.6
37	185.0
38	192.3
39	200.5
40	187.1
41	192.9
42	201.5
43	176.7
44	239.7
45	180.7
46	193.4
47	183.5
48	228.2
49	222.0
50	261.0
Average:	**200.7**
St. Dev:	**27.6**
St. Dev (%):	**13.7**

Moisture Optimization Test

Sample:	MO-MR-6.7
Client:	DOE
Coal:	McClure River - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	6.7%
Date:	4/8/2013
Time	2:00:00 PM

Comments:
1614.88 g coal
421.80 g sawdust
97.33 g water (target 97.32 g)
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 900-1200 ft-lb
Screw speed: 16-20 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	45.24	42.68	2.56	0.060
1	8.92	8.43	0.49	0.058
2	9.04	8.56	0.48	0.056
3	9.15	8.65	0.5	0.058
4	9.41	8.93	0.48	0.054
5	9.25	8.79	0.46	0.052
			Average:	**0.056**
			St. Dev:	**0.003**
			St. Dev (%):	**4.545**
1	8.86	8.46	0.40	0.047
2	9.36	8.92	0.44	0.049
3	9.22	8.81	0.41	0.047
4	9.20	8.80	0.40	0.045
5	9.10	8.69	0.41	0.047
			Average:	**0.047**
			St. Dev:	**0.001**
			St. Dev (%):	**3.000**
Durability 1	147.68	140.57	7.11	0.051
Durability 2			0.00	#DIV/0!
			Average:	**#DIV/0!**
			St. Dev:	**#DIV/0!**
			St. Dev (%):	**#DIV/0!**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.84	0.87	1.11	1.05
2	9.23	0.67	1.08	1.02
3	9.15	0.99	1.12	1.06
4	9.31	0.80	1.09	1.04
5	9.28	0.47	1.05	1.00
6	9.21	1.01	1.12	1.06
7	8.91	0.73	1.09	1.03
8	9.29	1.01	1.12	1.06
9	9.26	1.02	1.12	1.06
10	8.95	0.50	1.06	1.00
			Average:	**1.04**
			St. Dev:	**0.03**
			St. Dev (%):	**2.45**
1	9.14	0.96	1.12	1.07
2	9.17	0.69	1.08	1.03
3	9.22	0.86	1.10	1.05
4	9.40	0.74	1.09	1.04
5	9.34	0.48	1.05	1.01
6	9.18	0.93	1.11	1.06
7	9.29	0.87	1.10	1.05
8	9.03	0.77	1.09	1.04
9	9.15	0.79	1.09	1.05
10	9.03	0.59	1.07	1.02
			Average:	**1.04**
			St. Dev:	**0.02**
			St. Dev (%):	**1.78**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	182.49	147.80	80.99
2			
		Average:	**80.99**
		St. Dev:	**#DIV/0!**
		St. Dev (%):	**#DIV/0!**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	140.8
2	97.8
3	117.4
4	87.8
5	104.9
6	115.5
7	120.0
8	114.7
9	111.4
10	117.7
11	112.1
12	132.2
13	113.6
14	93.6
15	114.4
16	106.5
17	110.4
18	111.5
19	123.2
20	99.9
21	118.8
22	129.8
23	132.7
24	114.2
25	99.0
26	107.6
27	104.6
28	106.5
29	79.8
30	98.7
31	100.7
32	104.2
33	115.3
34	108.1
35	121.0
36	106.6
37	127.0
38	90.8
39	103.7
40	82.0
41	105.1
42	135.4
43	114.6
44	88.3
45	93.6
46	83.2
47	114.3
48	104.1
49	115.0
50	110.9
Average:	**109.2**
St. Dev:	**13.7**
St. Dev (%):	**12.5**

Moisture Optimization Test

Sample:	MO-MR-8.2
Client:	DOE
Coal:	McClure River - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	8.2%
Date:	4/12/2013
Time	1:00:00 PM

Comments:
1614.88 g coal
421.80 g sawdust
127.32 g water (target 127.32 g)
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 900-1300 ft-lb
Screw speed: 17-21 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	38.72	36.01	2.71	0.075
1	8.89	8.32	0.57	0.069
2	9.15	8.58	0.57	0.066
3	8.86	8.28	0.58	0.070
4	8.98	8.42	0.56	0.067
5	9.00	8.44	0.56	0.066
			Average:	**0.068**
			St. Dev:	**0.002**
			St. Dev (%):	**2.446**
1	9.16	8.63	0.53	0.061
2	8.90	8.37	0.53	0.063
3	9.17	8.64	0.53	0.061
4	8.99	8.48	0.51	0.060
5	9.09	8.55	0.54	0.063
			Average:	**0.062**
			St. Dev:	**0.001**
			St. Dev (%):	**2.174**
Durability 1	124.94	117.37	7.57	0.064
Durability 2			0.00	#DIV/0!
			Average:	**#DIV/0!**
			St. Dev:	**#DIV/0!**
			St. Dev (%):	**#DIV/0!**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.12	0.98	1.12	1.05
2	9.04	0.64	1.08	1.01
3	8.94	0.55	1.07	1.00
4	9.21	0.75	1.09	1.02
5	9.09	0.87	1.11	1.04
6	9.26	0.83	1.10	1.03
7	8.88	0.52	1.06	0.99
8	9.26	0.65	1.08	1.01
9	8.85	0.53	1.06	1.00
10	9.12	0.65	1.08	1.01
			Average:	**1.01**
			St. Dev:	**0.02**
			St. Dev (%):	**1.80**
1	9.02	0.42	1.05	0.99
2	9.04	0.66	1.08	1.02
3	9.11	0.64	1.08	1.01
4	8.89	0.42	1.05	0.99
5	8.98	0.49	1.06	1.00
6	9.14	0.54	1.06	1.00
7	9.07	0.56	1.07	1.00
8	9.01	0.37	1.04	0.98
9	9.06	0.45	1.05	0.99
10	9.12	0.52	1.06	1.00
			Average:	**1.00**
			St. Dev:	**0.01**
			St. Dev (%):	**1.10**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	180.01	124.99	69.44
2			
		Average:	**69.44**
		St. Dev:	**#DIV/0!**
		St. Dev (%):	**#DIV/0!**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	50.3
2	59.7
3	61.2
4	59.7
5	58.6
6	58.4
7	56.2
8	53.2
9	71.1
10	45.4
11	56.9
12	76.5
13	72.1
14	59.2
15	60.3
16	53.1
17	61.9
18	54.8
19	58.5
20	70.9
21	61.6
22	59.5
23	64.6
24	60.9
25	48.8
26	51.8
27	56.2
28	73.0
29	58.9
30	62.7
31	63.1
32	49.2
33	53.9
34	63.0
35	59.0
36	55.6
37	59.6
38	59.0
39	69.9
40	62.3
41	48.1
42	61.8
43	54.6
44	59.2
45	57.5
46	49.0
47	68.4
48	69.5
49	58.2
50	61.7
Average:	**59.6**
St. Dev:	**6.8**
St. Dev (%):	**11.5**

Moisture Optimization Test

Sample:	MO-EM-0.7
Client:	DOE
Coal:	Emerald - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	0.7%
Date:	4/26/2013
Time	2:00:00 PM

Comments:
1600.00 g coal
400.00 g sawdust
14.00 g water (target 14.00 g)
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 1000-1300 ft-lb
Screw speed:

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	27.38	27.19	0.19	0.007
1	9.04	9.00	0.04	0.004
2	9.21	9.13	0.08	0.009
3	9.22	9.16	0.06	0.007
4	9.04	9.00	0.04	0.004
5	9.10	9.03	0.07	0.008
			Average:	**0.006**
			St. Dev:	**0.002**
			St. Dev (%):	**30.381**
1	8.93	8.86	0.07	0.008
2	9.09	9.03	0.06	0.007
3	9.04	8.98	0.06	0.007
4	9.14	9.09	0.05	0.006
5	9.05	8.98	0.07	0.008
			Average:	**0.007**
			St. Dev:	**0.001**
			St. Dev (%):	**14.253**
Durability 1	169.96	168.85	1.11	0.007
Durability 2	171.60	170.50	1.10	0.006
			Average:	**0.007**
			St. Dev:	**0.000**
			St. Dev (%):	**1.328**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.96	1.09	1.14	1.13
2	9.26	1.18	1.15	1.14
3	9.14	1.26	1.16	1.15
4	8.90	0.78	1.10	1.09
5	9.05	1.09	1.14	1.13
6	9.23	1.16	1.14	1.14
7	9.10	1.21	1.15	1.15
8	8.76	0.72	1.09	1.08
9	8.98	1.26	1.16	1.16
10	9.19	1.02	1.12	1.12
			Average:	**1.13**
			St. Dev:	**0.02**
			St. Dev (%):	**2.21**
1	9.01	1.12	1.14	1.13
2	9.06	1.17	1.15	1.14
3	8.84	1.07	1.14	1.13
4	8.48	0.81	1.11	1.10
5	8.73	0.95	1.12	1.11
6	9.09	1.12	1.14	1.13
7	9.16	0.85	1.10	1.09
8	9.30	1.22	1.15	1.14
9	9.28	0.99	1.12	1.11
10	9.02	0.95	1.12	1.11
			Average:	**1.12**
			St. Dev:	**0.02**
			St. Dev (%):	**1.55**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	181.95	169.95	93.40
2	181.55	171.60	94.52
		Average:	**93.96**
		St. Dev:	**0.79**
		St. Dev (%):	**0.84**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	217.4
2	258.6
3	238.6
4	192.5
5	209.8
6	210.7
7	153.5
8	255.6
9	249.4
10	226.5
11	196.7
12	219.8
13	245.8
14	260.2
15	257.2
16	193.4
17	215.9
18	282.0
19	275.4
20	197.0
21	257.5
22	215.5
23	190.0
24	265.7
25	252.6
26	247.5
27	290.1
28	253.7
29	264.3
30	269.6
31	226.8
32	229.6
33	254.2
34	239.8
35	248.1
36	212.9
37	251.2
38	255.2
39	265.6
40	289.6
41	226.1
42	241.6
43	267.7
44	244.1
45	289.2
46	256.5
47	238.8
48	267.4
49	266.1
50	202.7
Average:	**240.7**
St. Dev:	**29.7**
St. Dev (%):	**12.3**

Moisture Optimization Test

Sample:	MO-EM-1.5
Client:	DOE
Coal:	Emerald - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	1.5%
Date:	4/26/2013
Time	11:00:00 AM

Comments:	1600.00 g coal
	421.80 g sawdust
	8.20 g water (target 8.20 g)
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1000-1300 ft-lb
	Screw speed:

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	28.55	28.05	0.50	0.018
1	9.17	9.05	0.12	0.013
2	9.27	9.15	0.12	0.013
3	9.11	8.99	0.12	0.013
4	9.07	8.94	0.13	0.015
5	9.12	9.00	0.12	0.013
			Average:	**0.014**
			St. Dev:	**0.001**
			St. Dev (%):	**4.281**
1	9.25	9.12	0.13	0.014
2	9.28	9.14	0.14	0.015
3	8.95	8.83	0.12	0.014
4	9.08	8.95	0.13	0.015
5	9.01	8.88	0.13	0.015
			Average:	**0.014**
			St. Dev:	**0.001**
			St. Dev (%):	**4.332**
Durability 1	173.14	170.59	2.55	0.015
Durability 2	173.04	170.50	2.54	0.015
			Average:	**0.015**
			St. Dev:	**0.000**
			St. Dev (%):	**0.241**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.94	1.33	1.17	1.16
2	9.00	1.24	1.16	1.14
3	9.42	0.96	1.11	1.10
4	8.74	0.98	1.13	1.11
5	9.10	1.31	1.17	1.15
6	9.02	1.28	1.17	1.15
7	9.22	0.68	1.08	1.07
8	9.11	1.20	1.15	1.14
9	9.40	1.46	1.18	1.17
10	9.11	1.32	1.17	1.15
			Average:	**1.13**
			St. Dev:	**0.03**
			St. Dev (%):	**2.85**
1	9.22	1.34	1.17	1.15
2	8.98	1.13	1.14	1.13
3	9.41	1.46	1.18	1.17
4	9.14	1.19	1.15	1.13
5	9.14	1.16	1.15	1.13
6	9.15	1.34	1.17	1.15
7	9.27	1.33	1.17	1.15
8	9.03	1.28	1.17	1.15
9	8.93	1.22	1.16	1.14
10	9.17	1.23	1.15	1.14
			Average:	**1.14**
			St. Dev:	**0.01**
			St. Dev (%):	**1.10**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	183.00	173.16	94.62
2	182.73	173.06	94.71
		Average:	**94.67**
		St. Dev:	**0.06**
		St. Dev (%):	**0.06**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	274.4
2	302.6
3	296.2
4	308.9
5	303.3
6	304.2
7	270.7
8	295.0
9	280.5
10	327.7
11	277.0
12	319.6
13	259.3
14	308.3
15	244.6
16	185.9
17	281.7
18	259.4
19	288.5
20	217.8
21	276.1
22	266.6
23	266.2
24	266.6
25	289.3
26	285.0
27	272.1
28	288.0
29	258.3
30	242.6
31	291.7
32	291.3
33	294.3
34	285.1
35	227.3
36	218.2
37	260.0
38	245.9
39	293.2
40	276.6
41	212.6
42	261.8
43	203.1
44	220.5
45	267.3
46	199.2
47	287.9
48	193.2
49	315.0
50	212.0
Average:	**267.5**
St. Dev:	**35.2**
St. Dev (%):	**13.2**

Moisture Optimization Test	
Sample:	MO-EM-2.2
Client:	DOE
Coal:	Emerald - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	2.2%
Date:	4/23/2013
Time	10:00:00 AM

Comments:	
	1618.24 g coal
	421.80 g sawdust
	3.97 g water (target 3.96 g)
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1000-1300 Nm
	Screw speed: 16-19 hz

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	33.13	32.32	0.81	0.025
1	9.27	9.09	0.18	0.020
2	9.34	9.15	0.19	0.021
3	9.14	8.96	0.18	0.020
4	9.13	8.95	0.18	0.020
5	9.07	8.89	0.18	0.020
			Average:	0.020
			St. Dev:	0.000
			St. Dev (%):	1.750
1	8.98	8.79	0.19	0.022
2	8.91	8.73	0.18	0.021
3	9.32	9.13	0.19	0.021
4	9.03	8.85	0.18	0.020
5	9.28	9.09	0.19	0.021
			Average:	0.021
			St. Dev:	0.000
			St. Dev (%):	2.280
Durability 1	174.68	171.06	3.62	0.021
Durability 2			0.00	#DIV/0!
			Average:	#DIV/0!
			St. Dev:	#DIV/0!
			St. Dev (%):	#DIV/0!

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.48	1.59	1.20	1.18
2	9.24	1.48	1.19	1.17
3	9.23	1.44	1.18	1.16
4	9.23	1.49	1.19	1.17
5	9.07	1.17	1.15	1.13
6	8.89	1.19	1.15	1.13
7	9.44	1.54	1.19	1.17
8	9.36	1.39	1.17	1.15
9	9.44	1.27	1.16	1.13
10	9.05	1.37	1.18	1.16
			Average:	1.15
			St. Dev:	0.02
			St. Dev (%):	1.61
1	9.00	1.23	1.16	1.13
2	9.08	1.39	1.18	1.16
3	9.21	1.46	1.19	1.16
4	9.08	1.20	1.15	1.13
5	9.15	1.37	1.18	1.15
6	9.06	1.14	1.14	1.12
7	9.31	1.34	1.17	1.14
8	9.14	1.15	1.14	1.12
9	9.00	1.37	1.18	1.16
10	8.88	1.21	1.16	1.13
			Average:	1.14
			St. Dev:	0.02
			St. Dev (%):	1.37

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	183.46	174.68	95.21
2			
		Average:	95.21
		St. Dev:	#DIV/0!
		St. Dev (%):	#DIV/0!

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	309.2
2	328.4
3	253.2
4	289.0
5	328.3
6	252.4
7	287.0
8	278.2
9	307.2
10	311.5
11	323.6
12	274.7
13	298.8
14	300.0
15	270.5
16	296.8
17	257.0
18	266.6
19	256.0
20	275.7
21	264.3
22	311.3
23	282.6
24	274.1
25	245.1
26	297.6
27	253.7
28	270.8
29	275.7
30	313.0
31	244.5
32	265.8
33	259.2
34	237.8
35	293.0
36	246.5
37	267.9
38	272.3
39	316.8
40	329.3
41	267.2
42	225.5
43	271.7
44	314.8
45	280.6
46	243.0
47	284.3
48	239.4
49	280.9
50	267.0
Average:	279.2
St. Dev:	26.5
St. Dev (%):	9.5

Moisture Optimization Test

Sample:	MO-EM-3.7
Client:	DOE
Coal:	Emerald - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	3.7%
Date:	4/25/2013
Time	9:00:00 AM

Comments:	1618.24 g coal
	421.80 g sawdust
	33.96 g water (target 33.96 g)
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 900-1300 ft-lb
	Screw speed:

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	28.04	26.87	1.17	0.044
1	9.29	9.01	0.28	0.031
2	9.29	8.99	0.30	0.033
3	9.21	8.93	0.28	0.031
4	9.44	9.14	0.30	0.033
5	9.45	9.15	0.30	0.033
			Average:	**0.032**
			St. Dev:	**0.001**
			St. Dev (%):	**3.115**
1	9.02	8.73	0.29	0.033
2	9.51	9.21	0.30	0.033
3	9.49	9.21	0.28	0.030
4	9.32	9.04	0.28	0.031
5	9.19	8.94	0.25	0.028
			Average:	**0.031**
			St. Dev:	**0.002**
			St. Dev (%):	**6.639**
Durability 1	175.64	171.01	4.63	0.027
Durability 2	177.60	172.22	5.38	0.031
			Average:	**0.029**
			St. Dev:	**0.003**
			St. Dev (%):	**10.100**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.45	1.66	1.21	1.18
2	9.11	1.37	1.18	1.14
3	9.10	1.45	1.19	1.15
4	9.15	1.44	1.19	1.15
5	9.31	1.46	1.19	1.15
6	9.55	1.47	1.18	1.14
7	9.35	1.28	1.16	1.12
8	9.52	1.45	1.18	1.14
9	9.52	1.37	1.17	1.13
10	9.28	1.40	1.18	1.14
			Average:	**1.14**
			St. Dev:	**0.01**
			St. Dev (%):	**1.21**
1	9.36	1.58	1.20	1.17
2	9.21	1.38	1.18	1.14
3	9.65	1.53	1.19	1.15
4	9.26	1.25	1.16	1.12
5	9.46	1.37	1.17	1.13
6	9.28	1.23	1.15	1.12
7	9.12	1.31	1.17	1.13
8	9.40	1.40	1.18	1.14
9	9.10	1.29	1.17	1.13
10	9.34	1.25	1.15	1.12
			Average:	**1.14**
			St. Dev:	**0.02**
			St. Dev (%):	**1.35**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	186.21	176.36	94.71
2	186.47	177.63	95.26
		Average:	**94.98**
		St. Dev:	**0.39**
		St. Dev (%):	**0.41**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	327.7
2	292.9
3	308.8
4	316.8
5	314.8
6	292.7
7	296.8
8	322.1
9	326.2
10	334.4
11	303.1
12	294.8
13	249.4
14	288.3
15	308.1
16	318.8
17	301.9
18	306.9
19	349.2
20	302.1
21	297.9
22	262.0
23	277.8
24	284.7
25	271.6
26	263.4
27	290.0
28	280.7
29	279.9
30	294.4
31	260.3
32	331.8
33	345.1
34	282.3
35	282.1
36	342.4
37	327.8
38	316.6
39	241.3
40	276.5
41	256.1
42	276.2
43	294.9
44	301.2
45	351.4
46	286.3
47	331.2
48	270.4
49	293.4
50	346.7
Average:	**299.4**
St. Dev:	**27.2**
St. Dev (%):	**9.1**

Moisture Optimization Test

Sample:	MO-EM-5.2
Client:	DOE
Coal:	Emerald - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	5.2%
Date:	4/25/2013
Time	11:00:00 AM

Comments:
1618.24 g coal
421.80 g sawdust
63.96 g water (target 63.96 g)
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 1000-1400 ft-lb
Screw speed:

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	31.31	29.75	1.56	0.052
1	9.56	9.16	0.40	0.044
2	9.31	8.92	0.39	0.044
3	9.53	9.14	0.39	0.043
4	9.57	9.14	0.43	0.047
5	9.47	9.04	0.43	0.048
			Average:	**0.045**
			St. Dev:	**0.002**
			St. Dev (%):	**4.925**
1	9.46	9.10	0.36	0.040
2	9.46	9.11	0.35	0.038
3	9.54	9.15	0.39	0.043
4	9.38	9.00	0.38	0.042
5	9.22	8.87	0.35	0.039
			Average:	**0.040**
			St. Dev:	**0.002**
			St. Dev (%):	**4.584**
Durability 1	173.34	166.26	7.08	0.043
Durability 2	173.46	166.37	7.09	0.043
			Average:	**0.043**
			St. Dev:	**0.000**
			St. Dev (%):	**0.053**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.46	1.55	1.20	1.14
2	9.38	1.58	1.20	1.15
3	9.18	1.16	1.14	1.10
4	9.50	1.28	1.16	1.11
5	9.70	1.41	1.17	1.12
6	9.09	1.07	1.13	1.08
7	9.46	1.14	1.14	1.09
8	9.75	1.36	1.16	1.11
9	9.38	1.17	1.14	1.09
10	9.47	1.37	1.17	1.12
			Average:	**1.11**
			St. Dev:	**0.02**
			St. Dev (%):	**2.04**
1	9.36	1.45	1.18	1.14
2	9.38	1.39	1.17	1.13
3	9.41	1.41	1.18	1.13
4	9.48	1.29	1.16	1.11
5	9.42	1.35	1.17	1.12
6	9.44	1.38	1.17	1.13
7	9.11	1.28	1.16	1.12
8	9.07	1.20	1.15	1.11
9	9.46	1.27	1.16	1.11
10	9.40	1.12	1.14	1.09
			Average:	**1.12**
			St. Dev:	**0.01**
			St. Dev (%):	**1.20**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.14	173.43	92.18
2	188.25	173.51	92.17
		Average:	**92.18**
		St. Dev:	**0.01**
		St. Dev (%):	**0.01**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	193.6
2	237.2
3	262.7
4	176.5
5	204.4
6	141.4
7	237.8
8	216.2
9	233.9
10	235.2
11	266.2
12	218.2
13	269.7
14	243.9
15	221.4
16	213.1
17	206.5
18	218.5
19	220.5
20	234.5
21	252.6
22	246.0
23	240.8
24	236.0
25	237.7
26	246.6
27	204.7
28	254.8
29	268.0
30	246.2
31	267.6
32	214.5
33	266.1
34	202.8
35	245.7
36	261.9
37	277.7
38	285.1
39	209.1
40	251.1
41	211.4
42	215.9
43	258.5
44	257.3
45	270.8
46	265.2
47	275.4
48	249.3
49	203.4
50	258.0
Average:	**236.6**
St. Dev:	**28.8**
St. Dev (%):	**12.2**

Moisture Optimization Test

Sample:	MO-EM-6.7
Client:	DOE
Coal:	Emerald - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	6.7%
Date:	4/25/2013
Time	2:00:00 PM

Comments:	1618.24 g coal
	421.80 g sawdust
	93.95 g water (target 93.96 g)
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 900-1300 ft-lb
	Screw speed:

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	28.49	26.66	1.83	0.069
1	9.26	8.80	0.46	0.052
2	9.27	8.80	0.47	0.053
3	9.22	8.72	0.50	0.057
4	9.43	8.96	0.47	0.052
5	9.75	9.27	0.48	0.052
			Average:	**0.053**
			St. Dev:	**0.002**
			St. Dev (%):	**4.214**
1	9.24	8.84	0.40	0.045
2	9.36	9.00	0.36	0.040
3	9.53	9.12	0.41	0.045
4	9.46	9.07	0.39	0.043
5	9.39	9.00	0.39	0.043
			Average:	**0.043**
			St. Dev:	**0.002**
			St. Dev (%):	**4.833**
Durability 1	155.69		155.69	#DIV/0!
Durability 2	160.07		160.07	#DIV/0!
			Average:	**#DIV/0!**
			St. Dev:	**#DIV/0!**
			St. Dev (%):	**#DIV/0!**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.13	1.32	1.17	1.11
2	9.68	1.38	1.17	1.11
3	9.55	1.37	1.17	1.11
4	9.47	1.35	1.17	1.11
5	9.50	1.15	1.14	1.08
6	9.25	1.25	1.16	1.10
7	9.02	1.10	1.14	1.08
8	9.43	1.22	1.15	1.09
9	9.56	1.13	1.13	1.08
10	9.11	1.06	1.13	1.07
			Average:	**1.09**
			St. Dev:	**0.01**
			St. Dev (%):	**1.32**
1	9.23	1.12	1.14	1.09
2	9.54	1.23	1.15	1.10
3	9.48	1.12	1.13	1.09
4	9.31	1.08	1.13	1.08
5	9.44	0.82	1.10	1.05
6	9.55	0.94	1.11	1.06
7	9.48	1.08	1.13	1.08
8	9.31	0.87	1.10	1.06
9	9.40	1.09	1.13	1.08
10	9.35	1.17	1.14	1.10
			Average:	**1.08**
			St. Dev:	**0.02**
			St. Dev (%):	**1.57**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	185.65	157.08	84.61
2	186.98	160.14	85.65
		Average:	**85.13**
		St. Dev:	**0.73**
		St. Dev (%):	**0.86**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	144.3
2	146.1
3	139.6
4	131.8
5	167.7
6	136.1
7	131.9
8	117.7
9	169.0
10	152.4
11	135.0
12	132.1
13	137.8
14	167.7
15	132.2
16	132.0
17	135.1
18	149.2
19	138.1
20	143.3
21	135.0
22	167.6
23	152.8
24	157.8
25	128.0
26	123.3
27	141.0
28	145.9
29	136.8
30	136.1
31	171.8
32	125.6
33	122.8
34	164.8
35	147.4
36	152.8
37	153.1
38	112.1
39	149.5
40	133.8
41	120.8
42	139.7
43	146.2
44	146.1
45	139.2
46	156.6
47	128.8
48	129.9
49	155.8
50	132.5
Average:	**141.9**
St. Dev:	**14.2**
St. Dev (%):	**10.0**

Moisture Optimization Test

Sample:	MO-EM-8.2
Client:	DOE
Coal:	Emerald - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	8.2%
Date:	4/26/2013
Time	9:00:00 AM

Comments:
1618.24 g coal
421.80 g sawdust
123.97 g water (target 123.96 g)
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 900-1300 ft-lb
Screw speed:

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed	28.58	26.41	2.17	0.082
1	9.19	8.56	0.63	0.074
2	9.16	8.51	0.65	0.076
3	9.19	8.57	0.62	0.072
4	9.18	8.55	0.63	0.074
5	9.06	8.46	0.60	0.071
			Average:	**0.073**
			St. Dev:	**0.002**
			St. Dev (%):	**2.747**
1	8.86	8.31	0.55	0.066
2	8.75	8.19	0.56	0.068
3	9.43	8.84	0.59	0.067
4	9.43	8.87	0.56	0.063
5	9.49	8.92	0.57	0.064
			Average:	**0.066**
			St. Dev:	**0.002**
			St. Dev (%):	**3.257**
Durability 1	131.56	123.40	8.16	0.066
Durability 2	134.98	126.67	8.31	0.066
			Average:	**0.066**
			St. Dev:	**0.000**
			St. Dev (%):	**0.561**

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.13	0.99	1.12	1.04
2	9.10	1.07	1.13	1.06
3	9.13	1.28	1.16	1.08
4	9.41	0.70	1.08	1.01
5	9.14	0.53	1.06	0.99
6	9.00	0.63	1.08	1.00
7	9.35	0.58	1.07	0.99
8	9.48	0.80	1.09	1.02
9	9.43	0.89	1.10	1.03
10	9.53	0.38	1.04	0.97
			Average:	**1.02**
			St. Dev:	**0.03**
			St. Dev (%):	**3.38**
1	9.17	1.08	1.13	1.06
2	9.35	0.98	1.12	1.05
3	9.02	0.98	1.12	1.05
4	9.58	1.12	1.13	1.06
5	9.27	0.88	1.10	1.04
6	9.53	0.56	1.06	1.00
7	9.23	0.66	1.08	1.01
8	9.42	0.79	1.09	1.02
9	9.21	0.86	1.10	1.04
10	9.31	0.78	1.09	1.02
			Average:	**1.04**
			St. Dev:	**0.02**
			St. Dev (%):	**2.12**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	182.82	131.67	72.02
2	182.45	135.06	74.03
		Average:	**73.02**
		St. Dev:	**1.42**
		St. Dev (%):	**1.94**

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	80.3
2	102.6
3	87.4
4	60.6
5	86.5
6	83.5
7	68.5
8	71.9
9	73.0
10	73.1
11	80.0
12	87.0
13	82.9
14	74.2
15	70.8
16	92.2
17	73.4
18	84.0
19	87.0
20	75.4
21	87.0
22	67.2
23	87.6
24	98.0
25	85.1
26	78.5
27	87.7
28	79.6
29	97.5
30	78.8
31	84.0
32	92.9
33	93.5
34	90.1
35	84.2
36	85.4
37	86.5
38	87.9
39	77.3
40	60.8
41	83.5
42	74.9
43	71.3
44	60.8
45	78.4
46	97.7
47	84.8
48	86.4
49	71.2
50	72.5
Average:	**81.3**
St. Dev:	**9.7**
St. Dev (%):	**12.0**

Moisture Optimization Test

Sample:	MO-EB-2.5
Client:	DOE
Coal:	Eagle Butte - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	2.5%
Date:	6/25/2013
Time	10:00:00 AM

Comments:	1210.80 g coal
	400.00 g sawdust
	14.00 g water
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1200 ft-lb

Water Content

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0400
Briquettes	44.19	42.96	1.23	0.029

Dry Density

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.98	-0.03	1.00	0.97
2	9.02	0.00	1.00	0.97
3	8.74	-0.10	0.99	0.96
4	9.21	-0.04	1.00	0.97
5	9.10	-0.06	0.99	0.97
6	8.67	-0.16	0.98	0.95
7	8.92	-0.14	0.98	0.96
8	9.13	-0.06	0.99	0.97
9	8.84	-0.21	0.98	0.95
10	8.85	-0.16	0.98	0.95
			Average:	**0.96**
			St. Dev:	**0.01**
			St. Dev (%):	**0.77**

Mechanical Durability

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	179.72	97.37	54.18

Crushing Strength

Measurement	Crushing Strength (lb$_f$)
1	95.1
2	94.2
3	89.5
4	81.5
5	80.8
6	77.6
7	84.6
8	87.3
9	88.8
10	69.2
11	92.7
12	77.2
13	88.0
14	86.3
15	84.3
16	93.1
17	93.0
18	101.8
19	91.7
20	79.0
21	82.7
22	81.7
23	80.0
24	78.4
25	84.4
Average:	**85.7**
St. Dev:	**7.2**
St. Dev (%):	**8.4**

Moisture Optimization Test

Sample:	MO-EB-4.0
Client:	DOE
Coal:	Eagle Butte - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	4.0%
Date:	7/24/2013
Time	1:30:00 PM

Comments:	1225.80 g coal 316.35 g sawdust 14.85 g water Roll force: 100 kN Roll speed: 450 rpm - 15 hz Roll torque: 1200 ft-lb

Water Content

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0490
Briquettes	46.66	44.58	2.08	0.047

Dry Density

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.37	0.51	1.06	1.01
2	9.43	0.54	1.06	1.01
3	9.04	0.14	1.02	0.97
4	9.14	0.58	1.07	1.02
5	9.20	0.43	1.05	1.00
6	8.93	0.39	1.05	1.00
7	9.50	0.53	1.06	1.01
8	9.38	0.46	1.05	1.00
9	9.12	0.44	1.05	1.00
10	9.13	0.47	1.05	1.01
			Average:	**1.00**
			St. Dev:	**0.01**
			St. Dev (%):	**1.33**

Mechanical Durability

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	184.53	121.21	65.69

Crushing Strength

Measurement	Crushing Strength (lb$_f$)
1	108.4
2	95.5
3	104.2
4	118.8
5	109.8
6	108.6
7	102.1
8	107.9
9	110.9
10	107.5
11	101.3
12	126.2
13	109.6
14	99.4
15	119.9
16	102.3
17	111.4
18	95.5
19	116.9
20	99.3
21	111.4
22	106.6
23	95.4
24	107.2
25	95.7
Average:	**106.9**
St. Dev:	**8.1**
St. Dev (%):	**7.6**

Moisture Optimization Test

Sample:	MO-EB-5.5
Client:	DOE
Coal:	Eagle Butte - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	5.5%
Date:	7/24/2013
Time	2:30:00 PM

Comments:	1225.80 g coal
	319.35 g sawdust
	37.35 g water
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1200 ft-lb

Water Content

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0530
Briquettes	46.66	44.11	2.55	0.058

Dry Density

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.15	0.69	1.08	1.02
2	8.99	0.88	1.11	1.05
3	9.33	0.75	1.09	1.03
4	9.31	0.82	1.10	1.04
5	9.17	0.64	1.08	1.02
6	9.24	0.65	1.08	1.02
7	9.07	0.63	1.07	1.02
8	9.51	0.78	1.09	1.03
9	9.20	0.75	1.09	1.03
10	9.02	0.57	1.07	1.01
			Average:	**1.03**
			St. Dev:	**0.01**
			St. Dev (%):	**1.12**

Mechanical Durability

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	185.20	131.49	71.00

Crushing Strength

Measurement	Crushing Strength (lb_f)
1	117.1
2	113.6
3	123.4
4	119.5
5	122.2
6	97.5
7	123.9
8	117.2
9	116.2
10	116.9
11	126.2
12	135.1
13	115.1
14	106.0
15	124.9
16	120.0
17	131.4
18	111.7
19	121.6
20	114.7
21	111.7
22	120.3
23	113.2
24	131.0
25	112.6
Average:	**118.5**
St. Dev:	**8.2**
St. Dev (%):	**6.9**

Moisture Optimization Test	
Sample:	MO-EB-7.0
Client:	DOE
Coal:	Eagle Butte - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	7.0%
Date:	7/24/2013
Time	3:30:00 PM

Comments:	1221.60 g coal
	319.35 g sawdust
	64.05 g water
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1200 ft-lb

Water Content

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0720
Briquettes	47.30	44.41	2.89	0.065

Dry Density

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.16	0.86	1.10	1.04
2	9.26	0.93	1.11	1.04
3	9.33	0.92	1.11	1.04
4	9.37	0.86	1.10	1.03
5	9.24	0.69	1.08	1.01
6	9.60	0.94	1.11	1.04
7	9.35	0.88	1.10	1.04
8	9.43	0.92	1.11	1.04
9	8.93	0.72	1.09	1.02
10	9.50	0.84	1.10	1.03
			Average:	**1.03**
			St. Dev:	**0.01**
			St. Dev (%):	**0.91**

Mechanical Durability

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	186.65	140.38	75.21

Crushing Strength

Measurement	Crushing Strength (lb$_f$)
1	136.8
2	122.5
3	125.1
4	125.5
5	143.8
6	139.3
7	149.8
8	109.9
9	126.0
10	135.0
11	141.8
12	139.0
13	157.1
14	135.8
15	119.7
16	143.2
17	149.6
18	139.9
19	113.7
20	128.1
21	127.0
22	130.1
23	135.2
24	138.2
25	129.2
Average:	**133.7**
St. Dev:	**11.3**
St. Dev (%):	**8.4**

Moisture Optimization Test

Sample:	MO-EB-8.5
Client:	DOE
Coal:	Eagle Butte - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	8.5%
Date:	7/24/2013
Time	4:30:00 PM

Comments:	1218.00 g coal
	319.35 g sawdust
	90.15 g water
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1200 ft-lb

Water Content

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0835
Briquettes	46.70	43.47	3.23	0.074

Dry Density

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.26	0.99	1.12	1.04
2	9.48	1.09	1.13	1.05
3	9.42	0.91	1.11	1.03
4	9.06	0.75	1.09	1.01
5	9.33	0.96	1.11	1.04
6	9.46	0.90	1.11	1.03
7	9.44	1.03	1.12	1.04
8	9.52	0.89	1.10	1.03
9	9.48	1.00	1.12	1.04
10	9.24	0.87	1.10	1.03
			Average:	**1.03**
			St. Dev:	**0.01**
			St. Dev (%):	**1.05**

Mechanical Durability

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.07	145.41	77.73

Crushing Strength

Measurement	Crushing Strength (lb$_f$)
1	175.1
2	156.6
3	135.8
4	147.0
5	141.5
6	157.3
7	148.3
8	153.1
9	146.6
10	140.1
11	133.5
12	142.7
13	157.7
14	136.7
15	148.0
16	144.0
17	142.3
18	142.3
19	174.2
20	151.2
21	127.5
22	144.0
23	137.7
24	151.0
25	143.1
Average:	**147.1**
St. Dev:	**11.1**
St. Dev (%):	**7.6**

Moisture Optimization Test

Sample:	MO-EB-10.0
Client:	DOE
Coal:	Eagle Butte - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	10.0%
Date:	7/30/2013
Time	3:00:00 PM

Comments:	1215.00 g coal
	319.35 g sawdust
	115.65 g water
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1200 ft-lb

Water Content

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0995
Briquettes	47.05	43.29	3.76	0.087

Dry Density

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.31	0.91	1.11	1.02
2	9.39	1.12	1.14	1.04
3	9.44	1.13	1.14	1.05
4	9.32	1.04	1.13	1.04
5	9.19	0.83	1.10	1.01
6	9.47	1.23	1.15	1.06
7	9.48	1.07	1.13	1.04
8	9.22	0.97	1.12	1.03
9	9.53	1.05	1.12	1.03
10	9.55	1.17	1.14	1.05
			Average:	**1.04**
			St. Dev:	**0.01**
			St. Dev (%):	**1.33**

Mechanical Durability

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.81	153.13	81.10

Crushing Strength

Measurement	Crushing Strength (lb$_f$)
1	188.7
2	158.4
3	150.4
4	176.7
5	156.5
6	153.4
7	174.8
8	157.6
9	165.9
10	153.9
11	162.2
12	175.4
13	168.1
14	153.3
15	178.8
16	167.9
17	152.8
18	168.3
19	182.3
20	187.1
21	171.0
22	158.1
23	149.1
24	153.5
25	201.4
Average:	**166.6**
St. Dev:	**13.8**
St. Dev (%):	**8.3**

Moisture Optimization Test

Sample:	MO-EB-12.5
Client:	DOE
Coal:	Eagle Butte - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	12.5%
Date:	7/30/2013
Time	4:00:00 PM

Comments:	1212.00 g coal
	319.35 g sawdust
	156.15 g water
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1200 ft-lb

Water Content

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1265
Briquettes	47.58	42.82	4.76	0.111

Dry Density

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.38	1.26	1.16	1.04
2	9.54	1.23	1.15	1.03
3	9.69	1.34	1.16	1.04
4	9.36	1.12	1.14	1.02
5	9.67	1.32	1.16	1.04
6	9.56	1.19	1.14	1.03
7	9.72	1.29	1.15	1.04
8	9.69	1.28	1.15	1.04
9	9.39	1.06	1.13	1.01
10	9.43	1.17	1.14	1.03
			Average:	**1.03**
			St. Dev:	**0.01**
			St. Dev (%):	**0.92**

Mechanical Durability

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.99	163.66	85.69

Crushing Strength

Measurement	Crushing Strength (lb_f)
1	218.5
2	210.6
3	242.0
4	245.9
5	236.7
6	236.9
7	198.1
8	213.7
9	234.1
10	210.9
11	238.5
12	202.3
13	218.4
14	214.1
15	219.8
16	196.2
17	223.6
18	221.3
19	214.3
20	211.4
21	249.9
22	241.1
23	206.7
24	214.4
25	198.2
Average:	**220.7**
St. Dev:	**15.8**
St. Dev (%):	**7.2**

Moisture Optimization Test

Sample:	MO-EB-15.0
Client:	DOE
Coal:	Eagle Butte - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	15.0%
Date:	7/30/2013
Time	5:00:00 PM

Comments:	1212.00 g coal
	319.35 g sawdust
	193.65 g water
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1200 ft-lb

Water Content

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1425
Briquettes	48.66	42.99	5.67	0.132

Dry Density

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.56	1.47	1.18	1.04
2	9.37	1.28	1.16	1.02
3	9.62	1.30	1.16	1.02
4	9.91	1.53	1.18	1.04
5	9.63	1.52	1.19	1.05
6	9.70	1.41	1.17	1.03
7	9.59	1.33	1.16	1.03
8	9.55	1.28	1.15	1.02
9	9.66	1.43	1.17	1.04
10	9.53	1.37	1.17	1.03
			Average:	**1.03**
			St. Dev:	**0.01**
			St. Dev (%):	**1.01**

Mechanical Durability

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.22	165.03	86.76

Crushing Strength

Measurement	Crushing Strength (lb$_f$)
1	232.6
2	231.7
3	216.2
4	255.2
5	222.8
6	237.3
7	211.5
8	233.7
9	229.4
10	221.1
11	214.0
12	286.1
13	197.7
14	217.1
15	225.9
16	247.6
17	227.8
18	205.1
19	240.6
20	226.4
21	263.6
22	220.0
23	286.1
24	231.8
25	288.5
Average:	**234.8**
St. Dev:	**24.4**
St. Dev (%):	**10.4**

Moisture Optimization Test

Sample:	MO-EB-17.5
Client:	DOE
Coal:	Eagle Butte - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	17.5%
Date:	7/31/2013
Time	2:00:00 PM

Comments:	1221.60 g coal
	319.35 g sawdust
	221.55 g water
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1200 ft-lb

Water Content

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1690
Briquettes	47.43	41.20	6.23	0.151

Dry Density

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.77	1.43	1.17	1.02
2	9.47	1.33	1.16	1.01
3	9.34	1.31	1.16	1.01
4	9.23	1.26	1.16	1.01
5	9.85	1.46	1.17	1.02
6	9.30	1.02	1.12	0.98
7	9.25	1.29	1.16	1.01
8	9.79	1.35	1.16	1.01
9	9.39	1.22	1.15	1.00
10	9.12	1.06	1.13	0.98
			Average:	**1.00**
			St. Dev:	**0.01**
			St. Dev (%):	**1.43**

Mechanical Durability

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.26	163.51	87.32

Crushing Strength

Measurement	Crushing Strength (lb$_f$)
1	199.1
2	212.8
3	205.8
4	233.9
5	210.4
6	184.2
7	215.6
8	209.9
9	192.8
10	204.7
11	192.7
12	221.4
13	202.6
14	176.7
15	207.6
16	183.8
17	219.4
18	191.1
19	207.4
20	214.5
21	234.8
22	219.4
23	222.7
24	212.4
25	190.3
Average:	**206.6**
St. Dev:	**15.1**
St. Dev (%):	**7.3**

Moisture Optimization Test

Sample:	MO-EB-20.0
Client:	DOE
Coal:	Eagle Butte - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	20.0%
Date:	7/31/2013
Time	3:00:00 PM

Comments:	1221.60 g coal
	319.35 g sawdust
	259.05 g water
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1200 ft-lb

Water Content

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1700
Briquettes	46.66	40.02	6.64	0.166

Dry Density

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.58	0.96	1.11	0.95
2	9.52	0.90	1.10	0.95
3	9.51	0.66	1.07	0.92
4	9.64	0.87	1.10	0.94
5	9.62	0.93	1.11	0.95
6	9.46	0.73	1.08	0.93
7	9.51	0.73	1.08	0.93
8	9.51	0.61	1.07	0.92
9	9.78	0.96	1.11	0.95
10	9.43	0.70	1.08	0.93
			Average:	**0.94**
			St. Dev:	**0.01**
			St. Dev (%):	**1.44**

Mechanical Durability

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	182.00	152.79	83.95

Crushing Strength

Measurement	Crushing Strength (lb$_f$)
1	111.2
2	130.8
3	106.8
4	175.8
5	149.6
6	140.6
7	142.9
8	119.4
9	126.7
10	120.7
11	120.1
12	149.7
13	102.3
14	108.8
15	135.6
16	127.4
17	122.3
18	126.6
19	141.9
20	141.7
21	135.4
22	129.4
23	129.0
24	136.1
25	151.0
Average:	**131.3**
St. Dev:	**16.4**
St. Dev (%):	**12.5**

Moisture Optimization Test

Sample:	MO-EB-22.5
Client:	DOE
Coal:	Eagle Butte - 80% - <1mm
Biomass:	Cabinet Sawdust - 20%
Target Moisture:	22.5%
Date:	7/31/2013
Time	4:00:00 PM

Comments:	1221.60 g coal
	319.35 g sawdust
	296.55 g water
	Roll force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1200 ft-lb

Water Content

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1875
Briquettes	47.35	39.82	7.53	0.189

Dry Density

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.98	0.60	1.07	0.90
2	9.58	0.89	1.10	0.93
3	8.81	0.64	1.08	0.91
4	9.57	0.66	1.07	0.90
5	9.32	0.64	1.07	0.90
6	8.88	0.52	1.06	0.89
7	9.43	0.80	1.09	0.92
8	8.93	0.38	1.04	0.88
9	9.45	0.51	1.06	0.89
10	9.37	0.57	1.06	0.90
			Average:	**0.90**
			St. Dev:	**0.01**
			St. Dev (%):	**1.56**

Mechanical Durability

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.68	136.60	71.26

Crushing Strength

Measurement	Crushing Strength (lb_f)
1	98.0
2	111.0
3	104.7
4	92.7
5	87.0
6	101.3
7	107.5
8	102.3
9	123.2
10	115.4
11	95.2
12	86.7
13	102.7
14	98.3
15	120.1
16	102.5
17	84.6
18	94.8
19	100.8
20	96.8
21	99.8
22	94.2
23	92.4
24	104.3
25	97.0
Average:	**100.5**
St. Dev:	**9.6**
St. Dev (%):	**9.6**

A.3 Evaluation of Briquette Production Variables

A.3.1 Evaluation of Feedstock Variables – Bituminous Coal

Material Variables Evaluation

Sample:	EM-CS-08
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Corn stover - 30% - #8
Target Moisture:	8.0%
Date:	5/29/2013
Time	11:00:00 AM

Comments:	1061.55 g coal
	512.33 g biomass
	46.13 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	Difficulties w/ feeding to sustain desired
	Strengths were very high due to

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.087
Briquettes	44.14	41.33	2.81	0.068

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.21	0.89	1.11	1.04
2	8.46	0.27	1.03	0.97
3	9.43	1.04	1.12	1.05
4	9.37	0.98	1.12	1.05
5	8.33	0.12	1.01	0.95
6	8.52	0.39	1.05	0.98
7	8.67	0.33	1.04	0.97
8	9.91	0.96	1.11	1.04
9	9.34	0.80	1.09	1.02
10	8.45	0.15	1.02	0.95
		Average:	**1.07**	**1.00**
		St. Dev:	**0.04**	**0.04**
		St. Dev (%):	**4.06**	**4.06**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	186.26	139.99	75.16

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	377.3
2	228.8
3	408.4
4	420.5
5	247.2
6	98.3
7	550.4
8	360.4
9	325.0
10	232.8
11	293.9
12	236.0
13	345.4
14	269.0
15	196.1
16	263.4
17	350.0
18	253.3
19	243.9
20	283.5
21	370.7
22	331.4
23	280.3
24	290.8
25	356.6
Average:	**304.5**
St. Dev:	**88.7**
St. Dev (%):	**29.1**

Material Variables Evaluation

Sample:	EM-CS-06
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Corn stover - 10% - #8
Target Moisture:	8.0%
Date:	5/29/2013
Time	12:00:00 PM

Comments:	1364.85 g coal
	170.78 g biomass
	84.38 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.084
Briquettes	45.34	42.59	2.75	0.065

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.17	1.60	1.21	1.14
2	9.28	1.63	1.21	1.14
3	8.92	1.32	1.17	1.10
4	9.19	1.21	1.15	1.08
5	9.08	1.44	1.19	1.12
6	9.38	1.42	1.18	1.11
7	9.04	1.27	1.16	1.09
8	9.17	1.14	1.14	1.07
9	9.19	1.08	1.13	1.06
10	9.32	1.18	1.14	1.08
		Average:	**1.17**	**1.10**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.41**	**2.41**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	183.34	34.95	19.06

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	30.4
2	45.9
3	42.5
4	28.1
5	40.7
6	42.4
7	29.8
8	29.1
9	27.1
10	29.6
11	26.4
12	39.8
13	26.1
14	30.8
15	38.7
16	23.7
17	36.2
18	42.3
19	33.3
20	37.6
21	32.5
22	22.2
23	28.2
24	23.4
25	35.1
Average:	**32.9**
St. Dev:	**6.8**
St. Dev (%):	**20.8**

Material Variables Evaluation

Sample:	EM-CS-05
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Corn stover - 10% - #8
Target Moisture:	2.0%
Date:	5/29/2013
Time	4:00:00 PM

Comments:	1364.85 g coal
	152.63 g biomass
	12.53 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.021
Briquettes	48.14	47.45	0.69	0.015

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.08	1.42	1.19	1.17
2	9.78	1.68	1.21	1.19
3	9.88	1.26	1.15	1.13
4	9.85	1.60	1.19	1.18
5	9.26	1.26	1.16	1.14
6	9.38	1.43	1.18	1.16
7	9.42	1.32	1.16	1.15
8	9.83	1.63	1.20	1.18
9	9.46	1.41	1.18	1.16
10	9.21	1.38	1.18	1.16
		Average:	**1.18**	**1.16**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.62**	**1.62**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.33	175.84	91.90

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	232.7
2	214.1
3	270.9
4	208.4
5	228.9
6	325.2
7	188.9
8	240.5
9	221.9
10	245.7
11	237.7
12	199.4
13	231.2
14	358.4
15	238.7
16	250.2
17	222.5
18	216.0
19	204.8
20	204.6
21	278.2
22	220.8
23	206.3
24	238.7
25	214.7
Average:	**236.0**
St. Dev:	**38.4**
St. Dev (%):	**16.3**

Material Variables Evaluation

Sample:	EM-CS-15
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Corn stover - 20% - #8
Target Moisture:	5.0%
Date:	5/30/2013
Time	9:00:00 AM

Comments:	1213.20 g coal
	341.55 g biomass
	20.25 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.050
Briquettes	46.28	44.55	1.73	0.039

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.43	1.40	1.17	1.13
2	9.41	1.22	1.15	1.11
3	9.29	0.88	1.10	1.06
4	10.04	1.27	1.14	1.10
5	9.20	1.22	1.15	1.11
6	9.68	1.13	1.13	1.09
7	9.63	1.22	1.15	1.10
8	9.78	1.10	1.13	1.08
9	9.77	1.42	1.17	1.13
10	9.92	1.42	1.17	1.12
		Average:	**1.15**	**1.10**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.87**	**1.87**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.60	162.74	85.83

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	310.6
2	236.2
3	290.2
4	258.9
5	311.1
6	287.6
7	318.2
8	194.6
9	229.7
10	268.7
11	327.8
12	241.8
13	321.6
14	224.9
15	271.0
16	280.9
17	286.3
18	258.6
19	305.1
20	256.7
21	228.0
22	290.0
23	306.9
24	317.0
25	327.7
Average:	**278.0**
St. Dev:	**37.2**
St. Dev (%):	**13.4**

Material Variables Evaluation

Sample:	EM-CS-07
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Corn stover - 30% - #8
Target Moisture:	2.0%
Date:	5/30/2013
Time	10:00:00 AM

Comments:	1065.75 g coal
	457.88 g biomass
	6.38 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0165
Briquettes	45.59	45.03	0.56	0.012

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.15	0.87	1.11	1.09
2	8.61	0.43	1.05	1.04
3	9.11	0.32	1.04	1.02
4	9.01	0.35	1.04	1.03
5	9.11	0.25	1.03	1.02
6	9.02	0.32	1.04	1.02
7	8.99	0.08	1.01	1.00
8	9.04	0.57	1.07	1.05
9	9.00	0.71	1.09	1.07
10	9.19	0.62	1.07	1.06
		Average:	**1.05**	**1.04**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.76**	**2.76**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	180.54	139.05	77.02

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	404.9
2	364.5
3	354.8
4	364.7
5	330.5
6	346.2
7	374.3
8	261.2
9	375.3
10	325.0
11	280.7
12	283.7
13	323.3
14	298.8
15	285.4
16	315.2
17	328.5
18	345.7
19	324.2
20	324.2
21	316.4
22	332.9
23	405.7
24	273.3
25	320.1
Average:	**330.4**
St. Dev:	**38.2**
St. Dev (%):	**11.6**

Material Variables Evaluation

Sample:	EM-CS-14
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Corn stover - 20% - #8
Target Moisture:	5.0%
Date:	5/30/2013
Time	11:00:00 AM

Comments:	1213.20 g coal
	341.55 g biomass
	20.25 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0605
Briquettes	47.78	46.04	1.74	0.038

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.27	0.88	1.10	1.06
2	9.27	1.20	1.15	1.11
3	9.92	1.32	1.15	1.11
4	9.65	1.29	1.15	1.11
5	9.62	1.46	1.18	1.14
6	9.95	1.56	1.19	1.14
7	8.75	0.50	1.06	1.02
8	9.59	0.79	1.09	1.05
9	9.40	1.08	1.13	1.09
10	9.94	1.39	1.16	1.12
		Average:	**1.14**	**1.10**
		St. Dev:	**0.04**	**0.04**
		St. Dev (%):	**3.55**	**3.55**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.55	165.15	86.67

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	294.2
2	285.5
3	275.9
4	266.9
5	315.6
6	312.1
7	236.2
8	310.8
9	284.3
10	248.2
11	286.1
12	270.8
13	256.0
14	302.1
15	247.0
16	268.8
17	309.7
18	281.9
19	297.3
20	300.0
21	220.5
22	250.1
23	269.5
24	264.4
25	349.9
Average:	**280.2**
St. Dev:	**29.1**
St. Dev (%):	**10.4**

Material Variables Evaluation

Sample:	EM-CS-13
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Corn stover - 20% - #8
Target Moisture:	5.0%
Date:	5/30/2013
Time	12:00:00 PM

Comments:	1218.20 g coal
	341.55 g biomass
	15.45 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0405
Briquettes	47.16	45.61	1.55	0.034

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.67	1.40	1.17	1.13
2	9.92	1.57	1.19	1.15
3	9.51	1.41	1.17	1.14
4	9.11	1.19	1.15	1.11
5	9.50	1.32	1.16	1.12
6	9.88	1.36	1.16	1.12
7	9.74	1.29	1.15	1.11
8	9.57	1.33	1.16	1.12
9	9.53	1.29	1.16	1.12
10	9.37	1.37	1.17	1.13
		Average:	**1.16**	**1.13**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.98**	**0.98**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.24	165.53	87.01

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	256.7
2	237.6
3	274.3
4	301.4
5	282.4
6	278.7
7	283.5
8	356.6
9	346.7
10	281.9
11	251.1
12	318.1
13	298.1
14	291.2
15	244.6
16	256.5
17	336.0
18	279.4
19	305.5
20	309.9
21	290.2
22	286.4
23	316.9
24	275.1
25	263.7
Average:	**288.9**
St. Dev:	**30.4**
St. Dev (%):	**10.5**

Material Variables Evaluation

Sample:	EM-CS-11
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Corn stover - 30% - #16
Target Moisture:	5.0%
Date:	5/30/2013
Time	1:00:00 PM

Comments:
1065.75 g coal
510.53 g biomass
0.00 g water
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0455
Briquettes	46.20	44.36	1.84	0.041

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.29	1.00	1.12	1.08
2	9.33	0.71	1.08	1.04
3	9.79	1.03	1.12	1.07
4	9.41	1.07	1.13	1.08
5	9.46	1.01	1.12	1.07
6	9.27	0.61	1.07	1.03
7	9.75	1.15	1.13	1.09
8	8.73	0.62	1.08	1.03
9	7.74	0.70	1.10	1.06
10	9.35	0.98	1.12	1.07
		Average:	**1.11**	**1.06**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.06**	**2.06**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	186.43	166.72	89.43

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	328.9
2	449.1
3	472.0
4	441.1
5	462.1
6	372.6
7	361.1
8	375.5
9	471.2
10	368.9
11	487.1
12	427.5
13	421.9
14	407.9
15	461.3
16	392.9
17	411.7
18	374.6
19	512.1
20	398.7
21	421.1
22	332.4
23	431.1
24	416.6
25	369.4
Average:	**414.8**
St. Dev:	**47.8**
St. Dev (%):	**11.5**

Material Variables Evaluation

Sample:	EM-CS-09
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Corn stover - 10% - #16
Target Moisture:	5.0%
Date:	5/30/2013
Time	2:00:00 PM

Comments:	1370.25 g coal
	170.18 g biomass
	34.58 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0465
Briquettes	48.83	47.14	1.69	0.036

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.97	1.60	1.19	1.15
2	9.59	1.11	1.13	1.09
3	9.70	1.36	1.16	1.12
4	9.69	1.31	1.16	1.12
5	9.72	0.99	1.11	1.07
6	9.62	1.36	1.16	1.12
7	10.00	1.61	1.19	1.15
8	9.73	1.34	1.16	1.12
9	9.72	0.92	1.10	1.07
10	9.75	1.44	1.17	1.13
		Average:	**1.15**	**1.11**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.59**	**2.59**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	192.25	154.51	80.37

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	164.0
2	132.1
3	152.2
4	167.8
5	129.0
6	170.4
7	148.5
8	117.8
9	149.6
10	150.3
11	141.9
12	152.4
13	132.6
14	147.9
15	147.8
16	144.4
17	147.6
18	157.1
19	129.4
20	162.9
21	122.9
22	149.8
23	152.7
24	154.3
25	152.0
Average:	**147.1**
St. Dev:	**13.5**
St. Dev (%):	**9.2**

Material Variables Evaluation

Sample:	EM-CS-12
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Corn stover - 30% - #4
Target Moisture:	5.0%
Date:	5/30/2013
Time	3:00:00 PM

Comments:	1065.75 g coal
	509.40 g biomass
	0.00 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.060
Briquettes	44.59	43.16	1.43	0.033

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.67	1.40	1.17	1.13
2	10.22	1.15	1.13	1.09
3	9.17	1.06	1.13	1.09
4	9.39	0.77	1.09	1.05
5	8.62	0.35	1.04	1.01
6	9.33	1.31	1.16	1.13
7	9.86	0.70	1.08	1.04
8	8.68	0.70	1.09	1.05
9				
10				
		Average:	**1.11**	**1.08**
		St. Dev:	**0.04**	**0.04**
		St. Dev (%):	**3.98**	**3.98**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.66	172.01	90.22

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	405.7
2	541.5
3	492.3
4	418.5
5	453.9
6	493.4
7	512.3
8	464.7
9	384.5
10	408.6
11	458.2
12	300.9
13	320.2
14	355.0
15	539.6
16	553.5
17	541.5
18	
19	
20	
21	
22	
23	
24	
25	
Average:	**449.7**
St. Dev:	**79.2**
St. Dev (%):	**17.6**

Material Variables Evaluation

Sample:	EM-CS-02
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Corn stover - 20% - #16
Target Moisture:	8.0%
Date:	5/31/2013
Time	9:00:00 AM

Comments:	1221.00 g coal
	340.35 g biomass
	58.65 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.081
Briquettes	47.55	44.80	2.75	0.061

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.64	1.22	1.14	1.08
2	9.44	0.93	1.11	1.05
3	9.61	0.87	1.10	1.04
4	9.55	1.08	1.13	1.06
5	9.69	1.07	1.12	1.06
6	9.58	0.94	1.11	1.04
7	9.82	0.99	1.11	1.05
8	9.44	0.43	1.05	0.99
9	9.34	0.89	1.11	1.04
10	9.66	0.66	1.07	1.01
		Average:	**1.11**	**1.04**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.50**	**2.50**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.76	123.20	64.92

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	128.4
2	113.7
3	103.8
4	116.6
5	107.1
6	124.2
7	137.2
8	130.4
9	120.2
10	124.5
11	127.2
12	117.3
13	124.0
14	133.7
15	125.7
16	131.2
17	112.2
18	116.3
19	125.3
20	126.0
21	141.1
22	117.6
23	112.2
24	115.6
25	117.9
Average:	**122.0**
St. Dev:	**9.1**
St. Dev (%):	**7.5**

Material Variables Evaluation

Sample:	EM-CS-10
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Corn stover - 10% - #4
Target Moisture:	5.0%
Date:	5/31/2013
Time	10:00:00 AM

Comments:	1373.63 g coal
	169.80 g biomass
	31.58 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0585
Briquettes	49.13	47.76	1.37	0.029

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.56	1.62	1.20	1.17
2	9.33	1.04	1.13	1.09
3	9.65	1.34	1.16	1.13
4	9.33	1.43	1.18	1.15
5	9.29	1.51	1.19	1.16
6	9.71	1.24	1.15	1.11
7	9.38	0.68	1.08	1.05
8	9.63	0.97	1.11	1.08
9	9.70	1.34	1.16	1.13
10	9.84	1.57	1.19	1.16
		Average:	**1.16**	**1.12**
		St. Dev:	**0.04**	**0.04**
		St. Dev (%):	**3.49**	**3.49**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	193.26	154.00	79.69

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	141.1
2	145.7
3	147.4
4	155.7
5	183.2
6	174.6
7	136.6
8	132.1
9	169.3
10	144.6
11	178.2
12	175.2
13	133.0
14	161.4
15	172.4
16	174.2
17	143.7
18	177.5
19	174.2
20	162.5
21	157.2
22	174.6
23	159.4
24	153.0
25	151.2
Average:	**159.1**
St. Dev:	**15.7**
St. Dev (%):	**9.9**

Material Variables Evaluation

Sample:	EM-CS-03
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Corn stover - 20% - #4
Target Moisture:	2.0%
Date:	5/31/2013
Time	11:00:00 AM

Comments:	1218.00 g coal
	303.45 g biomass
	8.55 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0165
Briquettes	50.22	49.63	0.59	0.012

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.03	1.13	1.14	1.13
2	8.97	0.85	1.10	1.09
3	8.86	0.86	1.11	1.09
4	9.57	1.22	1.15	1.13
5	10.30	1.25	1.14	1.12
6	10.04	1.24	1.14	1.13
7	9.36	0.80	1.09	1.08
8	8.68	0.81	1.10	1.09
9	8.95	0.74	1.09	1.08
10	9.66	1.23	1.15	1.13
		Average:	**1.12**	**1.11**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.08**	**2.08**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.67	166.35	88.64

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	329.2
2	334.0
3	282.8
4	293.8
5	362.7
6	277.8
7	194.5
8	283.4
9	228.4
10	220.6
11	224.2
12	266.0
13	248.4
14	314.3
15	298.6
16	250.7
17	327.9
18	227.1
19	276.9
20	302.7
21	224.6
22	309.5
23	265.0
24	307.0
25	306.3
Average:	**278.3**
St. Dev:	**42.7**
St. Dev (%):	**15.3**

Material Variables Evaluation

Sample:	EM-CS-01
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Corn stover - 20% - #16
Target Moisture:	2.0%
Date:	5/31/2013
Time	12:00:00 PM

Comments:	1218.00 g coal
	303.75 g biomass
	8.25 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.018
Briquettes	48.02	47.42	0.60	0.013

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.50	1.30	1.16	1.14
2	9.25	1.21	1.15	1.14
3	9.92	1.22	1.14	1.13
4	9.66	1.39	1.17	1.15
5	9.06	0.91	1.11	1.10
6	9.38	1.07	1.13	1.11
7	9.66	1.06	1.12	1.11
8	9.36	0.64	1.07	1.06
9	9.54	1.32	1.16	1.15
10	9.67	0.98	1.11	1.10
		Average:	**1.13**	**1.12**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.55**	**2.55**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	185.79	163.51	88.01

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	290.2
2	284.9
3	439.3
4	226.5
5	229.4
6	262.0
7	300.5
8	278.0
9	259.6
10	318.2
11	245.0
12	289.1
13	268.5
14	262.1
15	275.2
16	303.4
17	292.8
18	266.8
19	288.3
20	315.1
21	303.9
22	270.1
23	310.1
24	276.4
25	268.2
Average:	**284.9**
St. Dev:	**40.1**
St. Dev (%):	**14.1**

Material Variables Evaluation	
Sample:	EM-CS-04
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Corn stover - 20% - #4
Target Moisture:	8.0%
Date:	5/31/2013
Time	1:00:00 PM

Comments:	1216.80 g coal
	339.60 g biomass
	63.60 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0865
Briquettes	48.00	45.43	2.57	0.057

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.32	1.18	1.14	1.08
2	9.52	1.39	1.17	1.11
3	9.54	0.98	1.11	1.05
4	9.08	1.08	1.14	1.07
5	9.48	0.52	1.06	1.00
6	9.18	1.02	1.13	1.06
7	9.39	0.90	1.11	1.05
8	9.38	1.14	1.14	1.08
9	9.39	0.95	1.11	1.05
10	9.24	1.05	1.13	1.07
		Average:	**1.12**	**1.06**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.63**	**2.63**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	185.52	86.40	46.57

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	172.0
2	147.6
3	110.1
4	144.3
5	135.2
6	127.4
7	111.5
8	117.5
9	105.3
10	84.1
11	125.9
12	185.5
13	125.4
14	132.0
15	137.4
16	123.6
17	121.1
18	144.0
19	111.2
20	135.3
21	120.2
22	106.5
23	136.3
24	117.8
25	119.3
Average:	**127.9**
St. Dev:	**21.1**
St. Dev (%):	**16.5**

Material Variables Evaluation

Sample:	EM-SG-11
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Switchgrass - 30% - #16
Target Moisture:	5.0%
Date:	6/3/2013
Time	12:00:00 PM

Comments:	1064.70 g coal
	455.40 g biomass
	54.90 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0420
Briquettes	46.01	44.38	1.63	0.037

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.60	0.98	1.11	1.07
2	8.98	0.29	1.03	1.00
3	9.27	0.88	1.10	1.07
4	9.34	0.78	1.09	1.05
5	8.74	0.22	1.03	0.99
6	9.20	0.72	1.08	1.05
7	9.44	1.00	1.12	1.08
8	9.18	0.83	1.10	1.06
9	8.61	0.46	1.06	1.02
10	9.70	0.77	1.09	1.05
		Average:	**1.08**	**1.04**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**3.00**	**3.00**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	184.61	155.03	83.98

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	435.3
2	451.5
3	475.0
4	380.8
5	412.8
6	387.1
7	402.7
8	444.7
9	327.8
10	386.1
11	403.9
12	528.2
13	317.7
14	425.3
15	420.9
16	425.9
17	292.4
18	332.9
19	492.2
20	354.4
21	310.8
22	472.8
23	348.0
24	440.6
25	403.7
Average:	**402.9**
St. Dev:	**60.1**
St. Dev (%):	**14.9**

Material Variables Evaluation

Sample:	EM-SG-09
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Switchgrass - 10% - #16
Target Moisture:	5.0%
Date:	6/3/2013
Time	1:00:00 PM

Comments:	1368.90 g coal
	175.80 g biomass
	30.30 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0460
Briquettes	47.48	45.81	1.67	0.036

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.50	1.00	1.12	1.08
2	9.17	1.12	1.14	1.10
3	9.83	1.01	1.11	1.08
4	9.50	1.04	1.12	1.08
5	9.30	0.65	1.08	1.04
6	9.00	0.83	1.10	1.06
7	9.19	1.03	1.13	1.09
8	9.50	0.99	1.12	1.08
9	9.17	0.82	1.10	1.06
10	9.60	0.96	1.11	1.07
		Average:	**1.11**	**1.07**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.58**	**1.58**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.66	91.61	48.56

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	71.5
2	85.2
3	70.9
4	84.0
5	117.6
6	83.0
7	68.9
8	74.2
9	63.6
10	78.0
11	90.1
12	72.6
13	80.6
14	74.2
15	86.6
16	77.2
17	87.4
18	71.9
19	70.7
20	89.6
21	84.6
22	70.6
23	82.8
24	90.8
25	74.9
Average:	**80.1**
St. Dev:	**10.9**
St. Dev (%):	**13.6**

Material Variables Evaluation	
Sample:	EM-SG-14
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Switchgrass - 20% - #8
Target Moisture:	5.0%
Date:	6/3/2013
Time	2:00:00 PM

Comments:	
	1216.80 g coal
	349.50 g biomass
	8.70 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0560
Briquettes	48.14	46.20	1.94	0.042

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.00	0.15	1.02	0.98
2	9.98	1.03	1.12	1.07
3	8.87	0.25	1.03	0.99
4	9.69	1.05	1.12	1.08
5	10.08	0.69	1.07	1.03
6	9.82	0.75	1.08	1.04
7	9.04	0.59	1.07	1.03
8	9.72	0.76	1.08	1.04
9	9.19	0.43	1.05	1.01
10	9.29	0.46	1.05	1.01
		Average:	**1.07**	**1.03**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**3.17**	**3.17**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.96	133.94	71.26

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	243.3
2	229.4
3	189.5
4	284.6
5	216.8
6	215.6
7	277.0
8	217.1
9	195.6
10	184.3
11	220.8
12	204.9
13	246.0
14	234.1
15	190.4
16	218.5
17	197.8
18	198.8
19	248.2
20	208.2
21	246.5
22	177.2
23	183.3
24	153.2
25	230.6
Average:	**216.5**
St. Dev:	**30.9**
St. Dev (%):	**14.3**

Material Variables Evaluation

Sample:	EM-SG-12
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Switchgrass - 30% - #4
Target Moisture:	5.0%
Date:	6/3/2013
Time	4:00:00 PM

Comments:	1064.70 g coal
	454.73 g biomass
	55.57 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0455
Briquettes	48.17	46.67	1.50	0.032

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.44	1.00	1.12	1.08
2	9.11	0.92	1.11	1.08
3	9.64	0.69	1.08	1.04
4	9.26	0.65	1.08	1.04
5	8.91	0.39	1.05	1.01
6	8.95	0.33	1.04	1.01
7	10.02	1.04	1.12	1.08
8	9.34	0.63	1.07	1.04
9	8.67	0.36	1.04	1.01
10	9.48	0.64	1.07	1.04
		Average:	**1.08**	**1.04**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.79**	**2.79**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.37	154.83	82.63

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	389.5
2	293.7
3	335.1
4	260.7
5	330.5
6	347.2
7	491.5
8	322.4
9	394.4
10	390.4
11	549.8
12	468.3
13	500.0
14	371.3
15	493.5
16	299.4
17	472.8
18	546.4
19	251.8
20	551.0
21	289.3
22	389.9
23	505.6
24	486.4
25	383.7
Average:	**404.6**
St. Dev:	**94.9**
St. Dev (%):	**23.5**

Material Variables Evaluation

Sample:	EM-SG-07
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Switchgrass - 30% - #8
Target Moisture:	2.0%
Date:	6/4/2013
Time	5:00:00 PM

Comments:	1062.08 g coal
	453.83 g biomass
	14.10 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	Many briquettes initially float in water

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0200
Briquettes	46.17	45.49	0.68	0.015

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.12	0.50	1.06	1.04
2	8.76	0.11	1.01	1.00
3	8.59	0.31	1.04	1.02
4	10.16	1.17	1.13	1.11
5	8.90	0.35	1.04	1.03
6	9.34	0.56	1.06	1.05
7	7.88	0.01	1.00	0.99
8	8.83	0.04	1.00	0.99
9	9.35	0.68	1.08	1.06
10	9.10	0.48	1.06	1.04
		Average:	**1.05**	**1.03**
		St. Dev:	**0.04**	**0.04**
		St. Dev (%):	**3.70**	**3.70**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	185.84	154.57	83.17

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	327.6
2	423.3
3	482.3
4	425.6
5	374.3
6	317.9
7	378.0
8	383.3
9	436.8
10	406.7
11	409.8
12	406.3
13	571.4
14	388.0
15	514.6
16	362.7
17	404.3
18	385.1
19	420.4
20	317.6
21	432.4
22	375.3
23	463.5
24	373.7
25	424.1
Average:	**408.2**
St. Dev:	**57.6**
St. Dev (%):	**14.1**

Material Variables Evaluation

Sample:	EM-SG-08
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Switchgrass - 30% - #8
Target Moisture:	8.0%
Date:	6/4/2013
Time	11:00:00 AM

Comments:	1062.08 g coal
	524.25 g biomass
	33.68 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	Many briquettes initially float in water

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.071
Briquettes	49.95	46.87	3.08	0.066

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.34	0.72	1.08	1.02
2	9.70	0.55	1.06	0.99
3	9.11	0.42	1.05	0.98
4	9.90	0.45	1.05	0.98
5	9.67	0.26	1.03	0.96
6	8.96	0.17	1.02	0.96
7	9.64	0.32	1.03	0.97
8	8.97	0.21	1.02	0.96
9				
10				
		Average:	**1.04**	**0.98**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.06**	**2.06**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.61	72.52	38.25

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	142.4
2	128.9
3	92.0
4	185.4
5	89.5
6	137.1
7	155.6
8	108.1
9	236.3
10	117.2
11	103.6
12	56.5
13	112.2
14	124.3
15	118.1
16	130.0
17	112.9
18	123.0
19	84.7
20	251.8
21	157.2
22	183.4
23	
24	
25	
Average:	**134.1**
St. Dev:	**46.8**
St. Dev (%):	**34.9**

Material Variables Evaluation

Sample:	EM-SG-15
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Switchgrass - 20% - #8
Target Moisture:	5.0%
Date:	6/3/2013
Time	3:00:00 PM

Comments:	1216.80 g coal
	349.50 g biomass
	8.70 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.039
Briquettes	48.36	46.72	1.64	0.035

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.86	0.95	1.11	1.07
2	9.29	0.75	1.09	1.05
3	9.88	0.91	1.10	1.06
4	9.47	0.62	1.07	1.03
5	9.35	0.77	1.09	1.05
6	9.70	0.96	1.11	1.07
7	9.89	0.84	1.09	1.06
8	9.64	0.89	1.10	1.06
9	9.16	0.45	1.05	1.02
10	9.85	0.87	1.10	1.06
		Average:	**1.09**	**1.05**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.63**	**1.63**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.98	126.50	67.29

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	214.9
2	182.2
3	234.3
4	139.4
5	226.6
6	168.1
7	236.0
8	212.6
9	207.5
10	182.7
11	207.1
12	229.1
13	189.1
14	169.7
15	189.1
16	153.4
17	232.0
18	211.4
19	176.5
20	222.4
21	189.3
22	213.3
23	203.6
24	190.7
25	201.9
Average:	**199.3**
St. Dev:	**25.6**
St. Dev (%):	**12.8**

Material Variables Evaluation

Sample:	EM-SG-13
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Switchgrass - 20% - #8
Target Moisture:	5.0%
Date:	6/4/2013
Time	12:00:00 PM

Comments:	1213.80 g coal
	349.50 g biomass
	11.70 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0400
Briquettes	48.09	46.24	1.85	0.040

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.62	0.62	1.07	1.03
2	9.57	0.96	1.11	1.07
3	9.62	1.01	1.12	1.07
4	9.75	0.64	1.07	1.03
5	9.78	1.09	1.13	1.08
6	9.61	1.16	1.14	1.09
7	8.95	0.23	1.03	0.99
8	9.49	0.85	1.10	1.06
9	9.43	0.50	1.06	1.02
10	9.69	0.90	1.10	1.06
		Average:	**1.09**	**1.05**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**3.20**	**3.20**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.72	131.43	68.55

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	217.9
2	195.8
3	285.0
4	196.7
5	181.2
6	165.6
7	203.2
8	220.2
9	182.3
10	173.8
11	348.7
12	184.3
13	192.2
14	192.9
15	172.3
16	225.9
17	218.9
18	171.9
19	191.5
20	197.0
21	164.4
22	205.3
23	204.0
24	179.6
25	199.3
Average:	**202.8**
St. Dev:	**39.4**
St. Dev (%):	**19.4**

Material Variables Evaluation

Sample:	EM-SG-02
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Switchgrass - 20% - #16
Target Moisture:	8.0%
Date:	6/4/2013
Time	9:00:00 AM

Comments:	1214.40 g coal
	351.60 g biomass
	54.00 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	Many briquettes initially float in water

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.077
Briquettes	47.80	44.89	2.91	0.065

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.44	0.62	1.07	1.01
2	9.72	1.29	1.15	1.08
3	8.95	0.69	1.08	1.02
4	9.28	0.58	1.07	1.00
5	8.23	0.36	1.05	0.98
6	9.19	0.48	1.06	0.99
7	9.26	0.67	1.08	1.01
8	9.06	0.51	1.06	1.00
9	9.01	0.14	1.02	0.95
10	9.08	0.19	1.02	0.96
		Average:	**1.06**	**1.00**
		St. Dev:	**0.04**	**0.04**
		St. Dev (%):	**3.58**	**3.58**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	182.66	31.06	17.00

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	24.8
2	31.7
3	15.0
4	19.5
5	27.3
6	30.3
7	27.2
8	12.2
9	28.5
10	26.0
11	23.3
12	23.0
13	25.4
14	20.9
15	30.9
16	27.9
17	35.1
18	22.6
19	31.3
20	26.9
21	25.7
22	21.1
23	17.5
24	26.1
25	29.0
Average:	**25.2**
St. Dev:	**5.4**
St. Dev (%):	**21.4**

Material Variables Evaluation

Sample:	EM-SG-05
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Switchgrass - 10% - #8
Target Moisture:	2.0%
Date:	6/4/2013
Time	4:00:00 PM

Comments:	1366.20 g coal
	151.28 g biomass
	12.52 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0195
Briquettes	49.85	49.27	0.58	0.012

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.99	1.44	1.17	1.15
2	9.20	1.20	1.15	1.14
3	9.69	1.45	1.18	1.16
4	9.87	1.46	1.17	1.16
5	9.53	1.13	1.13	1.12
6	9.29	1.37	1.17	1.16
7	9.77	1.53	1.19	1.17
8	9.87	1.45	1.17	1.16
9	9.34	1.18	1.14	1.13
10	9.55	1.25	1.15	1.14
		Average:	**1.16**	**1.15**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.43**	**1.43**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	192.01	172.91	90.05

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	205.5
2	252.5
3	231.8
4	214.2
5	290.1
6	199.4
7	182.6
8	233.3
9	217.7
10	181.8
11	208.7
12	203.0
13	210.0
14	178.8
15	207.5
16	175.6
17	173.2
18	217.6
19	230.2
20	194.4
21	183.9
22	236.9
23	198.6
24	226.7
25	229.7
Average:	**211.3**
St. Dev:	**26.9**
St. Dev (%):	**12.8**

Material Variables Evaluation

Sample:	EM-SG-10
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Switchgrass - 10% - #4
Target Moisture:	5.0%
Date:	6/4/2013
Time	10:00:00 AM

Comments:	1365.53 g coal
	175.80 g biomass
	31.58 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0515
Briquettes	47.09	45.44	1.65	0.036

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.48	1.39	1.17	1.13
2	9.18	1.19	1.15	1.11
3	9.13	1.09	1.14	1.10
4	9.17	1.05	1.13	1.09
5	9.06	1.12	1.14	1.10
6	9.38	0.89	1.10	1.07
7	9.65	0.85	1.10	1.06
8	9.27	1.02	1.12	1.08
9				
10				
		Average:	**1.13**	**1.09**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.12**	**2.12**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.62	75.40	40.19

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	54.8
2	73.1
3	93.1
4	130.2
5	47.7
6	106.3
7	90.1
8	55.1
9	117.4
10	53.5
11	60.8
12	120.5
13	57.9
14	116.3
15	114.6
16	75.4
17	82.1
18	117.3
19	48.6
20	90.7
21	69.8
22	
23	
24	
25	
Average:	**84.5**
St. Dev:	**27.5**
St. Dev (%):	**32.5**

Material Variables Evaluation

Sample:	EM-SG-03
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Switchgrass - 20% - #4
Target Moisture:	2.0%
Date:	6/4/2013
Time	11:00:00 AM

Comments:	1213.80 g coal
	303.15 g biomass
	13.05 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0190
Briquettes	46.82	46.22	0.60	0.013

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.58	1.25	1.15	1.14
2	9.53	0.88	1.10	1.09
3	9.80	1.36	1.16	1.15
4	9.89	1.01	1.11	1.10
5	9.39	1.01	1.12	1.11
6	9.33	1.17	1.14	1.13
7	9.62	0.99	1.11	1.10
8	9.21	0.74	1.09	1.07
9	9.20	0.97	1.12	1.10
10	9.92	1.21	1.14	1.12
		Average:	**1.12**	**1.11**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.04**	**2.04**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.36	161.04	85.95

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	299.5
2	370.4
3	262.1
4	286.5
5	290.2
6	245.4
7	326.3
8	233.6
9	292.5
10	313.3
11	237.4
12	323.2
13	297.9
14	251.9
15	290.0
16	294.0
17	253.8
18	304.3
19	275.2
20	264.7
21	249.9
22	288.4
23	276.7
24	221.1
25	282.1
Average:	**281.2**
St. Dev:	**33.4**
St. Dev (%):	**11.9**

Material Variables Evaluation

Sample:	EM-SG-01
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Switchgrass - 20% - #16
Target Moisture:	2.0%
Date:	6/4/2013
Time	12:00:00 PM

Comments:	1213.80 g coal
	303.60 g biomass
	12.60 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0200
Briquettes	47.78	47.10	0.68	0.014

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.49	1.08	1.13	1.11
2	9.87	1.36	1.16	1.14
3	9.52	1.04	1.12	1.11
4	9.81	1.47	1.18	1.16
5	9.80	0.98	1.11	1.10
6	9.33	1.08	1.13	1.11
7	9.52	1.13	1.13	1.12
8	8.69	0.69	1.09	1.07
9	9.82	1.39	1.16	1.15
10	9.50	1.20	1.14	1.13
		Average:	1.14	1.12
		St. Dev:	0.03	0.03
		St. Dev (%):	2.36	2.36

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.06	167.73	89.67

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	292.3
2	271.2
3	319.3
4	287.1
5	313.0
6	347.1
7	325.6
8	327.5
9	266.9
10	286.7
11	377.8
12	328.4
13	290.4
14	279.5
15	300.4
16	346.4
17	312.9
18	328.6
19	298.6
20	312.8
21	276.3
22	287.9
23	360.8
24	327.0
25	293.6
Average:	310.3
St. Dev:	28.6
St. Dev (%):	9.2

Material Variables Evaluation

Sample:	EM-SG-06
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Switchgrass - 10% - #8
Target Moisture:	8.0%
Date:	5/29/2013
Time	12:00:00 PM

Comments:	1365.53 g coal
	174.75 g biomass
	79.72 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0820
Briquettes	45.86	43.06	2.80	0.065

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.12	0.96	1.12	1.05
2	8.69	1.29	1.17	1.10
3	8.74	1.30	1.17	1.10
4	8.98	1.37	1.18	1.11
5	8.79	1.31	1.18	1.10
6	8.64	1.12	1.15	1.08
7	8.88	1.20	1.16	1.09
8	9.10	1.08	1.13	1.07
9	9.44	1.16	1.14	1.07
10	8.37	0.81	1.11	1.04
		Average:	**1.15**	**1.08**
		St. Dev:	**0.03**	**0.02**
		St. Dev (%):	**2.24**	**2.24**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	182.32	10.67	5.85

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	12.0
2	15.8
3	10.9
4	19.8
5	12.1
6	12.8
7	13.3
8	11.3
9	15.6
10	13.7
11	11.1
12	12.7
13	15.6
14	11.9
15	17.0
16	10.6
17	16.2
18	20.3
19	11.3
20	17.4
21	14.4
22	14.6
23	12.2
24	14.3
25	13.8
Average:	**14.0**
St. Dev:	**2.7**
St. Dev (%):	**19.0**

Material Variables Evaluation

Sample:	EM-SG-04
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Switchgrass - 20% - #4
Target Moisture:	8.0%
Date:	5/31/2013
Time	1:00:00 PM

Comments:	1213.80 g coal
	351.60 g biomass
	54.60 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0835
Briquettes	46.84	43.96	2.88	0.066

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.58	1.30	1.16	1.09
2	8.77	0.72	1.09	1.02
3	8.90	0.63	1.08	1.01
4	8.82	0.85	1.11	1.04
5	9.01	0.94	1.12	1.05
6	9.44	1.04	1.12	1.05
7	9.04	0.93	1.11	1.05
8	9.18	0.87	1.10	1.04
9	9.24	1.14	1.14	1.07
10	9.18	1.03	1.13	1.06
		Average:	**1.12**	**1.05**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.11**	**2.11**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.58	24.07	12.83

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	10.3
2	19.1
3	20.1
4	14.6
5	13.0
6	12.6
7	25.5
8	21.8
9	14.8
10	18.0
11	22.7
12	14.4
13	16.1
14	33.4
15	13.0
16	16.2
17	19.2
18	21.0
19	20.8
20	11.2
21	17.1
22	15.8
23	17.6
24	23.5
25	18.6
Average:	**18.0**
St. Dev:	**5.1**
St. Dev (%):	**28.1**

Material Variables Evaluation

Sample:	EM-MC-01
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Miscanthus - 20% - #16
Target Moisture:	2.0%
Date:	7/1/2013
Time	1:00:00 PM

Comments:	1216.80 g coal
	303.15 g biomass
	10.05 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0225
Briquettes	47.06	46.36	0.70	0.015

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.54	1.26	1.15	1.14
2	9.47	1.28	1.16	1.14
3	9.47	1.26	1.15	1.14
4	9.15	1.00	1.12	1.11
5	9.86	1.37	1.16	1.14
6	9.41	1.25	1.15	1.14
7	9.38	1.13	1.14	1.12
8	9.58	1.37	1.17	1.15
9	9.54	1.04	1.12	1.11
10	9.62	1.28	1.15	1.14
		Average:	**1.15**	**1.13**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.34**	**1.34**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.40	168.53	88.98

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	303.9
2	310.9
3	292.3
4	327.2
5	265.1
6	356.1
7	262.0
8	335.9
9	268.9
10	375.2
11	353.9
12	304.2
13	378.4
14	364.6
15	281.7
16	305.6
17	324.7
18	268.2
19	333.2
20	273.7
21	236.8
22	357.0
23	313.5
24	341.9
25	270.8
Average:	**312.2**
St. Dev:	**39.8**
St. Dev (%):	**12.7**

Material Variables Evaluation

Sample:	EM-MC-14
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Miscanthus - 20% - #8
Target Moisture:	5.0%
Date:	7/1/2013
Time	2:00:00 PM

Comments:	1216.80 g coal
	348.60 g biomass
	9.60 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0450
Briquettes	46.29	44.54	1.75	0.039

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.52	1.25	1.15	1.11
2	9.82	1.08	1.12	1.08
3	9.77	1.17	1.14	1.09
4	9.27	0.96	1.12	1.07
5	9.61	1.25	1.15	1.11
6	9.26	0.96	1.12	1.07
7	9.06	0.89	1.11	1.07
8	9.56	1.24	1.15	1.11
9	9.41	1.14	1.14	1.09
10	9.39	1.08	1.13	1.09
		Average:	**1.13**	**1.09**
		St. Dev:	**0.02**	**0.01**
		St. Dev (%):	**1.37**	**1.37**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.69	137.54	72.51

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	257.4
2	266.6
3	241.0
4	219.2
5	228.5
6	216.7
7	198.0
8	205.9
9	231.1
10	205.8
11	245.2
12	187.5
13	234.5
14	219.4
15	176.6
16	266.3
17	226.5
18	193.3
19	315.1
20	239.3
21	216.6
22	203.0
23	226.9
24	199.3
25	262.0
Average:	**227.3**
St. Dev:	**30.6**
St. Dev (%):	**13.4**

Material Variables Evaluation

Sample:	EM-MC-12
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Miscanthus - 30% - #4
Target Moisture:	5.0%
Date:	7/1/2013
Time	3:00:00 PM

Comments:	1064.70 g coal
	455.85 g biomass
	54.45 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0355
Briquettes	45.35	43.77	1.58	0.036

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.99	0.79	1.10	1.06
2	9.34	1.09	1.13	1.09
3	9.52	1.21	1.15	1.11
4	8.79	0.67	1.08	1.04
5	9.35	0.97	1.12	1.08
6	9.05	1.07	1.13	1.09
7	9.69	1.13	1.13	1.09
8	8.80	0.70	1.09	1.05
9	8.71	0.57	1.07	1.03
10	9.00	0.70	1.08	1.05
		Average:	**1.11**	**1.07**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.44**	**2.44**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	183.27	152.54	83.23

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	480.4
2	570.8
3	452.5
4	422.5
5	549.0
6	556.4
7	537.3
8	493.6
9	309.0
10	288.9
11	457.2
12	469.9
13	369.0
14	291.6
15	465.2
16	511.1
17	387.1
18	400.8
19	542.9
20	420.0
21	549.7
22	512.0
23	498.5
24	396.2
25	
Average:	**455.5**
St. Dev:	**84.2**
St. Dev (%):	**18.5**

Material Variables Evaluation

Sample:	EM-MC-07
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Miscanthus - 30% - #8
Target Moisture:	2.0%
Date:	7/1/2013
Time	4:00:00 PM

Comments:	1064.70 g coal
	456.53 g biomass
	8.78 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0235
Briquettes	45.97	45.34	0.63	0.014

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.81	1.24	1.14	1.13
2	8.78	0.54	1.07	1.05
3	9.19	0.81	1.10	1.08
4	9.08	0.76	1.09	1.08
5	9.56	0.93	1.11	1.09
6	8.54	0.29	1.04	1.02
7	9.58	0.94	1.11	1.09
8	9.22	0.80	1.10	1.08
9	8.64	0.36	1.04	1.03
10	9.53	0.90	1.10	1.09
		Average:	**1.09**	**1.07**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**3.01**	**3.01**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.15	162.07	86.14

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	402.2
2	430.0
3	431.1
4	468.5
5	316.0
6	499.2
7	419.6
8	414.5
9	443.7
10	508.5
11	460.8
12	340.9
13	470.9
14	483.4
15	444.0
16	471.5
17	452.9
18	489.4
19	524.2
20	378.0
21	472.7
22	363.8
23	354.7
24	444.5
25	453.6
Average:	**437.5**
St. Dev:	**53.6**
St. Dev (%):	**12.2**

Material Variables Evaluation

Sample:	EM-MC-08
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Miscanthus - 30% - #8
Target Moisture:	8.0%
Date:	7/1/2013
Time	5:00:00 PM

Comments:	1064.70 g coal
	522.90 g biomass
	32.40 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0765
Briquettes	44.69	41.87	2.82	0.067

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.62	0.96	1.11	1.04
2	9.12	0.56	1.07	1.00
3	9.14	0.92	1.11	1.04
4	8.65	0.57	1.07	1.00
5	9.12	0.77	1.09	1.02
6	9.44	0.67	1.08	1.01
7	8.97	0.32	1.04	0.97
8	9.30	0.51	1.06	0.99
9	9.77	0.81	1.09	1.02
10	9.51	0.49	1.05	0.99
		Average:	**1.08**	**1.01**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.28**	**2.28**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	182.60	84.91	46.50

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	132.4
2	158.2
3	206.5
4	296.0
5	167.3
6	207.4
7	125.9
8	358.9
9	246.5
10	124.4
11	157.4
12	126.3
13	209.6
14	177.5
15	152.4
16	85.1
17	145.8
18	135.2
19	147.0
20	213.6
21	228.0
22	193.5
23	300.8
24	171.0
25	284.9
Average:	**190.1**
St. Dev:	**66.2**
St. Dev (%):	**34.9**

Material Variables Evaluation

Sample:	EM-MC-11
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Miscanthus - 30% - #16
Target Moisture:	5.0%
Date:	7/2/2013
Time	10:00:00 AM

Comments:	1068.38 g coal
	454.73 g biomass
	51.90 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0495
Briquettes	47.34	45.57	1.77	0.039

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.76	0.54	1.07	1.03
2	8.72	0.48	1.06	1.02
3	9.56	1.11	1.13	1.09
4	9.32	0.99	1.12	1.08
5	9.57	1.17	1.14	1.10
6	9.27	0.80	1.09	1.05
7	9.34	0.70	1.08	1.04
8	9.73	1.16	1.14	1.09
9	8.95	0.69	1.08	1.04
10	9.85	1.08	1.12	1.08
		Average:	**1.10**	**1.06**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.73**	**2.73**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.84	161.44	85.04

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	370.5
2	434.2
3	307.4
4	315.6
5	389.7
6	455.3
7	498.7
8	361.7
9	372.8
10	359.4
11	361.5
12	403.2
13	481.5
14	358.4
15	406.1
16	364.1
17	360.2
18	457.0
19	428.9
20	359.0
21	365.7
22	543.7
23	391.5
24	497.1
25	415.5
Average:	**402.3**
St. Dev:	**59.3**
St. Dev (%):	**14.7**

Material Variables Evaluation

Sample:	EM-MC-09
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Miscanthus - 10% - #16
Target Moisture:	5.0%
Date:	7/2/2013
Time	11:00:00 AM

Comments:	1373.63 g coal
	173.03 g biomass
	28.35 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0475
Briquettes	48.49	46.66	1.83	0.039

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.56	1.43	1.18	1.13
2	9.79	1.60	1.20	1.15
3	9.18	1.33	1.17	1.13
4	9.48	1.38	1.17	1.13
5	9.46	1.49	1.19	1.14
6	9.70	1.35	1.16	1.12
7	9.85	1.45	1.17	1.13
8	9.57	1.32	1.16	1.12
9	9.13	1.32	1.17	1.12
10	9.60	1.41	1.17	1.13
		Average:	**1.17**	**1.13**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.91**	**0.91**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.75	70.29	36.66

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	84.1
2	98.4
3	73.3
4	50.6
5	62.1
6	70.7
7	67.8
8	44.1
9	68.0
10	74.8
11	66.0
12	95.8
13	57.5
14	57.7
15	61.5
16	64.2
17	78.6
18	49.3
19	47.6
20	75.8
21	79.7
22	55.2
23	59.7
24	75.9
25	58.6
Average:	**67.1**
St. Dev:	**13.9**
St. Dev (%):	**20.8**

Material Variables Evaluation

Sample:	EM-MC-15
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Miscanthus - 20% - #8
Target Moisture:	5.0%
Date:	7/2/2013
Time	12:00:00 PM

Comments:	1221.00 g coal
	348.60 g biomass
	5.40 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0525
Briquettes	48.25	46.40	1.85	0.040

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.16	1.11	1.14	1.09
2	9.81	1.08	1.12	1.08
3	9.45	1.02	1.12	1.08
4	9.47	0.93	1.11	1.07
5	9.39	1.13	1.14	1.09
6	9.25	0.81	1.10	1.05
7	9.33	0.68	1.08	1.04
8	9.32	1.04	1.13	1.08
9	9.31	0.94	1.11	1.07
10	9.71	0.94	1.11	1.06
		Average:	**1.11**	**1.07**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.64**	**1.64**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.72	124.50	65.28

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	234.0
2	235.3
3	168.0
4	185.0
5	193.1
6	277.6
7	220.8
8	192.2
9	232.0
10	206.0
11	165.2
12	205.6
13	167.0
14	216.5
15	169.2
16	207.6
17	148.8
18	243.1
19	211.5
20	224.2
21	163.7
22	250.4
23	195.5
24	206.2
25	273.7
Average:	**207.7**
St. Dev:	**34.1**
St. Dev (%):	**16.4**

Material Variables Evaluation

Sample:	EM-MC-04
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Miscanthus - 20% - #4
Target Moisture:	8.0%
Date:	7/2/2013
Time	1:00:00 PM

Comments:	1221.00 g coal
	348.90 g biomass
	50.10 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0795
Briquettes	47.94	44.97	2.97	0.066

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.35	1.38	1.17	1.10
2	9.24	1.27	1.16	1.09
3	9.28	1.19	1.15	1.08
4	9.54	1.39	1.17	1.10
5	8.94	1.25	1.16	1.09
6	9.47	1.33	1.16	1.09
7	9.82	1.42	1.17	1.10
8	9.36	1.28	1.16	1.09
9	9.24	1.31	1.17	1.09
10	9.63	1.33	1.16	1.09
		Average:	**1.16**	**1.09**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.64**	**0.64**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	182.73	24.94	13.65

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	30.7
2	35.9
3	68.1
4	34.6
5	62.9
6	36.5
7	20.3
8	45.6
9	23.1
10	29.7
11	57.5
12	48.5
13	60.5
14	29.7
15	45.4
16	20.9
17	71.1
18	46.2
19	33.0
20	20.9
21	19.9
22	45.1
23	59.5
24	22.6
25	31.9
Average:	**40.0**
St. Dev:	**16.0**
St. Dev (%):	**40.1**

Material Variables Evaluation

Sample:	EM-MC-02
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Miscanthus - 20% - #16
Target Moisture:	8.0%
Date:	7/2/2013
Time	2:00:00 PM

Comments:	1221.00 g coal
	346.05 g biomass
	52.95 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0760
Briquettes	46.95	44.19	2.76	0.062

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.06	1.25	1.16	1.09
2	9.12	1.28	1.16	1.09
3	8.98	1.39	1.18	1.11
4	9.65	1.49	1.18	1.11
5	8.85	1.26	1.17	1.10
6	9.43	1.23	1.15	1.08
7	9.03	1.06	1.13	1.07
8	9.26	1.19	1.15	1.08
9	9.42	1.15	1.14	1.07
10	9.36	1.14	1.14	1.07
		Average:	**1.16**	**1.09**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.54**	**1.54**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	184.95	28.86	15.60

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	22.5
2	20.5
3	23.9
4	23.3
5	20.4
6	22.8
7	26.6
8	28.9
9	28.7
10	19.5
11	21.4
12	22.3
13	35.7
14	30.6
15	27.1
16	22.9
17	23.0
18	32.5
19	30.6
20	24.7
21	36.7
22	29.4
23	18.8
24	14.3
25	38.4
Average:	**25.8**
St. Dev:	**6.0**
St. Dev (%):	**23.1**

Material Variables Evaluation

Sample:	EM-MC-05
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Miscanthus - 10% - #8
Target Moisture:	2.0%
Date:	7/2/2013
Time	3:00:00 PM

Comments:	1373.63 g coal
	152.18 g biomass
	4.20 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0205
Briquettes	48.42	47.70	0.72	0.015

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.47	1.62	1.21	1.19
2	9.83	1.64	1.20	1.18
3	9.94	1.72	1.21	1.19
4	9.76	1.65	1.20	1.19
5	9.83	1.65	1.20	1.18
6	9.63	1.47	1.18	1.16
7	9.70	1.68	1.21	1.19
8	9.64	1.53	1.19	1.17
9	9.85	1.61	1.20	1.18
10	9.77	1.53	1.19	1.17
		Average:	1.20	1.18
		St. Dev:	0.01	0.01
		St. Dev (%):	0.85	0.85

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	195.04	177.57	91.04

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	209.2
2	204.4
3	211.5
4	174.8
5	219.0
6	268.6
7	173.9
8	209.7
9	230.2
10	207.4
11	198.7
12	211.7
13	207.3
14	181.9
15	176.7
16	210.5
17	178.5
18	207.1
19	211.1
20	185.0
21	214.7
22	162.6
23	180.7
24	227.0
25	192.1
Average:	202.2
St. Dev:	22.7
St. Dev (%):	11.2

Material Variables Evaluation

Sample:	EM-MC-10
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Miscanthus - 10% - #4
Target Moisture:	5.0%
Date:	7/2/2013
Time	4:00:00 PM

Comments:	1373.63 g coal
	174.45 g biomass
	26.93 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0465
Briquettes	46.75	45.07	1.68	0.037

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.84	1.36	1.18	1.14
2	9.13	1.40	1.18	1.14
3	9.26	1.51	1.19	1.15
4	9.67	1.47	1.18	1.14
5	9.82	1.44	1.17	1.13
6	9.11	1.35	1.17	1.13
7	9.51	1.10	1.13	1.09
8	9.37	1.45	1.18	1.14
9	9.29	1.28	1.16	1.12
10	9.34	1.40	1.18	1.13
		Average:	**1.17**	**1.13**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.48**	**1.48**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.87	61.83	32.39

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	66.5
2	56.0
3	48.5
4	71.0
5	68.9
6	58.9
7	68.7
8	107.0
9	66.0
10	46.9
11	69.8
12	64.4
13	78.8
14	71.8
15	58.9
16	48.8
17	89.3
18	67.2
19	77.7
20	75.0
21	78.9
22	69.8
23	86.3
24	57.4
25	82.5
Average:	**69.4**
St. Dev:	**13.7**
St. Dev (%):	**19.8**

Material Variables Evaluation

Sample:	EM-MC-13
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Miscanthus - 20% - #8
Target Moisture:	5.0%
Date:	7/8/2013
Time	10:00:00 AM

Comments:	1221.00 g coal
	348.60 g biomass
	5.40 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0505
Briquettes	45.12	43.44	1.68	0.039

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.46	1.31	1.16	1.12
2	9.53	1.20	1.14	1.10
3	9.31	0.94	1.11	1.07
4	9.55	1.11	1.13	1.09
5	9.56	1.13	1.13	1.09
6	9.54	1.14	1.14	1.09
7	9.25	0.84	1.10	1.06
8				
9				
10				
		Average:	**1.13**	**1.09**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.77**	**1.77**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	193.15	128.11	66.33

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	214.7
2	171.5
3	171.3
4	216.4
5	220.5
6	198.2
7	176.9
8	194.0
9	214.4
10	172.1
11	189.4
12	204.1
13	255.5
14	200.5
15	185.3
16	159.3
17	200.9
18	188.9
19	174.2
20	195.7
21	218.7
22	166.7
23	178.6
24	
25	
Average:	**194.3**
St. Dev:	**22.5**
St. Dev (%):	**11.6**

Material Variables Evaluation

Sample:	EM-MC-03
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Miscanthus - 20% - #4
Target Moisture:	2.0%
Date:	7/8/2013
Time	11:00:00 AM

Comments:	1221.00 g coal
	303.90 g biomass
	5.10 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0235
Briquettes	47.25	46.55	0.70	0.015

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.07	1.58	1.19	1.17
2	9.22	1.12	1.14	1.12
3	9.96	1.43	1.17	1.15
4	9.12	1.07	1.13	1.12
5	9.98	1.35	1.16	1.14
6	9.65	1.30	1.16	1.14
7	9.55	1.31	1.16	1.14
8	9.65	1.27	1.15	1.13
9	9.67	1.10	1.13	1.11
10	9.33	1.13	1.14	1.12
		Average:	**1.15**	**1.13**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.53**	**1.53**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	193.70	172.86	89.24

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	252.6
2	264.2
3	241.6
4	303.8
5	295.8
6	315.7
7	268.0
8	298.1
9	251.7
10	243.7
11	263.7
12	219.6
13	299.4
14	201.1
15	284.3
16	258.2
17	300.4
18	249.8
19	268.5
20	281.3
21	199.8
22	296.8
23	319.0
24	304.9
25	325.4
Average:	**272.3**
St. Dev:	**34.8**
St. Dev (%):	**12.8**

Material Variables Evaluation

Sample:	EM-MC-06
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Miscanthus - 10% - #8
Target Moisture:	8.0%
Date:	7/9/2013
Time	9:00:00 AM

Comments:	1373.63 g coal
	174.30 g biomass
	72.08 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0760
Briquettes	46.15	43.28	2.87	0.066

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.34	1.55	1.20	1.12
2	8.44	1.12	1.15	1.08
3	9.28	1.52	1.20	1.12
4	9.14	1.45	1.19	1.11
5	8.92	1.44	1.19	1.12
6	9.16	1.48	1.19	1.12
7	9.01	1.42	1.19	1.11
8	8.93	1.44	1.19	1.12
9	9.18	1.58	1.21	1.13
10	8.95	1.41	1.19	1.11
		Average:	**1.19**	**1.12**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.20**	**1.20**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	183.66	9.34	5.09

Crushing Strength Tests

Measurement	Crushing Strength ($\mathrm{lb_f}$)
1	13.0
2	11.6
3	14.2
4	11.7
5	17.5
6	15.9
7	23.8
8	10.8
9	12.2
10	26.9
11	8.9
12	14.2
13	15.8
14	10.2
15	20.5
16	16.3
17	19.5
18	12.5
19	14.3
20	22.4
21	21.2
22	21.7
23	17.8
24	13.8
25	16.3
Average:	**16.1**
St. Dev:	**4.6**
St. Dev (%):	**28.8**

Material Variables Evaluation

Sample:	EM-WS-11
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Wheat Straw - 30% - #16
Target Moisture:	5.0%
Date:	6/20/2013
Time	9:00:00 AM

Comments:	1062.08 g coal
	498.15 g biomass
	14.78 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0585
Briquettes	47.93	45.77	2.16	0.047

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.38	1.09	1.13	1.08
2	9.32	0.99	1.12	1.07
3	9.52	1.09	1.13	1.08
4	9.62	1.16	1.14	1.09
5	9.71	1.20	1.14	1.09
6	9.50	1.10	1.13	1.08
7	9.90	1.35	1.16	1.11
8	9.66	1.18	1.14	1.09
9	9.80	1.24	1.14	1.09
10	9.69	1.29	1.15	1.10
		Average:	**1.14**	**1.09**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.03**	**1.03**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.16	163.73	86.10

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	320.1
2	351.9
3	340.0
4	333.9
5	313.4
6	295.8
7	329.7
8	284.1
9	304.4
10	351.3
11	292.2
12	289.2
13	353.6
14	258.2
15	340.7
16	299.7
17	272.4
18	274.9
19	343.5
20	345.6
21	322.1
22	347.0
23	329.4
24	342.1
25	309.0
Average:	**317.8**
St. Dev:	**28.3**
St. Dev (%):	**8.9**

Material Variables Evaluation

Sample:	EM-WS-09
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Wheat Straw - 10% - #16
Target Moisture:	5.0%
Date:	6/20/2013
Time	10:00:00 AM

Comments:	1366.88 g coal
	166.05 g biomass
	42.08 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0490
Briquettes	48.14	46.21	1.93	0.042

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.58	1.52	1.19	1.14
2	9.75	1.53	1.19	1.14
3	9.47	1.36	1.17	1.12
4	9.16	1.42	1.18	1.14
5	9.62	1.40	1.17	1.12
6	9.58	1.36	1.17	1.12
7	9.77	1.47	1.18	1.13
8	9.61	1.38	1.17	1.12
9	9.42	1.40	1.17	1.13
10	9.60	1.44	1.18	1.13
		Average:	**1.18**	**1.13**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.70**	**0.70**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	192.03	121.88	63.47

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	102.8
2	86.4
3	96.9
4	89.4
5	76.0
6	92.1
7	88.4
8	105.4
9	97.6
10	110.0
11	85.2
12	97.0
13	97.9
14	87.3
15	101.1
16	80.2
17	104.1
18	120.0
19	96.2
20	99.0
21	89.2
22	81.6
23	91.8
24	84.1
25	92.8
Average:	**94.1**
St. Dev:	**10.0**
St. Dev (%):	**10.6**

Material Variables Evaluation

Sample:	EM-WS-14
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Wheat Straw - 20% - #8
Target Moisture:	5.0%
Date:	6/20/2013
Time	11:00:00 AM

Comments:	1215.00 g coal
	334.35 g biomass
	25.65 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0570
Briquettes	47.71	45.62	2.09	0.046

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.76	1.27	1.15	1.10
2	9.74	1.39	1.17	1.12
3	9.74	1.28	1.15	1.10
4	9.70	1.17	1.14	1.09
5	9.34	1.14	1.14	1.09
6	9.18	1.02	1.13	1.08
7	9.44	1.36	1.17	1.12
8	9.43	1.16	1.14	1.09
9	9.61	1.26	1.15	1.10
10	9.37	1.04	1.12	1.08
		Average:	**1.15**	**1.10**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.31**	**1.31**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.19	152.74	79.89

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	221.8
2	226.8
3	251.3
4	214.9
5	240.0
6	271.0
7	235.1
8	178.8
9	232.8
10	251.0
11	228.1
12	281.1
13	250.9
14	232.7
15	211.1
16	225..9
17	352.9
18	224.1
19	242.8
20	242.5
21	246.8
22	226.3
23	201.7
24	283.3
25	188.8
Average:	**239.0**
St. Dev:	**35.0**
St. Dev (%):	**14.6**

Material Variables Evaluation

Sample:	EM-WS-05
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Wheat Straw - 10% - #8
Target Moisture:	2.0%
Date:	6/20/2013
Time	12:00:00 PM

Comments:	1366.88 g coal
	152.63 g biomass
	10.50 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0220
Briquettes	48.52	47.87	0.65	0.014

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.03	1.70	1.20	1.19
2	10.02	1.60	1.19	1.17
3	9.70	1.51	1.18	1.17
4	9.83	1.70	1.21	1.19
5	9.88	1.64	1.20	1.18
6	9.66	1.65	1.21	1.19
7	9.74	1.58	1.19	1.18
8	10.09	1.80	1.22	1.20
9	9.69	1.40	1.17	1.15
10	9.72	1.64	1.20	1.19
		Average:	**1.20**	**1.18**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.16**	**1.16**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.68	178.42	91.65

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	162.4
2	185.8
3	237.9
4	197.0
5	199.4
6	191.5
7	224.1
8	200.8
9	187.2
10	227.2
11	215.6
12	236.1
13	196.6
14	199.7
15	236.8
16	224.9
17	215.3
18	210.0
19	220.2
20	260.9
21	264.6
22	190.9
23	221.1
24	190.1
25	205.0
Average:	**212.0**
St. Dev:	**24.0**
St. Dev (%):	**11.3**

Material Variables Evaluation

Sample:	EM-WS-06
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Wheat Straw - 10% - #8
Target Moisture:	8.0%
Date:	6/20/2013
Time	2:00:00 PM

Comments:	1366.88 g coal
	167.18 g biomass
	85.95 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0785
Briquettes	46.48	43.64	2.84	0.065

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.43	1.64	1.21	1.14
2	9.36	1.66	1.22	1.14
3	9.23	1.39	1.18	1.11
4	9.56	1.43	1.18	1.10
5	9.09	1.25	1.16	1.09
6	9.35	1.50	1.19	1.12
7	8.96	1.28	1.17	1.10
8	9.42	1.46	1.18	1.11
9	9.62	1.36	1.16	1.09
10	9.10	1.38	1.18	1.11
		Average:	**1.18**	**1.11**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.58**	**1.58**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.82	39.51	21.04

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	37.9
2	25.7
3	21.3
4	32.3
5	38.1
6	30.6
7	24.8
8	49.6
9	38.8
10	41.8
11	45.2
12	32.4
13	44.3
14	32.6
15	31.3
16	28.8
17	31.1
18	26.8
19	25.1
20	34.0
21	25.3
22	33.2
23	30.9
24	29.0
25	47.3
Average:	**33.5**
St. Dev:	**7.6**
St. Dev (%):	**22.6**

Material Variables Evaluation

Sample:	EM-WS-13
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Wheat Straw - 20% - #8
Target Moisture:	5.0%
Date:	6/20/2013
Time	3:00:00 PM

Comments:	1215.00 g coal
	334.35 g biomass
	25.65 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0495
Briquettes	47.62	45.75	1.87	0.041

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.17	0.93	1.11	1.07
2	9.51	1.07	1.13	1.08
3	9.34	1.14	1.14	1.09
4	9.69	1.26	1.15	1.10
5	9.35	1.07	1.13	1.08
6	9.87	1.16	1.13	1.09
7	9.42	1.16	1.14	1.10
8	9.27	1.00	1.12	1.08
9	9.42	1.17	1.14	1.10
10	9.74	1.27	1.15	1.10
		Average:	**1.13**	**1.09**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.06**	**1.06**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.82	153.80	81.02

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	205.9
2	225.8
3	206.4
4	269.9
5	206.2
6	266.7
7	194.3
8	255.7
9	213.3
10	281.6
11	259.7
12	273.0
13	273.1
14	240.7
15	359.3
16	282.0
17	244.8
18	252.5
19	265.7
20	206.0
21	249.5
22	256.1
23	241.7
24	248.7
25	247.2
Average:	**249.0**
St. Dev:	**34.8**
St. Dev (%):	**14.0**

Material Variables Evaluation

Sample:	EM-WS-07
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Wheat Straw - 30% - #8
Target Moisture:	2.0%
Date:	6/20/2013
Time	4:00:00 PM

Comments:
1063.13 g coal
457.88 g biomass
9.00 g water
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0240
Briquettes	46.39	45.64	0.75	0.016

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.33	0.80	1.09	1.08
2	9.56	0.88	1.10	1.08
3	9.66	0.68	1.08	1.06
4	9.33	0.59	1.07	1.05
5	9.79	1.01	1.12	1.10
6	9.70	0.90	1.10	1.08
7	9.53	0.74	1.08	1.07
8	9.24	0.60	1.07	1.05
9	9.21	0.50	1.06	1.04
10	9.05	0.39	1.05	1.03
		Average:	**1.08**	**1.06**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.04**	**2.04**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.09	145.65	77.03

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	387.8
2	292.6
3	549.8
4	389.4
5	319.6
6	360.8
7	382.9
8	418.4
9	325.1
10	408.1
11	273.5
12	224.7
13	355.6
14	393.7
15	294.6
16	336.2
17	412.8
18	367.2
19	400.4
20	366.7
21	353.1
22	371.7
23	307.1
24	447.3
25	327.7
Average:	**362.7**
St. Dev:	**64.3**
St. Dev (%):	**17.7**

Material Variables Evaluation

Sample:	EM-WS-01
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Wheat Straw - 20% - #16
Target Moisture:	2.0%
Date:	6/6/2013
Time	5:00:00 PM

Comments:	1215.00 g coal
	305.25 g biomass
	9.75 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0210
Briquettes	47.67	46.94	0.73	0.016

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.62	1.37	1.17	1.15
2	10.24	1.64	1.19	1.17
3	9.80	1.44	1.17	1.15
4	10.37	1.56	1.18	1.16
5	10.08	1.48	1.17	1.15
6	9.40	1.08	1.13	1.11
7	9.53	1.25	1.15	1.13
8	9.79	1.38	1.16	1.15
9	9.59	1.27	1.15	1.13
10	9.85	1.32	1.15	1.14
		Average:	**1.16**	**1.15**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.45**	**1.45**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	197.60	178.85	90.51

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	268.7
2	251.3
3	240.0
4	314.2
5	260.7
6	318.2
7	205.8
8	240.9
9	272.7
10	214.6
11	254.0
12	286.1
13	236.1
14	259.7
15	213.0
16	229.7
17	311.7
18	260.0
19	336.9
20	227.7
21	263.5
22	239.5
23	262.7
24	201.6
25	242.8
Average:	**256.5**
St. Dev:	**35.5**
St. Dev (%):	**13.8**

Material Variables Evaluation

Sample:	EM-WS-04
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Wheat Straw - 20% - #4
Target Moisture:	8.0%
Date:	6/7/2013
Time	12:00:00 PM

Comments:	1215.00 g coal
	336.75 g biomass
	68.25 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0765
Briquettes	46.49	43.67	2.82	0.065

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.49	0.92	1.11	1.04
2	9.42	1.25	1.15	1.08
3	9.27	1.19	1.15	1.08
4	9.65	1.12	1.13	1.06
5	9.41	1.01	1.12	1.05
6	9.41	1.10	1.13	1.06
7	9.42	1.12	1.13	1.07
8	9.71	1.32	1.16	1.09
9	9.36	0.69	1.08	1.01
10	8.69	0.82	1.10	1.04
		Average:	**1.13**	**1.06**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.16**	**2.16**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.09	77.62	41.27

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	93.7
2	113.2
3	92.2
4	128.3
5	86.6
6	79.0
7	203.0
8	95.7
9	118.1
10	104.8
11	192.8
12	93.5
13	130.9
14	103.3
15	130.2
16	161.3
17	109.3
18	113.4
19	100.5
20	99.3
21	163.1
22	164.6
23	148.0
24	108.5
25	104.9
Average:	**121.5**
St. Dev:	**33.0**
St. Dev (%):	**27.2**

Material Variables Evaluation

Sample:	EM-WS-10
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Wheat Straw - 10% - #4
Target Moisture:	5.0%
Date:	6/21/2013
Time	9:00:00 AM

Comments:	1366.88 g coal
	168.38 g biomass
	39.75 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0550
Briquettes	47.77	45.97	1.80	0.039

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.37	1.46	1.18	1.14
2	9.61	1.49	1.18	1.14
3	9.55	1.42	1.17	1.13
4	9.38	1.28	1.16	1.11
5	9.37	1.34	1.17	1.12
6	9.44	1.28	1.16	1.11
7	9.38	1.21	1.15	1.10
8	9.62	1.29	1.15	1.11
9	8.99	1.29	1.17	1.12
10	9.49	1.33	1.16	1.12
		Average:	**1.17**	**1.12**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.04**	**1.04**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	192.03	101.63	52.92

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	158.7
2	120.3
3	103.6
4	103.2
5	136.0
6	72.1
7	114.5
8	133.2
9	130.2
10	108.9
11	109.3
12	124.1
13	125.1
14	139.6
15	128.6
16	130.6
17	102.5
18	94.5
19	130.2
20	119.9
21	128.4
22	105.5
23	113.3
24	121.6
25	104.6
Average:	**118.3**
St. Dev:	**17.5**
St. Dev (%):	**14.8**

Material Variables Evaluation

Sample:	EM-WS-08
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Wheat Straw - 30% - #8
Target Moisture:	8.0%
Date:	6/21/2013
Time	10:00:00 AM

Comments:	1063.13 g coal
	501.53 g biomass
	55.35 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	Some briquettes initially float in water

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0800
Briquettes	47.91	44.75	3.16	0.071

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.69	0.53	1.06	0.99
2	9.26	0.16	1.02	0.95
3	9.39	0.41	1.05	0.98
4	9.59	0.79	1.09	1.02
5	9.15	0.29	1.03	0.96
6	9.49	0.73	1.08	1.01
7	9.54	0.76	1.09	1.01
8	9.50	0.27	1.03	0.96
9	9.38	0.23	1.03	0.96
10	9.43	0.48	1.05	0.98
		Average:	**1.05**	**0.98**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.55**	**2.55**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.59	140.54	74.13

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	136.7
2	144.1
3	193.6
4	232.5
5	214.7
6	126.9
7	238.4
8	201.6
9	150.9
10	203.1
11	212.1
12	175.5
13	254.1
14	199.5
15	171.4
16	210.8
17	214.3
18	174.0
19	180.6
20	169.2
21	131.6
22	209.9
23	237.0
24	160.9
25	163.9
Average:	**188.3**
St. Dev:	**35.4**
St. Dev (%):	**18.8**

Material Variables Evaluation

Sample:	EM-WS-03
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Wheat Straw - 20% - #4
Target Moisture:	2.0%
Date:	6/21/2013
Time	11:00:00 AM

Comments:	1215.00 g coal
	304.50 g biomass
	10.50 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0260
Briquettes	48.36	47.63	0.73	0.015

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.91	1.50	1.18	1.16
2	9.65	1.39	1.17	1.15
3	10.15	1.52	1.18	1.16
4	9.12	0.94	1.11	1.10
5	9.50	1.26	1.15	1.14
6	9.63	1.25	1.15	1.13
7	9.86	1.29	1.15	1.13
8	10.06	1.42	1.16	1.15
9	9.69	1.23	1.15	1.13
10	9.63	1.16	1.14	1.12
		Average:	**1.15**	**1.14**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.67**	**1.67**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	193.05	168.28	87.17

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	206.3
2	278.7
3	252.7
4	295.0
5	347.6
6	306.6
7	245.9
8	273.8
9	229.6
10	273.7
11	308.9
12	346.0
13	275.2
14	349.9
15	394.3
16	271.4
17	278.5
18	267.8
19	258.4
20	312.7
21	327.7
22	322.1
23	270.1
24	247.4
25	241.6
Average:	**287.3**
St. Dev:	**43.7**
St. Dev (%):	**15.2**

Material Variables Evaluation

Sample:	EM-WS-02
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Wheat Straw - 20% - #16
Target Moisture:	8.0%
Date:	6/21/2013
Time	12:00:00 PM

Comments:	1215.00 g coal
	333.90 g biomass
	71.10 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0835
Briquettes	47.01	44.09	2.92	0.066

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.42	1.24	1.15	1.08
2	9.27	0.82	1.10	1.03
3	9.17	0.77	1.09	1.02
4	8.92	0.73	1.09	1.02
5	9.02	0.86	1.11	1.04
6	9.01	0.81	1.10	1.03
7	9.29	0.88	1.10	1.04
8	9.68	1.10	1.13	1.06
9	9.27	0.92	1.11	1.04
10	9.16	0.78	1.09	1.03
		Average:	**1.11**	**1.04**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.75**	**1.75**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.55	80.64	42.77

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	77.6
2	73.1
3	69.6
4	77.4
5	73.4
6	70.4
7	72.5
8	74.2
9	81.6
10	67.8
11	71.2
12	87.6
13	66.1
14	80.8
15	65.5
16	70.7
17	63.1
18	70.5
19	78.1
20	73.8
21	74.0
22	75.0
23	55.7
24	71.1
25	68.8
Average:	**72.4**
St. Dev:	**6.4**
St. Dev (%):	**8.9**

Material Variables Evaluation

Sample:	EM-WS-12
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Wheat Straw - 30% - #4
Target Moisture:	5.0%
Date:	6/21/2013
Time	1:00:00 PM

Comments:	1063.13 g coal
	505.13 g biomass
	6.75 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0555
Briquettes	42.22	40.42	1.80	0.045

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.58	1.27	1.15	1.10
2	9.56	1.37	1.17	1.12
3	9.87	1.37	1.16	1.11
4	8.83	0.67	1.08	1.04
5	9.86	1.33	1.16	1.11
6	9.73	1.30	1.15	1.11
7	9.80	1.19	1.14	1.09
8	9.22	0.75	1.09	1.04
9	9.52	1.11	1.13	1.08
10	9.71	1.29	1.15	1.10
		Average:	**1.14**	**1.09**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.62**	**2.62**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	193.85	170.72	88.07

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	477.0
2	292.4
3	413.4
4	323.9
5	557.6
6	546.1
7	382.7
8	559.0
9	498.8
10	544.0
11	558.5
12	557.3
13	557.6
14	439.5
15	361.0
16	435.8
17	457.9
18	557.1
19	307.8
20	547.1
21	354.5
22	497.2
23	474.4
24	542.6
25	557.9
Average:	**472.0**
St. Dev:	**90.3**
St. Dev (%):	**19.1**

Material Variables Evaluation

Sample:	EM-WS-15
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Wheat Straw - 20% - #8
Target Moisture:	5.0%
Date:	6/21/2013
Time	2:00:00 PM

Comments:	1215.00 g coal
	334.35 g biomass
	25.65 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0505
Briquettes	47.38	45.51	1.87	0.041

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.82	1.35	1.16	1.11
2	9.36	1.26	1.16	1.11
3	9.60	1.08	1.13	1.08
4	9.47	1.29	1.16	1.11
5	9.57	1.38	1.17	1.12
6	9.52	1.08	1.13	1.08
7	9.67	1.36	1.16	1.12
8	9.57	1.29	1.16	1.11
9	9.53	1.10	1.13	1.09
10	9.90	1.29	1.15	1.10
		Average:	**1.15**	**1.10**
		St. Dev:	**0.02**	**0.01**
		St. Dev (%):	**1.34**	**1.34**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.72	162.78	84.91

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	272.6
2	265.3
3	202.2
4	200.8
5	163.3
6	268.6
7	229.2
8	275.2
9	239.5
10	207.1
11	233.4
12	231.2
13	291.5
14	220.4
15	246.0
16	216.0
17	182.0
18	252.7
19	234.8
20	244.3
21	204.0
22	219.1
23	251.9
24	234.3
25	237.9
Average:	**232.9**
St. Dev:	**30.1**
St. Dev (%):	**12.9**

Material Variables Evaluation

Sample:	EM-SD-11
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Sawdust - 30% - #16
Target Moisture:	5.0%
Date:	6/6/2013
Time	10:00:00 AM

Comments:	1062.08 g coal
	497.70 g biomass
	15.22 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0545
Briquettes	48.09	46.20	1.89	0.041

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.32	0.77	1.09	1.05
2	9.25	0.81	1.10	1.05
3	9.39	0.60	1.07	1.03
4	9.29	0.73	1.09	1.04
5	9.41	0.83	1.10	1.05
6	9.39	0.63	1.07	1.03
7	9.45	0.76	1.09	1.04
8	9.16	0.49	1.06	1.01
9	9.19	0.74	1.09	1.04
10	8.70	0.48	1.06	1.02
		Average:	**1.08**	**1.04**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.38**	**1.38**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.79	151.14	80.48

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	243.1
2	253.7
3	231.3
4	200.9
5	181.0
6	211.4
7	195.4
8	206.1
9	192.2
10	184.5
11	204.4
12	221.1
13	203.8
14	196.6
15	202.4
16	178.2
17	198.2
18	226.5
19	219.2
20	198.0
21	235.9
22	225.7
23	208.8
24	198.3
25	180.6
Average:	**207.9**
St. Dev:	**19.9**
St. Dev (%):	**9.6**

Material Variables Evaluation

Sample:	EM-SD-09
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Sawdust - 10% - #16
Target Moisture:	5.0%
Date:	6/6/2013
Time	11:00:00 AM

Comments:	1365.53 g coal
	165.90 g biomass
	43.57 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0515
Briquettes	48.25	46.50	1.75	0.038

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.44	1.02	1.12	1.08
2	9.71	0.95	1.11	1.07
3	9.60	1.05	1.12	1.08
4	9.38	0.31	1.03	1.00
5	9.35	0.96	1.11	1.07
6	9.71	0.90	1.10	1.06
7	9.43	0.84	1.10	1.06
8	9.56	0.59	1.07	1.03
9	9.49	0.51	1.06	1.02
10	9.74	0.94	1.11	1.07
		Average:	**1.09**	**1.05**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.76**	**2.76**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.41	88.10	46.76

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	57.5
2	60.6
3	48.9
4	50.8
5	53.6
6	57.3
7	48.5
8	48.6
9	52.5
10	51.4
11	61.9
12	48.5
13	46.8
14	45.9
15	53.4
16	53.8
17	59.1
18	61.9
19	49.7
20	66.1
21	51.8
22	56.2
23	49.8
24	51.7
25	57.3
Average:	**53.7**
St. Dev:	**5.3**
St. Dev (%):	**9.9**

Material Variables Evaluation

Sample:	EM-SD-14
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Sawdust - 20% - #8
Target Moisture:	5.0%
Date:	6/6/2013
Time	12:00:00 PM

Comments:	1213.80 g coal
	331.50 g biomass
	29.70 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0515
Briquettes	49.37	47.48	1.89	0.040

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.51	0.96	1.11	1.07
2	9.17	0.79	1.09	1.05
3	9.46	0.96	1.11	1.07
4	9.47	0.69	1.08	1.04
5	9.49	0.84	1.10	1.06
6	9.47	0.81	1.09	1.05
7	9.60	0.61	1.07	1.03
8	9.19	0.61	1.07	1.03
9	9.73	0.63	1.07	1.03
10	9.39	0.85	1.10	1.06
		Average:	**1.09**	**1.05**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.56**	**1.56**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.42	130.28	68.42

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	121.1
2	133.4
3	134.5
4	116.2
5	107.3
6	137.7
7	143.8
8	127.1
9	125.4
10	125.5
11	136.2
12	114.5
13	149.1
14	124.8
15	147.3
16	170.8
17	110.2
18	143.9
19	157.2
20	166.6
21	145.9
22	147.9
23	122.4
24	138.5
25	185.3
Average:	**137.3**
St. Dev:	**19.2**
St. Dev (%):	**14.0**

Material Variables Evaluation

Sample:	EM-SD-05
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Sawdust - 10% - #8
Target Moisture:	2.0%
Date:	6/4/2013
Time	1:00:00 PM

Comments:	1365.53 g coal
	151.58 g biomass
	12.90 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0225
Briquettes	48.47	47.76	0.71	0.015

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.62	1.54	1.19	1.17
2	9.55	1.50	1.19	1.17
3	9.86	1.63	1.20	1.18
4	9.80	1.61	1.20	1.18
5	9.62	1.56	1.19	1.18
6	9.51	1.32	1.16	1.14
7	9.55	1.38	1.17	1.15
8	9.71	1.27	1.15	1.13
9	9.59	0.95	1.11	1.09
10	9.68	1.35	1.16	1.15
		Average:	**1.17**	**1.15**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.35**	**2.35**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	192.28	177.76	92.45

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	198.7
2	237.3
3	205.3
4	213.7
5	208.8
6	217.5
7	207.0
8	183.6
9	198.2
10	221.4
11	198.2
12	221.4
13	279.8
14	195.8
15	239.9
16	275.9
17	231.6
18	234.2
19	221.6
20	221.8
21	206.3
22	228.4
23	260.9
24	217.2
25	239.3
Average:	**222.6**
St. Dev:	**23.9**
St. Dev (%):	**10.8**

Material Variables Evaluation

Sample:	EM-SD-06
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Sawdust - 10% - #8
Target Moisture:	8.0%
Date:	6/6/2013
Time	2:00:00 PM

Comments:	1365.53 g coal
	165.75 g biomass
	88.72 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0805
Briquettes	38.92	36.59	2.33	0.064

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.63	1.23	1.15	1.08
2	9.68	1.39	1.17	1.10
3	9.50	1.29	1.16	1.09
4	9.10	1.11	1.14	1.07
5	9.64	1.56	1.19	1.12
6	9.64	1.06	1.12	1.06
7	9.44	1.33	1.16	1.09
8	9.24	1.26	1.16	1.09
9	9.60	1.09	1.13	1.06
10				
		Average:	**1.15**	**1.08**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.87**	**1.87**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.79	37.82	20.03

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	16.2
2	12.4
3	16.4
4	21.6
5	28.6
6	21.9
7	15.5
8	26.1
9	21.6
10	25.4
11	24.3
12	20.6
13	26.3
14	31.5
15	26.0
16	29.0
17	29.4
18	37.2
19	24.9
20	35.6
21	21.1
22	17.5
23	24.3
24	
25	
Average:	**24.1**
St. Dev:	**6.3**
St. Dev (%):	**26.0**

Material Variables Evaluation

Sample:	EM-SD-13
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Sawdust - 20% - #8
Target Moisture:	5.0%
Date:	6/6/2013
Time	3:00:00 PM

Comments:	1213.80 g coal
	331.50 g biomass
	29.70 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0550
Briquettes	47.96	46.06	1.90	0.041

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.33	0.93	1.11	1.07
2	9.67	0.97	1.11	1.07
3	9.68	0.78	1.09	1.04
4	9.53	0.39	1.04	1.00
5	9.79	0.67	1.07	1.03
6	9.57	0.74	1.08	1.04
7	9.47	0.43	1.05	1.01
8	9.69	0.75	1.08	1.04
9	9.49	0.49	1.05	1.01
10	9.48	0.35	1.04	1.00
		Average:	1.07	1.03
		St. Dev:	0.03	0.03
		St. Dev (%):	2.50	2.50

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.54	124.97	65.93

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	117.8
2	109.5
3	149.3
4	139.0
5	161.5
6	125.7
7	120.7
8	130.3
9	110.0
10	126.1
11	100.7
12	113.2
13	123.7
14	114.3
15	95.4
16	103.0
17	126.7
18	135.0
19	141.5
20	134.0
21	124.9
22	111.9
23	153.3
24	156.2
25	126.0
Average:	126.0
St. Dev:	17.4
St. Dev (%):	13.8

Material Variables Evaluation

Sample:	EM-SD-07
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Sawdust - 30% - #8
Target Moisture:	2.0%
Date:	6/6/2013
Time	4:00:00 PM

Comments:	1062.08 g coal
	454.73 g biomass
	13.20 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0220
Briquettes	46.87	46.10	0.77	0.017

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.79	1.39	1.17	1.15
2	9.65	1.19	1.14	1.12
3	9.35	0.98	1.12	1.10
4	9.22	0.84	1.10	1.08
5	9.45	0.76	1.09	1.07
6	9.59	1.13	1.13	1.11
7	9.16	0.83	1.10	1.08
8	9.46	1.00	1.12	1.10
9	9.28	0.71	1.08	1.07
10	9.33	0.94	1.11	1.09
		Average:	**1.12**	**1.10**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.28**	**2.28**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.86	171.51	91.30

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	309.6
2	360.1
3	364.9
4	382.7
5	423.1
6	429.0
7	364.2
8	375.2
9	382.9
10	379.9
11	280.5
12	282.6
13	371.2
14	303.2
15	559.5
16	421.4
17	326.5
18	365.6
19	395.2
20	349.0
21	358.6
22	461.1
23	386.9
24	411.1
25	350.0
Average:	**375.8**
St. Dev:	**58.5**
St. Dev (%):	**15.6**

Material Variables Evaluation

Sample:	EM-SD-01
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Sawdust - 20% - #16
Target Moisture:	2.0%
Date:	6/6/2013
Time	5:00:00 PM

Comments:	1213.80 g coal
	304.95 g biomass
	11.25 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0215
Briquettes	48.03	47.28	0.75	0.016

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.67	1.20	1.14	1.12
2	9.50	1.30	1.16	1.14
3	9.57	1.30	1.16	1.14
4	9.50	1.24	1.15	1.13
5	9.47	1.22	1.15	1.13
6	9.56	1.34	1.16	1.14
7	9.70	1.21	1.14	1.12
8	9.64	1.46	1.18	1.16
9	9.56	1.33	1.16	1.14
10	9.39	1.29	1.16	1.14
		Average:	**1.16**	**1.14**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.95**	**0.95**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.98	176.95	92.65

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	293.9
2	325.8
3	293.1
4	277.2
5	253.4
6	329.4
7	298.0
8	314.5
9	297.6
10	309.6
11	322.2
12	279.4
13	285.4
14	330.0
15	316.6
16	348.9
17	265.0
18	359.3
19	313.8
20	318.4
21	323.3
22	352.1
23	273.3
24	274.8
25	270.9
Average:	**305.0**
St. Dev:	**28.4**
St. Dev (%):	**9.3**

Material Variables Evaluation

Sample:	EM-SD-04
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Sawdust - 20% - #4
Target Moisture:	8.0%
Date:	6/7/2013
Time	12:00:00 PM

Comments:
1213.80 g coal
332.10 g biomass
74.10 g water
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 1500 ft-lb
Many briquettes initially float in water

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0885
Briquettes	49.34	46.35	2.99	0.065

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.34	1.26	1.16	1.09
2	9.57	1.00	1.12	1.05
3	9.39	1.08	1.13	1.06
4	9.43	0.86	1.10	1.03
5	9.54	0.53	1.06	0.99
6	9.68	1.01	1.12	1.05
7	9.31	1.29	1.16	1.09
8	8.75	0.65	1.08	1.01
9	9.24	0.99	1.12	1.05
10	9.33	0.29	1.03	0.97
		Average:	**1.11**	**1.04**
		St. Dev:	**0.04**	**0.04**
		St. Dev (%):	**3.67**	**3.67**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	182.33	30.03	16.47

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	14.0
2	19.7
3	18.2
4	22.7
5	18.2
6	13.3
7	13.4
8	11.7
9	23.9
10	22.4
11	18.8
12	14.7
13	30.1
14	16.4
15	21.5
16	21.1
17	18.9
18	17.2
19	17.6
20	23.6
21	31.8
22	17.5
23	20.8
24	17.3
25	19.8
Average:	**19.4**
St. Dev:	**4.8**
St. Dev (%):	**24.6**

Material Variables Evaluation

Sample:	EM-SD-10
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Sawdust - 10% - #4
Target Moisture:	5.0%
Date:	6/7/2013
Time	1:00:00 PM

Comments:	1365.53 g coal
	166.05 g biomass
	43.43 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0575
Briquettes	48.68	46.87	1.81	0.039

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.40	1.35	1.17	1.12
2	9.68	1.30	1.16	1.11
3	9.50	1.05	1.12	1.08
4	9.62	1.12	1.13	1.09
5	9.64	1.20	1.14	1.10
6	9.66	1.20	1.14	1.10
7	9.59	1.09	1.13	1.09
8	9.73	0.92	1.10	1.06
9	9.36	0.87	1.10	1.06
10	9.59	0.92	1.11	1.06
		Average:	**1.13**	**1.09**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.95**	**1.95**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.42	84.94	44.37

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	46.3
2	66.7
3	62.9
4	66.7
5	61.6
6	56.8
7	50.9
8	55.5
9	33.7
10	40.9
11	59.5
12	62.0
13	61.7
14	70.1
15	55.5
16	58.7
17	78.2
18	69.2
19	67.7
20	51.9
21	62.0
22	53.1
23	64.8
24	73.4
25	56.1
Average:	**59.4**
St. Dev:	**10.0**
St. Dev (%):	**16.8**

Material Variables Evaluation

Sample:	EM-SD-08
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Sawdust - 30% - #8
Target Moisture:	8.0%
Date:	6/7/2013
Time	2:00:00 PM

Comments:	1062.08 g coal
	497.25 g biomass
	60.68 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	Many briquettes initially float in water

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0880
Briquettes	47.29	44.44	2.85	0.064

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.22	0.89	1.11	1.04
2	9.02	0.12	1.01	0.95
3	8.91	0.11	1.01	0.95
4	8.90	0.69	1.08	1.02
5	9.53	0.13	1.01	0.95
6	9.21	0.23	1.03	0.96
7	9.01	0.12	1.01	0.95
8	9.15	0.18	1.02	0.96
9	9.54	0.37	1.04	0.98
10	9.30	0.12	1.01	0.95
		Average:	**1.03**	**0.97**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**3.26**	**3.26**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	184.30	56.55	30.68

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	48.9
2	37.5
3	46.1
4	28.9
5	33.6
6	30.5
7	40.1
8	34.9
9	33.1
10	23.6
11	58.0
12	46.2
13	36.4
14	41.4
15	35.4
16	40.0
17	30.4
18	46.2
19	36.2
20	31.8
21	39.4
22	42.5
23	46.5
24	44.1
25	31.5
Average:	**38.5**
St. Dev:	**7.7**
St. Dev (%):	**19.9**

Material Variables Evaluation

Sample:	EM-SD-02
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Sawdust - 20% - #16
Target Moisture:	8.0%
Date:	6/7/2013
Time	4:00:00 PM

Comments:	1214.40 g coal
	331.80 g biomass
	74.40 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	Many briquettes initially float in water

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0835
Briquettes	45.63	42.82	2.81	0.066

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.52	0.57	1.07	1.01
2	8.71	0.31	1.04	0.97
3	8.77	0.41	1.05	0.98
4	8.79	0.24	1.03	0.96
5	8.69	0.10	1.01	0.95
6	9.08	0.42	1.05	0.98
7	8.81	0.11	1.01	0.95
8	8.76	0.18	1.02	0.96
9	8.88	0.13	1.01	0.95
10	8.61	0.15	1.02	0.96
		Average:	**1.03**	**0.97**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.93**	**1.93**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	177.70	28.39	15.98

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	10.1
2	14.4
3	12.8
4	23.2
5	13.1
6	11.9
7	13.1
8	11.7
9	10.2
10	14.6
11	20.3
12	10.5
13	13.4
14	22.6
15	16.1
16	12.1
17	21.7
18	13.0
19	21.0
20	20.0
21	17.6
22	11.4
23	16.7
24	11.6
25	11.6
Average:	**15.0**
St. Dev:	**4.2**
St. Dev (%):	**28.0**

Material Variables Evaluation

Sample:	EM-SD-03
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Sawdust - 20% - #4
Target Moisture:	2.0%
Date:	6/7/2013
Time	3:00:00 PM

Comments:
1213.80 g coal
304.20 g biomass
12.00 g water
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0210
Briquettes	50.31	49.61	0.70	0.014

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.44	1.29	1.16	1.14
2	9.35	1.23	1.15	1.14
3	10.05	1.56	1.18	1.17
4	9.33	0.91	1.11	1.09
5	9.91	1.41	1.17	1.15
6	9.87	1.52	1.18	1.17
7	9.21	1.23	1.15	1.14
8	9.57	1.22	1.15	1.13
9	9.82	1.34	1.16	1.14
10	9.68	1.02	1.12	1.10
		Average:	**1.15**	**1.14**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.11**	**2.11**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	192.63	177.24	92.01

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	366.8
2	245.5
3	295.4
4	292.4
5	357.0
6	329.8
7	254.7
8	249.1
9	229.5
10	226.1
11	264.7
12	279.9
13	286.5
14	295.9
15	265.7
16	257.2
17	312.4
18	325.5
19	258.1
20	303.9
21	299.7
22	295.8
23	256.5
24	274.2
25	358.1
Average:	**287.2**
St. Dev:	**38.7**
St. Dev (%):	**13.5**

Material Variables Evaluation

Sample:	EM-SD-12
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Sawdust - 30% - #4
Target Moisture:	5.0%
Date:	6/7/2013
Time	5:00:00 PM

Comments:	1062.08 g coal
	498.15 g biomass
	14.78 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0570
Briquettes	47.39	45.50	1.89	0.042

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.50	0.85	1.10	1.05
2	9.44	0.74	1.09	1.04
3	9.22	0.78	1.09	1.05
4	9.77	0.87	1.10	1.05
5	9.32	0.88	1.10	1.06
6	9.15	0.61	1.07	1.03
7	9.30	0.48	1.05	1.01
8	9.31	0.73	1.09	1.04
9	9.40	0.76	1.09	1.04
10	9.31	0.76	1.09	1.05
		Average:	**1.09**	**1.04**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.33**	**1.33**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.52	148.57	78.81

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	254.4
2	236.0
3	225.2
4	210.0
5	309.5
6	270.7
7	247.5
8	241.1
9	214.3
10	230.1
11	252.3
12	238.4
13	232.3
14	257.0
15	309.1
16	260.1
17	251.5
18	283.0
19	242.7
20	267.3
21	258.9
22	229.8
23	248.1
24	251.8
25	247.5
Average:	**250.7**
St. Dev:	**24.3**
St. Dev (%):	**9.7**

Material Variables Evaluation

Sample:	EM-SD-15
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Sawdust - 20% - #8
Target Moisture:	5.0%
Date:	6/7/2013
Time	6:00:00 PM

Comments:	1213.80 g coal
	331.50 g biomass
	29.70 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0560
Briquettes	49.28	47.43	1.85	0.039

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.43	0.86	1.10	1.06
2	9.70	0.79	1.09	1.05
3	9.53	0.38	1.04	1.00
4	9.84	0.68	1.07	1.03
5	9.37	0.58	1.07	1.03
6	9.43	0.46	1.05	1.01
7	9.46	0.73	1.08	1.04
8	9.71	0.54	1.06	1.02
9	9.51	0.80	1.09	1.05
10	9.59	0.41	1.04	1.01
		Average:	**1.07**	**1.03**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.94**	**1.94**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.10	129.94	68.00

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	141.1
2	106.3
3	161.6
4	138.2
5	123.8
6	130.0
7	99.7
8	161.8
9	135.5
10	121.7
11	143.6
12	128.0
13	169.5
14	130.4
15	134.1
16	141.0
17	137.8
18	123.0
19	110.4
20	141.4
21	135.2
22	133.6
23	128.9
24	138.2
25	142.7
Average:	**134.3**
St. Dev:	**16.0**
St. Dev (%):	**11.9**

Material Variables Evaluation

Sample:	MR-CS-12
Client:	DOE
Coal:	McClure River - 70% - 1mm
Biomass:	Corn Stover - 30% - #4
Target Moisture:	5.0%
Date:	6/27/2013
Time	10:00:00 AM

Comments:	1059.77 g coal
	509.40 g biomass
	5.84 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	Difficulty feeding and maintaining torque

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0675
Briquettes	45.40	43.27	2.13	0.049

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.93	1.25	1.14	1.09
2	9.46	1.16	1.14	1.09
3	10.00	1.31	1.15	1.10
4	9.64	1.12	1.13	1.08
5	8.85	0.65	1.08	1.03
6	9.81	1.09	1.13	1.07
7	9.87	1.21	1.14	1.09
8	9.16	0.84	1.10	1.05
9	9.55	1.03	1.12	1.07
10	9.14	0.91	1.11	1.06
		Average:	**1.12**	**1.07**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.96**	**1.96**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.45	158.23	83.96

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	527.9
2	559.7
3	336.0
4	467.8
5	416.2
6	393.7
7	503.5
8	542.3
9	542.0
10	327.8
11	365.4
12	444.5
13	547.9
14	489.7
15	543.9
16	534.2
17	550.7
18	381.7
19	365.3
20	546.4
21	487.5
22	544.1
23	421.1
24	545.4
25	497.3
Average:	**475.3**
St. Dev:	**77.1**
St. Dev (%):	**16.2**

Material Variables Evaluation

Sample:	MR-WS-12
Client:	DOE
Coal:	McClure River - 70% - 1mm
Biomass:	Wheat Straw - 30% - #4
Target Moisture:	5.0%
Date:	6/27/2013
Time	11:00:00 AM

Comments:	1059.77 g coal
	505.13 g biomass
	10.11 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	Difficulty feeding and maintaining torque

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0600
Briquettes	43.43	41.77	1.66	0.040

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.61	1.23	1.15	1.10
2	9.64	1.01	1.12	1.07
3	9.59	1.14	1.13	1.09
4	9.26	1.03	1.13	1.08
5	8.83	0.47	1.06	1.02
6	8.71	0.25	1.03	0.99
7	9.80	1.22	1.14	1.10
8	9.50	0.90	1.10	1.06
9	10.02	1.18	1.13	1.09
10				
		Average:	**1.11**	**1.07**
		St. Dev:	**0.04**	**0.04**
		St. Dev (%):	**3.66**	**3.66**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.24	156.16	82.96

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	300.9
2	281.0
3	551.6
4	547.4
5	370.3
6	543.6
7	543.4
8	558.1
9	214.0
10	532.0
11	436.0
12	543.7
13	447.1
14	546.0
15	501.9
16	562.8
17	295.5
18	525.1
19	409.4
20	286.8
21	434.8
22	382.7
23	420.8
24	348.6
25	
Average:	**441.0**
St. Dev:	**109.1**
St. Dev (%):	**24.7**

Material Variables Evaluation

Sample:	MR-SG-01
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Switchgrass - 20% - #16
Target Moisture:	2.0%
Date:	6/27/2013
Time	12:00:00 PM

Comments:	1211.16 g coal
	304.50 g biomass
	14.34 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0215
Briquettes	47.57	46.84	0.73	0.016

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.83	1.17	1.14	1.12
2	9.15	1.02	1.13	1.11
3	9.69	1.27	1.15	1.13
4	9.42	0.99	1.12	1.10
5	9.79	1.11	1.13	1.11
6	9.74	1.14	1.13	1.12
7	9.34	0.93	1.11	1.09
8	9.59	1.11	1.13	1.11
9	9.73	1.28	1.15	1.13
10	9.30	1.05	1.13	1.11
		Average:	**1.13**	**1.11**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.14**	**1.14**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.32	168.14	88.35

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	255.1
2	296.6
3	309.9
4	296.6
5	227.0
6	252.4
7	288.5
8	224.3
9	236.1
10	283.1
11	256.6
12	271.0
13	277.8
14	325.2
15	292.3
16	280.3
17	297.4
18	227.7
19	280.1
20	299.5
21	293.8
22	341.2
23	242.4
24	281.5
25	280.9
Average:	**276.7**
St. Dev:	**30.3**
St. Dev (%):	**11.0**

Material Variables Evaluation

Sample:	MR-SD-01
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Sawdust - 20% - #16
Target Moisture:	2.0%
Date:	6/27/2013
Time	1:00:00 PM

Comments:	1211.16 g coal
	304.20 g biomass
	14.64 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0225
Briquettes	47.58	46.88	0.70	0.015

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.73	1.49	1.18	1.16
2	9.70	1.34	1.16	1.14
3	9.47	1.26	1.15	1.14
4	9.62	1.35	1.16	1.15
5	9.68	1.36	1.16	1.15
6	9.49	1.22	1.15	1.13
7	9.43	1.21	1.15	1.13
8	9.58	1.35	1.16	1.15
9	9.61	1.30	1.16	1.14
10	9.58	1.35	1.16	1.15
		Average:	**1.16**	**1.14**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.84**	**0.84**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.25	175.80	92.40

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	306.4
2	297.4
3	319.9
4	288.9
5	331.9
6	275.6
7	302.7
8	242.6
9	220.3
10	269.1
11	211.7
12	275.3
13	300.7
14	290.6
15	269.7
16	269.1
17	218.1
18	236.5
19	204.5
20	222.7
21	305.3
22	240.1
23	300.7
24	232.9
25	278.4
Average:	**268.4**
St. Dev:	**36.9**
St. Dev (%):	**13.7**

Material Variables Evaluation

Sample:	MR-MC-01
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Miscanthus - 20% - #16
Target Moisture:	2.0%
Date:	6/28/2013
Time	12:00:00 PM

Comments:	1211.16 g coal
	304.65 g biomass
	14.19 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0240
Briquettes	47.39	46.69	0.70	0.015

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.36	1.00	1.12	1.10
2	9.02	1.06	1.13	1.12
3	9.22	0.88	1.11	1.09
4	9.08	0.89	1.11	1.09
5	9.77	1.24	1.15	1.13
6	9.30	1.08	1.13	1.11
7	9.57	1.16	1.14	1.12
8	9.43	1.09	1.13	1.11
9	9.74	1.19	1.14	1.12
10	9.66	1.31	1.16	1.14
		Average:	**1.13**	**1.11**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.41**	**1.41**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.27	169.76	89.69

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	414.8
2	282.3
3	351.0
4	301.7
5	288.8
6	299.3
7	274.0
8	323.8
9	268.9
10	308.0
11	281.6
12	240.4
13	293.3
14	227.4
15	347.6
16	351.8
17	323.0
18	310.4
19	276.9
20	256.7
21	256.2
22	400.6
23	281.7
24	285.5
25	322.8
Average:	**302.7**
St. Dev:	**45.0**
St. Dev (%):	**14.9**

Material Variables Evaluation

Sample:	TC-CS-12
Client:	DOE
Coal:	Toms Creek - 70% - 1mm
Biomass:	Corn Stover - 30% - #4
Target Moisture:	5.0%
Date:	6/27/2013
Time	3:00:00 PM

Comments:	1491.32 g coal
	713.16 g biomass
	0.53 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	Difficulty feeding and maintaining torque

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0600
Briquettes	47.07	45.02	2.05	0.046

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.69	1.21	1.14	1.09
2	9.81	1.39	1.17	1.11
3	9.56	1.21	1.14	1.10
4	9.32	1.02	1.12	1.07
5	9.57	1.06	1.12	1.08
6	9.89	1.36	1.16	1.11
7	9.51	1.43	1.18	1.13
8	9.29	1.12	1.14	1.09
9	9.72	1.36	1.16	1.11
10	9.92	1.45	1.17	1.12
		Average:	**1.15**	**1.10**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.66**	**1.66**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.75	141.98	74.04

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	259.6
2	469.0
3	384.8
4	548.6
5	551.3
6	459.9
7	335.2
8	460.8
9	559.9
10	267.3
11	401.7
12	470.8
13	554.9
14	531.1
15	418.0
16	452.9
17	436.6
18	564.6
19	540.7
20	338.1
21	365.2
22	515.9
23	502.0
24	381.4
25	403.8
Average:	**447.0**
St. Dev:	**90.4**
St. Dev (%):	**20.2**

Material Variables Evaluation

Sample:	TC-WS-12
Client:	DOE
Coal:	Toms Creek - 70% - 1mm
Biomass:	Wheat Straw - 30% - #4
Target Moisture:	5.0%
Date:	6/27/2013
Time	4:00:00 PM

Comments:	1491.32 g coal
	707.18 g biomass
	6.51 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	Difficulty feeding and maintaining torque

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0460
Briquettes	45.09	43.16	1.93	0.045

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.19	1.26	1.16	1.11
2	9.69	1.30	1.15	1.11
3	9.58	1.16	1.14	1.09
4	9.56	1.04	1.12	1.07
5	10.01	1.51	1.18	1.13
6	9.42	1.06	1.13	1.08
7	8.67	0.48	1.06	1.01
8	9.20	1.06	1.13	1.08
9	9.63	1.08	1.13	1.08
10	9.85	1.26	1.15	1.10
		Average:	**1.13**	**1.09**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.80**	**2.80**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.28	130.02	68.33

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	327.7
2	280.0
3	216.4
4	346.5
5	332.5
6	274.6
7	320.1
8	239.5
9	354.2
10	295.4
11	565.0
12	320.8
13	280.4
14	549.0
15	281.8
16	543.0
17	245.0
18	229.5
19	443.6
20	339.7
21	500.9
22	545.6
23	457.0
24	504.5
25	564.0
Average:	**374.3**
St. Dev:	**119.1**
St. Dev (%):	**31.8**

Material Variables Evaluation

Sample:	TC-SD-01
Client:	DOE
Coal:	Toms Creek - 80% - 1mm
Biomass:	Sawdust - 20% - #16
Target Moisture:	2.0%
Date:	6/28/2013
Time	9:00:00 AM

Comments:	1217.40 g coal
	304.20 g biomass
	8.40 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0205
Briquettes	48.34	47.66	0.68	0.014

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.59	1.38	1.17	1.15
2	10.07	1.59	1.19	1.17
3	9.69	1.36	1.16	1.15
4	9.26	1.15	1.14	1.13
5	10.36	1.66	1.19	1.17
6	9.62	1.34	1.16	1.15
7	9.77	1.39	1.17	1.15
8	9.41	1.13	1.14	1.12
9	9.93	1.53	1.18	1.17
10	9.92	1.46	1.17	1.16
		Average:	**1.17**	**1.15**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.53**	**1.53**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	193.08	170.17	88.13

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	201.9
2	205.4
3	215.0
4	197.5
5	206.6
6	175.7
7	199.8
8	200.4
9	209.1
10	239.1
11	227.9
12	186.4
13	231.2
14	203.4
15	205.9
16	185.2
17	251.8
18	204.0
19	201.6
20	247.7
21	240.2
22	160.9
23	154.2
24	199.4
25	204.4
Average:	**206.2**
St. Dev:	**24.1**
St. Dev (%):	**11.7**

Material Variables Evaluation

Sample:	TC-SG-01
Client:	DOE
Coal:	Toms Creek - 80% - 1mm
Biomass:	Switchgrass - 20% - #16
Target Moisture:	2.0%
Date:	6/28/2013
Time	10:00:00 AM

Comments:	1217.40 g coal
	304.50 g biomass
	8.10 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0210
Briquettes	46.10	45.39	0.71	0.016

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.99	0.73	1.09	1.07
2	9.19	0.81	1.10	1.08
3	9.92	1.29	1.15	1.13
4	9.87	1.25	1.15	1.13
5	9.34	1.02	1.12	1.11
6	9.90	1.27	1.15	1.13
7	9.43	1.04	1.12	1.11
8	9.62	1.13	1.13	1.12
9	9.58	1.08	1.13	1.11
10	9.54	0.92	1.11	1.09
		Average:	**1.12**	**1.11**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.88**	**1.88**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	193.07	155.16	80.36

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	203.3
2	167.6
3	238.8
4	202.1
5	208.6
6	244.0
7	191.4
8	224.0
9	194.7
10	222.5
11	231.2
12	198.1
13	186.2
14	171.6
15	204.3
16	167.8
17	225.0
18	198.3
19	237.4
20	223.5
21	192.3
22	167.7
23	226.6
24	231.2
25	212.3
Average:	**206.8**
St. Dev:	**23.4**
St. Dev (%):	**11.3**

Material Variables Evaluation

Sample:	TC-MC-01
Client:	DOE
Coal:	Toms Creek - 80% - 1mm
Biomass:	Miscanthus - 20% - #16
Target Moisture:	2.0%
Date:	6/28/2013
Time	11:00:00 AM

Comments:	1217.40 g coal
	304.65 g biomass
	7.95 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0220
Briquettes	47.22	46.51	0.71	0.015

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.38	1.20	1.15	1.13
2	9.65	1.36	1.16	1.15
3	9.26	1.13	1.14	1.12
4	9.86	1.22	1.14	1.12
5	9.50	1.10	1.13	1.11
6	9.81	1.38	1.16	1.15
7	9.29	1.03	1.12	1.11
8	9.82	1.22	1.14	1.12
9	9.50	1.07	1.13	1.11
10	10.15	1.43	1.16	1.15
		Average:	**1.14**	**1.13**
		St. Dev:	**0.02**	**0.01**
		St. Dev (%):	**1.32**	**1.32**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.50	147.57	77.06

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	218.6
2	263.3
3	174.8
4	256.7
5	231.8
6	228.2
7	257.9
8	223.1
9	206.5
10	214.6
11	212.1
12	169.4
13	203.9
14	228.8
15	210.4
16	250.4
17	177.0
18	244.0
19	189.9
20	198.1
21	227.7
22	202.1
23	189.5
24	259.8
25	261.4
Average:	**220.0**
St. Dev:	**28.5**
St. Dev (%):	**13.0**

A.3.2 Evaluation of Additive Variables – Bituminous Coal

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-06
Client:	DOE
Coal:	Emerald - 67.5% - 1mm
Biomass:	Corn stover - 30% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Cure time:	0 days
Production date:	7/9/2013
Production time:	1:00:00 PM

Comments:	1030.22 g coal
	498.15 g biomass
	42.56 g binder
	4.07 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0525
Briquettes	47.34	45.33	2.01	0.044

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.96	1.60	1.19	1.14
2	9.97	1.60	1.19	1.14
3	9.19	1.21	1.15	1.10
4	8.98	1.09	1.14	1.09
5	9.92	1.48	1.18	1.13
6	9.34	1.33	1.17	1.12
7	9.51	1.37	1.17	1.12
8	9.54	1.33	1.16	1.11
9	9.35	1.36	1.17	1.12
10	9.29	1.21	1.15	1.10
		Average:	**1.17**	**1.12**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.47**	**1.47**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	193.43	177.61	91.82

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	380.3
2	410.6
3	458.9
4	393.4
5	442.0
6	389.9
7	367.8
8	547.8
9	496.9
10	443.0
11	355.1
12	432.5
13	470.8
14	368.3
15	427.8
16	397.5
17	430.2
18	394.3
19	427.7
20	400.7
21	532.4
22	525.8
23	419.5
24	471.0
25	370.0
Average:	**430.2**
St. Dev:	**53.4**
St. Dev (%):	**12.4**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-15
Client:	DOE
Coal:	Emerald - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Cure time:	1 day
Production date:	7/9/2013
Production time:	1:40:00 PM

Comments:	1182.84 g coal
	332.10 g biomass
	42.56 g binder
	17.49 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0470
Briquettes	48.31	46.87	1.44	0.031

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.72	1.63	1.20	1.17
2	9.76	1.51	1.18	1.15
3	9.71	1.60	1.20	1.16
4	9.45	1.34	1.17	1.13
5	9.73	1.59	1.20	1.16
6	9.75	1.59	1.19	1.16
7	9.85	1.63	1.20	1.16
8	9.44	1.56	1.20	1.16
9	9.87	1.59	1.19	1.16
10	9.95	1.61	1.19	1.16
		Average:	**1.19**	**1.16**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.89**	**0.89**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.10	184.63	95.12

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	282.0
2	372.1
3	405.1
4	336.9
5	347.3
6	317.0
7	320.2
8	339.1
9	373.7
10	352.6
11	308.2
12	325.6
13	368.8
14	382.8
15	308.1
16	295.2
17	333.7
18	425.2
19	369.9
20	367.9
21	329.2
22	293.1
23	383.0
24	359.4
25	360.0
Average:	**346.2**
St. Dev:	**35.8**
St. Dev (%):	**10.3**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-11
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 0.0%
Cure time:	7 days
Production date:	7/9/2013
Production time:	2:05:00 PM

Comments:	1221.00 g coal
	332.10 g biomass
	0.00 g binder
	21.90 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb
	*Torque was limited to low end of target value (i.e. 1200-1500 ft-lb)

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0475
Briquettes	47.53	46.19	1.34	0.029

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.50	1.39	1.17	1.14
2	9.51	1.37	1.17	1.14
3	9.19	1.32	1.17	1.13
4	9.21	1.22	1.15	1.12
5	9.77	1.49	1.18	1.15
6	9.53	1.41	1.17	1.14
7	9.56	1.48	1.18	1.15
8	9.30	1.12	1.14	1.10
9	9.11	1.17	1.15	1.12
10	9.54	1.36	1.17	1.13
		Average:	**1.16**	**1.13**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.26**	**1.26**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.41	169.22	88.41

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	289.7
2	286.0
3	295.6
4	288.5
5	261.3
6	307.4
7	266.8
8	246.9
9	308.3
10	232.2
11	298.9
12	290.6
13	300.6
14	298.8
15	284.2
16	247.8
17	279.6
18	300.0
19	261.5
20	227.5
21	273.7
22	277.2
23	315.7
24	241.9
25	258.4
Average:	**277.6**
St. Dev:	**24.8**
St. Dev (%):	**8.9**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-14
Client:	DOE
Coal:	Emerald - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Cure time:	1 day
Production date:	7/9/2013
Production time:	2:40:00 PM

Comments:	1182.84 g coal
	332.10 g biomass
	42.56 g binder
	17.49 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0495
Briquettes	48.32	46.96	1.36	0.029

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.87	1.74	1.21	1.18
2	9.54	1.44	1.18	1.14
3	9.59	1.42	1.17	1.14
4	10.03	1.73	1.21	1.17
5	9.80	1.68	1.21	1.17
6	9.61	1.53	1.19	1.16
7	9.63	1.58	1.20	1.16
8	9.86	1.56	1.19	1.15
9	9.61	1.37	1.17	1.13
10	9.59	1.39	1.17	1.14
		Average:	**1.19**	**1.16**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.44**	**1.44**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	193.69	182.51	94.23

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	308.8
2	305.5
3	332.4
4	279.4
5	310.9
6	347.5
7	325.0
8	329.4
9	355.7
10	370.5
11	368.0
12	387.1
13	326.7
14	326.4
15	378.7
16	335.5
17	272.0
18	353.0
19	320.2
20	298.1
21	362.6
22	350.8
23	399.5
24	345.1
25	311.6
Average:	**336.0**
St. Dev:	**32.1**
St. Dev (%):	**9.6**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-09
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 0.0%
Cure time:	0 days
Production date:	7/10/2013
Production time:	9:00:00 AM

Comments:	1221.00 g coal
	332.10 g biomass
	0.00 g binder
	21.90 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0530
Briquettes	48.30	46.25	2.05	0.044

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.50	1.37	1.17	1.12
2	9.49	1.37	1.17	1.12
3	9.54	1.48	1.18	1.13
4	9.66	1.48	1.18	1.13
5	9.67	1.33	1.16	1.11
6	9.71	1.27	1.15	1.10
7	9.32	1.33	1.17	1.12
8	9.77	1.43	1.17	1.12
9	9.57	1.35	1.16	1.11
10	9.28	1.18	1.15	1.10
		Average:	**1.17**	**1.12**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.02**	**1.02**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.46	165.04	84.87

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	230.4
2	226.1
3	222.2
4	190.5
5	258.8
6	231.2
7	255.7
8	265.5
9	229.8
10	254.8
11	231.6
12	230.6
13	212.0
14	235.4
15	240.9
16	224.9
17	207.7
18	253.9
19	255.3
20	220.5
21	246.6
22	214.6
23	262.1
24	283.6
25	201.0
Average:	**235.4**
St. Dev:	**22.2**
St. Dev (%):	**9.4**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-01
Client:	DOE
Coal:	Emerald - 90% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	Pregelatinized wheat starch - 0.0%
Cure time:	1 day
Production date:	7/9/2013
Production time:	3:40:00 PM

Comments:	1373.63 g coal
	166.05 g biomass
	0.00 g binder
	35.33 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0370
Briquettes	47.64	46.74	0.90	0.019

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.44	1.42	1.18	1.15
2	9.53	1.47	1.18	1.16
3	9.26	1.31	1.16	1.14
4	9.58	1.44	1.18	1.15
5	9.20	1.32	1.17	1.15
6	9.34	1.42	1.18	1.16
7	9.31	1.24	1.15	1.13
8	9.75	1.44	1.17	1.15
9	9.32	1.36	1.17	1.15
10	9.75	1.48	1.18	1.16
		Average:	**1.17**	**1.15**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.74**	**0.74**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.87	144.99	76.36

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	183.1
2	142.0
3	170.0
4	136.2
5	162.6
6	177.0
7	139.5
8	129.9
9	161.0
10	120.2
11	177.8
12	145.9
13	153.5
14	179.6
15	133.7
16	162.4
17	172.2
18	155.3
19	146.4
20	151.6
21	122.1
22	181.0
23	155.8
24	160.0
25	153.8
Average:	**154.9**
St. Dev:	**18.3**
St. Dev (%):	**11.8**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-12
Client:	DOE
Coal:	Emerald - 75% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 5.0%
Cure time:	7 days
Production date:	7/9/2013
Production time:	3:10:00 PM

Comments:	1144.69 g coal
	332.10 g biomass
	85.13 g binder
	13.09 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0485
Briquettes	46.92	45.45	1.47	0.032

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.73	1.74	1.22	1.18
2	9.51	1.53	1.19	1.15
3	9.74	1.62	1.20	1.16
4	9.47	1.49	1.19	1.15
5	9.58	1.66	1.21	1.17
6	9.89	1.62	1.20	1.16
7	9.97	1.64	1.20	1.16
8	9.94	1.76	1.22	1.18
9	9.74	1.71	1.21	1.17
10	9.54	1.63	1.21	1.17
		Average:	**1.20**	**1.17**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.89**	**0.89**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	193.96	186.48	96.14

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	369.3
2	339.3
3	368.2
4	401.5
5	379.1
6	404.7
7	372.2
8	364.3
9	370.1
10	329.9
11	417.0
12	383.0
13	418.0
14	444.0
15	380.1
16	368.7
17	362.7
18	364.8
19	526.3
20	334.8
21	405.0
22	308.5
23	459.4
24	436.7
25	332.2
Average:	**385.6**
St. Dev:	**47.3**
St. Dev (%):	**12.3**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-03
Client:	DOE
Coal:	Emerald - 85% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	Pregelatinized wheat starch - 5.0%
Cure time:	1 day
Production date:	7/9/2013
Production time:	4:40:00 PM

Comments:	1297.31 g coal
	166.05 g biomass
	85.13 g binder
	26.51 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0470
Briquettes	47.90	46.68	1.22	0.026

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.42	1.49	1.19	1.16
2	9.47	1.63	1.21	1.18
3	9.68	1.65	1.21	1.17
4	9.55	1.54	1.19	1.16
5	9.52	1.66	1.21	1.18
6	9.83	1.74	1.22	1.18
7	9.76	1.60	1.20	1.17
8	9.58	1.55	1.19	1.16
9	9.75	1.55	1.19	1.16
10	9.65	1.61	1.20	1.17
		Average:	**1.20**	**1.17**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.80**	**0.80**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.11	185.08	97.35

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	258.4
2	345.3
3	284.4
4	363.1
5	289.5
6	305.5
7	282.0
8	289.9
9	283.3
10	277.9
11	292.9
12	280.3
13	367.5
14	297.0
15	238.2
16	348.8
17	312.6
18	364.8
19	332.4
20	308.0
21	271.9
22	313.2
23	330.6
24	251.0
25	264.2
Average:	**302.1**
St. Dev:	**36.2**
St. Dev (%):	**12.0**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-05
Client:	DOE
Coal:	Emerald - 87.5% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Cure time:	0 days
Production date:	7/10/2013
Production time:	10:00:00 AM

Comments:	1335.47 g coal
	166.05 g biomass
	42.56 g binder
	30.92 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0440
Briquettes	48.81	47.14	1.67	0.035

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.61	1.62	1.20	1.16
2	9.87	1.68	1.21	1.16
3	9.78	1.56	1.19	1.15
4	9.82	1.48	1.18	1.14
5	9.84	1.70	1.21	1.17
6	9.56	1.60	1.20	1.16
7	9.26	1.45	1.19	1.15
8	9.01	1.55	1.21	1.17
9	9.49	1.51	1.19	1.15
10	9.71	1.62	1.20	1.16
		Average:	**1.20**	**1.16**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.88**	**0.88**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.10	184.43	95.02

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	199.7
2	170.9
3	195.3
4	161.3
5	174.3
6	172.6
7	188.4
8	173.5
9	187.8
10	158.9
11	166.7
12	180.0
13	165.9
14	192.4
15	214.0
16	172.4
17	191.8
18	145.3
19	180.5
20	211.0
21	186.6
22	187.8
23	189.2
24	171.6
25	184.0
Average:	**180.9**
St. Dev:	**15.9**
St. Dev (%):	**8.8**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-02
Client:	DOE
Coal:	Emerald - 70% - 1mm
Biomass:	Corn stover - 30% - 3/16"
Binder:	Pregelatinized wheat starch - 0.0%
Cure time:	1 day
Production date:	7/15/2013
Production time:	10:20:00 AM

Comments:
1424.50 g coal
664.20 g biomass
0.00 g binder
11.30 g water
Target moisture: 5.0%
Force: 100 kN
Roll speed: 450 rpm - 15 hz
Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0585
Briquettes	48.75	46.94	1.81	0.039

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.77	1.37	1.16	1.12
2	9.80	1.29	1.15	1.11
3	9.85	1.45	1.17	1.13
4	9.25	1.04	1.13	1.08
5	9.89	1.35	1.16	1.12
6	9.31	1.05	1.13	1.09
7	9.48	1.22	1.15	1.11
8	9.41	1.19	1.14	1.10
9	9.66	1.17	1.14	1.10
10	9.44	1.28	1.16	1.11
		Average:	**1.15**	**1.11**
		St. Dev:	**0.02**	**0.01**
		St. Dev (%):	**1.31**	**1.31**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.02	171.06	89.55

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	408.3
2	527.8
3	457.0
4	410.2
5	380.3
6	324.2
7	419.3
8	367.8
9	458.0
10	385.7
11	399.2
12	340.5
13	409.6
14	459.0
15	413.2
16	405.2
17	384.7
18	336.4
19	433.1
20	323.7
21	398.6
22	382.7
23	416.9
24	466.8
25	479.2
Average:	**407.5**
St. Dev:	**49.7**
St. Dev (%):	**12.2**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-08
Client:	DOE
Coal:	Emerald - 67.5% - 1mm
Biomass:	Corn stover - 30% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Cure time:	7 days
Production date:	7/9/2013
Production time:	4:15:00 PM

Comments:	1030.22 g coal
	498.15 g biomass
	42.56 g binder
	4.07 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0505
Briquettes	47.66	45.81	1.85	0.040

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.83	1.57	1.19	1.14
2	9.41	1.22	1.15	1.10
3	9.74	1.52	1.18	1.14
4	9.75	1.47	1.18	1.13
5	9.92	1.46	1.17	1.13
6	9.90	1.55	1.19	1.14
7	9.23	1.02	1.12	1.08
8	9.44	1.25	1.15	1.11
9	9.64	1.35	1.16	1.12
10	9.45	1.39	1.17	1.13
		Average:	**1.17**	**1.12**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.75**	**1.75**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.45	184.08	94.67

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	471.2
2	510.3
3	555.2
4	495.8
5	484.5
6	403.2
7	474.6
8	485.7
9	489.9
10	462.1
11	438.6
12	493.4
13	434.7
14	440.5
15	542.4
16	406.3
17	389.3
18	450.5
19	491.6
20	513.3
21	443.4
22	490.7
23	544.1
24	376.9
25	490.9
Average:	**471.2**
St. Dev:	**46.9**
St. Dev (%):	**10.0**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-13
Client:	DOE
Coal:	Emerald - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Cure time:	1 day
Production date:	7/15/2013
Production time:	10:45:00 AM

Comments:	1182.84 g coal
	332.10 g biomass
	42.56 g binder
	17.49 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0675
Briquettes	46.90	45.46	1.44	0.032

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.76	1.59	1.19	1.16
2	9.62	1.54	1.19	1.15
3	9.31	1.39	1.18	1.14
4	9.75	1.40	1.17	1.13
5	9.61	1.48	1.18	1.15
6	9.90	1.43	1.17	1.13
7	9.85	1.65	1.20	1.16
8	9.96	1.54	1.18	1.15
9	9.69	1.59	1.20	1.16
10	9.68	1.41	1.17	1.13
		Average:	**1.18**	**1.15**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.04**	**1.04**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	192.63	181.57	94.26

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	281.4
2	318.3
3	388.5
4	336.7
5	329.8
6	309.7
7	398.4
8	329.8
9	358.7
10	349.3
11	346.5
12	320.0
13	277.0
14	358.7
15	391.3
16	276.0
17	327.2
18	326.4
19	314.2
20	321.6
21	312.0
22	349.5
23	318.9
24	307.4
25	357.4
Average:	**332.2**
St. Dev:	**32.4**
St. Dev (%):	**9.8**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-10
Client:	DOE
Coal:	Emerald - 75% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 5.0%
Cure time:	0 days
Production date:	7/10/2013
Production time:	10:30:00 AM

Comments:	1144.69 g coal
	332.10 g biomass
	85.13 g binder
	13.09 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0575
Briquettes	48.67	46.78	1.89	0.040

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.66	1.59	1.20	1.15
2	9.71	1.60	1.20	1.15
3	9.86	1.62	1.20	1.15
4	9.76	1.60	1.20	1.15
5	9.48	1.50	1.19	1.14
6	9.81	1.52	1.18	1.14
7	9.57	1.59	1.20	1.15
8	9.68	1.67	1.21	1.16
9	9.63	1.57	1.19	1.15
10	9.40	1.59	1.20	1.16
		Average:	**1.20**	**1.15**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.59**	**0.59**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.22	184.35	94.92

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	358.2
2	362.6
3	406.0
4	384.9
5	343.1
6	332.5
7	311.4
8	287.6
9	360.4
10	314.1
11	353.6
12	489.5
13	386.1
14	414.6
15	326.0
16	551.2
17	329.5
18	431.7
19	406.7
20	397.7
21	391.9
22	319.0
23	426.1
24	393.3
25	354.7
Average:	**377.3**
St. Dev:	**58.5**
St. Dev (%):	**15.5**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-04
Client:	DOE
Coal:	Emerald - 65% - 1mm
Biomass:	Corn stover - 30% - 3/16"
Binder:	Pregelatinized wheat starch - 5.0%
Cure time:	1 day
Production date:	7/15/2013
Production time:	11:20:00 AM

Comments:	992.06 g coal
	498.15 g biomass
	85.13 g binder
	0.00 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0600
Briquettes	47.40	45.49	1.91	0.042

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.98	1.58	1.19	1.14
2	9.42	1.31	1.16	1.11
3	9.64	1.55	1.19	1.14
4	9.43	1.26	1.15	1.11
5	9.61	1.35	1.16	1.12
6	9.63	1.37	1.17	1.12
7	9.58	1.41	1.17	1.13
8	9.83	1.58	1.19	1.14
9	9.20	1.26	1.16	1.11
10	9.73	1.44	1.17	1.13
		Average:	**1.17**	**1.12**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.19**	**1.19**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.19	178.30	93.75

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	555.9
2	542.8
3	475.5
4	543.9
5	469.5
6	442.5
7	543.7
8	543.4
9	434.3
10	525.7
11	504.8
12	544.0
13	472.6
14	545.3
15	452.2
16	439.7
17	449.4
18	554.5
19	551.6
20	490.5
21	472.1
22	439.8
23	535.7
24	509.6
25	475.6
Average:	**500.6**
St. Dev:	**43.7**
St. Dev (%):	**8.7**

Binder/Cure Time Evaluation

Sample:	EM-CS-PGWS-07
Client:	DOE
Coal:	Emerald - 87.5% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Cure time:	7 days
Production date:	7/9/2013
Production time:	5:10:00 PM

Comments:	1335.47 g coal
	166.05 g biomass
	42.56 g binder
	30.92 g water
	Target moisture: 5.0%
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0420
Briquettes	47.13	46.15	0.98	0.021

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.76	1.67	1.21	1.18
2	9.10	1.52	1.20	1.18
3	9.54	1.56	1.20	1.17
4	9.40	1.58	1.20	1.18
5	9.49	1.46	1.18	1.16
6	9.38	1.39	1.17	1.15
7	9.26	1.52	1.20	1.17
8	9.76	1.61	1.20	1.17
9	9.41	1.61	1.21	1.18
10	9.59	1.67	1.21	1.19
		Average:	**1.20**	**1.17**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.95**	**0.95**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	191.08	181.88	95.19

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	209.4
2	253.6
3	251.1
4	251.6
5	223.5
6	230.1
7	232.1
8	227.6
9	194.9
10	262.6
11	186.7
12	240.5
13	186.6
14	231.2
15	256.2
16	238.0
17	258.8
18	203.1
19	242.0
20	268.2
21	267.9
22	212.1
23	240.9
24	247.9
25	193.1
Average:	**232.4**
St. Dev:	**25.4**
St. Dev (%):	**10.9**

A.3.3 Evaluation of Mixture Variables – Sub-Bituminous Coal

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-08
Client:	DOE
Coal:	Eagle Butte - 75% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 5.0%
Target moisture:	20.0%
Production date:	8/1/2013
Production time:	3:40:00 PM

Comments:	1145.81 g coal
	331.05 g biomass
	85.13 g binder
	238.01 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.2485
Briquettes	46.59	40.15	6.44	0.160

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.26	1.40	1.18	1.02
2	9.28	1.37	1.17	1.01
3	9.18	1.25	1.16	1.00
4	9.10	1.29	1.17	1.00
5	9.21	1.12	1.14	0.98
6	9.13	1.26	1.16	1.00
7	9.32	1.30	1.16	1.00
8	9.35	1.32	1.16	1.00
9	9.18	1.21	1.15	0.99
10	9.26	1.35	1.17	1.01
		Average:	**1.16**	**1.00**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.98**	**0.98**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	184.77	181.24	98.09

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	394.1
2	336.4
3	345.6
4	383.3
5	357.5
6	363.3
7	315.1
8	341.8
9	329.5
10	362.4
11	373.0
12	331.3
13	370.6
14	319.6
15	301.4
16	340.4
17	388.8
18	356.8
19	333.6
20	373.6
21	360.3
22	369.5
23	323.6
24	374.4
25	349.7
Average:	**351.8**
St. Dev:	**24.2**
St. Dev (%):	**6.9**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-12
Client:	DOE
Coal:	Eagle Butte - 65% - 1mm
Biomass:	Corn stover - 30% - 3/16"
Binder:	Pregelatinized wheat starch - 5.0%
Target moisture:	15.0%
Production date:	8/1/2013
Production time:	4:15:00 PM

Comments:	993.04 g coal
	496.58 g biomass
	85.13 g binder
	150.26 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1630
Briquettes	47.69	42.27	5.42	0.128

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.53	1.23	1.15	1.02
2	9.50	1.12	1.13	1.00
3	10.06	1.34	1.15	1.02
4	9.85	1.26	1.15	1.02
5	9.71	1.31	1.16	1.02
6	9.55	1.28	1.15	1.02
7	9.45	1.15	1.14	1.01
8	9.78	1.28	1.15	1.02
9	9.49	0.95	1.11	0.98
10	9.92	1.23	1.14	1.01
		Average:	**1.14**	**1.01**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.18**	**1.18**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.39	189.66	97.57

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	425.5
2	375.0
3	421.2
4	459.8
5	455.5
6	513.2
7	401.8
8	467.1
9	421.9
10	441.8
11	492.8
12	435.5
13	432.2
14	468.5
15	409.4
16	526.4
17	460.0
18	432.4
19	535.8
20	413.4
21	458.1
22	449.7
23	419.4
24	477.6
25	505.3
Average:	**452.0**
St. Dev:	**40.1**
St. Dev (%):	**8.9**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-11
Client:	DOE
Coal:	Eagle Butte - 85% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	Pregelatinized wheat starch - 5.0%
Target moisture:	15.0%
Production date:	8/1/2013
Production time:	4:40:00 PM

Comments:	1298.59 g coal
	165.53 g biomass
	85.13 g binder
	175.76 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1560
Briquettes	48.18	42.80	5.38	0.126

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.91	1.79	1.22	1.08
2	9.84	1.56	1.19	1.06
3	9.53	1.68	1.21	1.08
4	9.85	1.70	1.21	1.07
5	9.60	1.46	1.18	1.05
6	9.82	1.61	1.20	1.06
7	9.80	1.65	1.20	1.07
8	9.61	1.57	1.20	1.06
9	9.65	1.69	1.21	1.08
10	9.66	1.49	1.18	1.05
		Average:	**1.20**	**1.07**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.16**	**1.16**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	195.25	191.53	98.09

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	415.3
2	429.0
3	411.6
4	345.9
5	418.4
6	373.2
7	467.6
8	406.3
9	450.4
10	438.8
11	408.5
12	389.3
13	394.4
14	388.3
15	404.2
16	399.2
17	416.5
18	397.6
19	470.8
20	379.2
21	420.9
22	399.6
23	400.8
24	386.5
25	415.8
Average:	**409.1**
St. Dev:	**27.9**
St. Dev (%):	**6.8**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-14
Client:	DOE
Coal:	Eagle Butte - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Target moisture:	15.0%
Production date:	8/1/2013
Production time:	5:10:00 PM

Comments:	1184.01 g coal
	331.05 g biomass
	42.56 g binder
	167.38 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1550
Briquettes	48.35	42.84	5.51	0.129

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.64	1.43	1.17	1.04
2	9.60	1.39	1.17	1.04
3	9.67	1.47	1.18	1.04
4	10.04	1.45	1.17	1.04
5	9.49	1.27	1.15	1.02
6	9.65	1.40	1.17	1.04
7	9.96	1.59	1.19	1.05
8	9.51	1.30	1.16	1.03
9	9.56	1.18	1.14	1.01
10	9.75	1.29	1.15	1.02
		Average:	**1.17**	**1.03**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.23**	**1.23**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.63	181.32	93.16

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	348.2
2	342.9
3	351.2
4	332.2
5	398.5
6	320.8
7	351.2
8	314.3
9	354.5
10	367.8
11	320.7
12	377.0
13	371.7
14	304.5
15	366.4
16	386.1
17	318.0
18	349.2
19	312.1
20	386.1
21	393.1
22	333.5
23	329.4
24	357.2
25	372.3
Average:	**350.4**
St. Dev:	**27.2**
St. Dev (%):	**7.8**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-15
Client:	DOE
Coal:	Eagle Butte - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Target moisture:	15.0%
Production date:	8/5/2013
Production time:	3:15:00 PM

Comments:	1195.05 g coal
	331.05 g biomass
	42.56 g binder
	156.34 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1615
Briquettes	47.42	42.25	5.17	0.122

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.67	1.37	1.17	1.04
2	9.46	1.28	1.16	1.03
3	10.00	1.29	1.15	1.02
4	9.52	1.28	1.16	1.03
5	9.66	1.14	1.13	1.01
6	10.13	1.38	1.16	1.03
7	9.78	1.26	1.15	1.02
8	9.89	1.41	1.17	1.04
9	9.86	1.28	1.15	1.02
10	9.59	1.15	1.14	1.01
		Average:	**1.15**	**1.03**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.94**	**0.94**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.32	177.16	91.17

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	282.2
2	286.0
3	291.4
4	328.3
5	281.8
6	249.4
7	366.3
8	310.9
9	323.0
10	314.2
11	308.8
12	292.2
13	317.9
14	268.7
15	296.5
16	328.7
17	281.8
18	307.8
19	298.2
20	309.9
21	296.0
22	267.4
23	300.4
24	336.8
25	305.2
Average:	**302.0**
St. Dev:	**24.7**
St. Dev (%):	**8.2**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-06
Client:	DOE
Coal:	Eagle Butte - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 0.0%
Target moisture:	20.0%
Production date:	8/5/2013
Production time:	2:50:00 PM

Comments:	1233.60 g coal
	331.05 g biomass
	0.00 g binder
	235.35 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.2140
Briquettes	47.99	41.84	6.15	0.147

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.61	1.08	1.13	0.98
2	9.37	1.12	1.14	0.99
3	9.49	1.13	1.14	0.99
4	9.41	1.09	1.13	0.99
5	9.54	0.97	1.11	0.97
6	9.43	0.92	1.11	0.97
7	9.61	1.00	1.12	0.97
8	9.49	1.13	1.14	0.99
9	9.45	1.11	1.13	0.99
10	9.39	1.04	1.12	0.98
		Average:	**1.13**	**0.98**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.90**	**0.90**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.55	161.02	84.95

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	190.2
2	205.2
3	196.0
4	221.1
5	200.3
6	179.8
7	209.2
8	199.2
9	190.1
10	222.7
11	261.9
12	203.4
13	202.1
14	195.5
15	183.1
16	224.2
17	219.4
18	180.1
19	215.8
20	232.4
21	207.4
22	189.7
23	196.2
24	173.2
25	212.5
Average:	**204.4**
St. Dev:	**19.4**
St. Dev (%):	**9.5**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-10
Client:	DOE
Coal:	Eagle Butte - 70% - 1mm
Biomass:	Corn stover - 30% - 3/16"
Binder:	Pregelatinized wheat starch - 0.0%
Target moisture:	15.0%
Production date:	8/5/2013
Production time:	3:40:00 PM

Comments:	1079.40 g coal
	496.58 g biomass
	0.00 g binder
	149.03 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1525
Briquettes	49.32	43.95	5.37	0.122

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.98	1.12	1.13	1.00
2	9.38	1.08	1.13	1.01
3	9.36	0.79	1.09	0.97
4	9.43	0.72	1.08	0.96
5	9.65	1.09	1.13	1.00
6	9.84	1.01	1.11	0.99
7	9.29	0.82	1.10	0.98
8	9.15	0.68	1.08	0.96
9	9.69	1.05	1.12	1.00
10	9.94	1.13	1.13	1.01
		Average:	**1.11**	**0.99**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.80**	**1.80**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	195.64	170.90	87.35

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	250.6
2	297.6
3	282.3
4	276.8
5	317.6
6	376.6
7	274.4
8	334.9
9	318.3
10	236.1
11	319.3
12	296.3
13	257.8
14	286.5
15	334.4
16	237.3
17	337.7
18	329.4
19	232.6
20	318.1
21	367.4
22	294.8
23	338.7
24	348.2
25	325.1
Average:	**303.6**
St. Dev:	**40.4**
St. Dev (%):	**13.3**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-04
Client:	DOE
Coal:	Eagle Butte - 67.5% - 1mm
Biomass:	Corn stover - 30% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Target moisture:	20.0%
Production date:	8/5/2013
Production time:	4:10:00 PM

Comments:	1040.85 g coal
	496.58 g biomass
	42.56 g binder
	220.01 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.2420
Briquettes	46.71	40.75	5.96	0.146

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.24	1.10	1.14	0.99
2	9.30	0.95	1.11	0.97
3	9.37	1.00	1.12	0.98
4	9.27	0.93	1.11	0.97
5	9.44	1.16	1.14	0.99
6	8.99	0.97	1.12	0.98
7	9.26	1.05	1.13	0.98
8	9.42	0.92	1.11	0.97
9	9.34	1.09	1.13	0.99
10	9.13	0.93	1.11	0.97
		Average:	**1.12**	**0.98**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.98**	**0.98**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	185.75	179.76	96.78

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	396.5
2	338.0
3	355.2
4	325.7
5	329.0
6	340.4
7	344.2
8	306.5
9	333.2
10	386.9
11	338.5
12	329.9
13	339.4
14	335.3
15	365.8
16	313.6
17	266.8
18	324.6
19	377.8
20	381.5
21	315.0
22	375.6
23	317.3
24	335.3
25	341.8
Average:	**340.6**
St. Dev:	**28.7**
St. Dev (%):	**8.4**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-13
Client:	DOE
Coal:	Eagle Butte - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Target moisture:	15.0%
Production date:	8/5/2013
Production time:	4:35:00 PM

Comments:	1195.05 g coal
	331.05 g biomass
	42.56 g binder
	156.34 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1700
Briquettes	48.79	43.47	5.32	0.122

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.94	1.65	1.20	1.07
2	9.67	1.40	1.17	1.04
3	9.67	1.44	1.17	1.05
4	10.13	1.51	1.18	1.05
5	9.85	1.45	1.17	1.04
6	9.64	1.27	1.15	1.03
7	10.01	1.46	1.17	1.04
8	9.73	1.40	1.17	1.04
9	9.81	1.44	1.17	1.04
10	9.89	1.27	1.15	1.02
		Average:	**1.17**	**1.04**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.19**	**1.19**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	197.68	182.20	92.17

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	298.3
2	307.5
3	302.0
4	275.5
5	325.3
6	275.1
7	308.1
8	267.5
9	310.0
10	335.3
11	312.8
12	340.6
13	304.5
14	355.7
15	298.5
16	314.5
17	292.8
18	328.3
19	324.0
20	327.6
21	277.5
22	313.1
23	321.2
24	283.9
25	297.6
Average:	**307.9**
St. Dev:	**22.0**
St. Dev (%):	**7.1**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-05
Client:	DOE
Coal:	Eagle Butte - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 0.0%
Target moisture:	10.0%
Production date:	8/5/2013
Production time:	5:30:00 PM

Comments:	1242.00 g coal
	331.05 g biomass
	0.00 g binder
	76.95 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1010
Briquettes	49.36	45.06	4.30	0.095

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.16	1.17	1.13	1.03
2	9.84	1.05	1.12	1.02
3	9.84	1.14	1.13	1.03
4	9.68	1.02	1.12	1.02
5	9.60	0.88	1.10	1.01
6	9.57	0.76	1.09	0.99
7	10.02	1.07	1.12	1.02
8	9.90	1.18	1.14	1.04
9	9.96	1.14	1.13	1.03
10	10.00	1.15	1.13	1.03
		Average:	**1.12**	**1.02**
		St. Dev:	**0.02**	**0.01**
		St. Dev (%):	**1.38**	**1.38**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	197.49	134.62	68.17

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	211.7
2	189.0
3	191.8
4	250.2
5	145.3
6	163.3
7	225.2
8	190.3
9	163.8
10	164.8
11	251.8
12	231.0
13	185.3
14	204.9
15	200.3
16	208.5
17	222.1
18	202.0
19	195.6
20	169.3
21	159.1
22	188.6
23	232.5
24	211.0
25	202.5
Average:	**198.4**
St. Dev:	**28.0**
St. Dev (%):	**14.1**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-02
Client:	DOE
Coal:	Eagle Butte - 87.5% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Target moisture:	20.0%
Production date:	8/5/2013
Production time:	5:50:00 PM

Comments:	1386.00 g coal
	165.53 g biomass
	42.56 g binder
	205.91 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.2115
Briquettes	47.35	40.93	6.42	0.157

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.32	1.36	1.17	1.01
2	9.59	1.40	1.17	1.01
3	9.32	1.40	1.18	1.02
4	9.16	1.23	1.16	1.00
5	9.46	1.30	1.16	1.00
6	9.27	1.40	1.18	1.02
7	9.31	1.40	1.18	1.02
8	9.31	1.44	1.18	1.02
9	9.52	1.37	1.17	1.01
10	9.01	1.12	1.14	0.99
		Average:	**1.17**	**1.01**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.07**	**1.07**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	188.02	179.63	95.54

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	253.7
2	234.7
3	232.1
4	226.0
5	257.6
6	241.9
7	241.3
8	237.9
9	251.5
10	233.4
11	232.9
12	257.0
13	282.4
14	229.9
15	222.6
16	259.1
17	244.2
18	258.9
19	216.0
20	280.6
21	245.3
22	228.5
23	301.5
24	259.0
25	235.5
Average:	**246.5**
St. Dev:	**20.1**
St. Dev (%):	**8.2**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-01
Client:	DOE
Coal:	Eagle Butte - 87.5% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Target moisture:	10.0%
Production date:	8/7/2013
Production time:	4:45:00 PM

Comments:	1386.00 g coal
	165.53 g biomass
	42.56 g binder
	71.66 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1095
Briquettes	49.68	45.15	4.53	0.100

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.04	1.53	1.18	1.07
2	9.81	1.32	1.16	1.05
3	10.18	1.57	1.18	1.07
4	9.98	1.57	1.19	1.08
5	9.68	1.38	1.17	1.06
6	10.02	1.43	1.17	1.06
7	10.19	1.51	1.17	1.07
8	9.94	1.31	1.15	1.05
9	10.17	1.41	1.16	1.06
10	9.82	1.33	1.16	1.05
		Average:	**1.17**	**1.06**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.04**	**1.04**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	198.67	159.43	80.25

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	207.8
2	181.4
3	140.4
4	169.9
5	215.5
6	199.8
7	193.5
8	197.3
9	200.9
10	202.5
11	202.3
12	184.0
13	193.9
14	185.2
15	186.3
16	199.2
17	185.5
18	159.5
19	155.2
20	179.2
21	198.7
22	153.9
23	175.3
24	217.9
25	195.0
Average:	**187.2**
St. Dev:	**19.5**
St. Dev (%):	**10.4**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-09
Client:	DOE
Coal:	Eagle Butte - 90% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	Pregelatinized wheat starch - 0.0%
Target moisture:	15.0%
Production date:	8/7/2013
Production time:	5:05:00 PM

Comments:	1409.40 g coal
	165.53 g biomass
	0.00 g binder
	150.08 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1510
Briquettes	48.91	43.53	5.38	0.124

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.77	1.52	1.18	1.05
2	9.46	1.44	1.18	1.05
3	9.82	1.32	1.16	1.03
4	9.51	1.33	1.16	1.03
5	9.81	1.46	1.17	1.05
6	9.71	1.49	1.18	1.05
7	9.81	1.49	1.18	1.05
8	9.82	1.46	1.17	1.05
9	9.69	1.49	1.18	1.05
10	9.80	1.47	1.18	1.05
		Average:	**1.17**	**1.05**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.78**	**0.78**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	193.93	160.89	82.96

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	221.7
2	193.6
3	218.5
4	244.6
5	250.9
6	231.1
7	244.3
8	243.1
9	196.6
10	236.2
11	256.8
12	256.6
13	260.0
14	261.6
15	242.9
16	232.9
17	264.0
18	258.1
19	244.2
20	198.1
21	220.3
22	213.8
23	266.1
24	259.9
25	246.3
Average:	**238.5**
St. Dev:	**21.8**
St. Dev (%):	**9.1**

Material Variables and Binder Evaluation	
Sample:	EB-CS-PGWS-03
Client:	DOE
Coal:	Eagle Butte - 67.5% - 1mm
Biomass:	Corn stover - 30% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Target moisture:	10.0%
Production date:	8/7/2013
Production time:	5:30:00 PM

Comments:	1057.05 g coal
	496.58 g biomass
	42.56 g binder
	53.81 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0930
Briquettes	48.99	44.68	4.31	0.096

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.52	0.80	1.09	1.00
2	9.66	0.81	1.09	1.00
3	10.01	1.13	1.13	1.03
4	9.75	0.83	1.09	1.00
5	9.98	0.96	1.11	1.01
6	9.64	0.80	1.09	0.99
7	9.94	1.06	1.12	1.02
8	9.65	0.83	1.09	1.00
9	9.86	0.85	1.09	1.00
10	9.75	0.75	1.08	0.99
		Average:	**1.10**	**1.00**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.28**	**1.28**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	195.74	161.82	82.67

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	256.7
2	239.1
3	288.0
4	242.0
5	275.1
6	273.7
7	249.4
8	251.3
9	268.3
10	240.8
11	256.0
12	269.3
13	245.7
14	262.2
15	260.5
16	255.3
17	254.0
18	267.5
19	250.4
20	289.6
21	254.3
22	268.9
23	279.5
24	281.8
25	283.6
Average:	**262.5**
St. Dev:	**14.9**
St. Dev (%):	**5.7**

Material Variables and Binder Evaluation

Sample:	EB-CS-PGWS-07
Client:	DOE
Coal:	Eagle Butte - 75% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 5.0%
Target moisture:	10.0%
Production date:	8/7/2013
Production time:	5:50:00 PM

Comments:	1178.44 g coal
	331.05 g biomass
	85.13 g binder
	55.39 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1030
Briquettes	48.81	44.62	4.19	0.094

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.80	1.09	1.13	1.03
2	9.98	1.06	1.12	1.02
3	9.86	1.17	1.13	1.04
4	9.86	1.00	1.11	1.02
5	9.68	1.01	1.12	1.02
6	9.96	1.00	1.11	1.02
7	9.74	0.93	1.11	1.01
8	9.67	0.98	1.11	1.02
9	9.81	1.09	1.13	1.03
10	9.98	1.01	1.11	1.02
		Average:	**1.12**	**1.02**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.76**	**0.76**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	197.99	168.58	85.15

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	261.8
2	228.8
3	236.0
4	230.1
5	241.7
6	213.2
7	231.9
8	272.0
9	203.8
10	283.5
11	236.4
12	222.6
13	204.3
14	258.1
15	243.7
16	282.6
17	267.3
18	235.4
19	269.5
20	257.6
21	236.4
22	234.1
23	232.2
24	255.6
25	233.4
Average:	**242.9**
St. Dev:	**22.0**
St. Dev (%):	**9.1**

Material Variables Evaluation

Sample:	EB-CS-01
Client:	DOE
Coal:	Eagle Butte - 70% - 1mm
Biomass:	Corn Stover - 30% - #4
Target Moisture:	15.0%
Date:	8/14/2013
Time	1:50:00 PM

Comments:	1068.38 g coal
	509.40 g biomass
	147.23 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1515
Briquettes	46.98	41.42	5.56	0.134

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.37	0.79	1.09	0.96
2	9.65	1.02	1.12	0.99
3	9.69	1.22	1.14	1.01
4	9.18	0.49	1.06	0.93
5	8.50	0.37	1.05	0.92
6	9.72	1.01	1.12	0.98
7	9.65	0.97	1.11	0.98
8	10.21	1.15	1.13	0.99
9	9.21	0.67	1.08	0.95
10	9.38	0.74	1.09	0.96
		Average:	**1.10**	**0.97**
		St. Dev:	**0.03**	**0.03**
		St. Dev (%):	**2.87**	**2.87**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.51	152.82	80.22

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	295.0
2	363.3
3	455.7
4	362.4
5	326.8
6	288.4
7	268.3
8	394.2
9	403.1
10	287.2
11	280.5
12	375.8
13	342.2
14	349.1
15	378.9
16	298.2
17	341.4
18	366.1
19	337.2
20	408.0
21	412.7
22	515.7
23	381.8
24	312.1
25	537.1
Average:	**363.2**
St. Dev:	**68.2**
St. Dev (%):	**18.8**

Material Variables Evaluation

Sample:	EB-MC-01
Client:	DOE
Coal:	Eagle Butte - 70% - 1mm
Biomass:	Miscanthus - 30% - #4
Target Moisture:	15.0%
Date:	8/14/2013
Time	2:30:00 PM

Comments:	1102.50 g coal
	523.35 g biomass
	133.28 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1330
Briquettes	46.78	41.44	5.34	0.129

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.37	0.61	1.07	0.95
2	9.54	0.90	1.10	0.98
3	9.27	0.78	1.09	0.97
4	10.23	1.04	1.11	0.99
5	9.52	0.66	1.07	0.95
6	8.82	0.21	1.02	0.91
7	9.21	0.52	1.06	0.94
8	9.82	0.94	1.11	0.98
9	9.66	0.70	1.08	0.96
10	9.95	0.86	1.09	0.97
		Average:	**1.08**	**0.96**
		St. Dev:	**0.03**	**0.02**
		St. Dev (%):	**2.45**	**2.45**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.35	135.11	70.98

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	289.2
2	288.0
3	463.5
4	397.2
5	324.3
6	354.2
7	307.2
8	349.4
9	292.7
10	260.1
11	355.8
12	304.5
13	282.7
14	235.9
15	347.8
16	220.0
17	274.7
18	265.1
19	304.3
20	324.7
21	294.9
22	344.0
23	264.9
24	287.0
25	327.8
Average:	**310.4**
St. Dev:	**51.7**
St. Dev (%):	**16.7**

Material Variables Evaluation

Sample:	EB-SG-01
Client:	DOE
Coal:	Eagle Butte - 70% - 1mm
Biomass:	Switchgrass - 30% - #4
Target Moisture:	15.0%
Date:	8/14/2013
Time	3:30:00 PM

Comments:	1068.38 g coal
	527.40 g biomass
	129.23 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1390
Briquettes	47.25	41.74	5.51	0.132

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.85	0.90	1.10	0.97
2	9.49	0.71	1.08	0.95
3	9.22	0.31	1.03	0.91
4	10.02	0.55	1.06	0.93
5	9.73	0.71	1.08	0.95
6	9.86	0.75	1.08	0.96
7	10.04	0.62	1.07	0.94
8	9.65	0.29	1.03	0.91
9	9.91	0.73	1.08	0.95
10	9.62	0.69	1.08	0.95
		Average:	**1.07**	**0.94**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.05**	**2.05**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	192.46	123.11	63.97

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	208.4
2	231.9
3	249.8
4	252.5
5	285.3
6	256.8
7	269.4
8	219.9
9	236.4
10	183.9
11	201.9
12	251.2
13	234.0
14	252.7
15	184.9
16	260.2
17	215.0
18	246.6
19	233.5
20	226.0
21	285.0
22	207.5
23	287.6
24	250.4
25	238.4
Average:	**238.8**
St. Dev:	**28.6**
St. Dev (%):	**12.0**

Material Variables Evaluation

Sample:	EB-WS-01
Client:	DOE
Coal:	Eagle Butte - 70% - 1mm
Biomass:	Wheat Straw - 30% - #4
Target Moisture:	15.0%
Date:	8/14/2013
Time	4:20:00 PM

Comments:	1068.38 g coal
	505.13 g biomass
	151.50 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1500
Briquettes	46.79	41.32	5.47	0.132

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.78	0.88	1.10	0.97
2	9.86	0.98	1.11	0.98
3	9.86	0.64	1.07	0.94
4	9.70	0.80	1.09	0.96
5	9.65	0.57	1.06	0.94
6	9.70	0.64	1.07	0.95
7	9.75	0.67	1.07	0.95
8	10.04	0.97	1.11	0.98
9	9.73	0.76	1.08	0.96
10	9.22	0.41	1.05	0.92
		Average:	**1.08**	**0.95**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.89**	**1.89**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	195.83	138.15	70.55

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	205.6
2	281.6
3	203.3
4	285.3
5	205.1
6	224.7
7	297.1
8	163.4
9	235.9
10	261.9
11	229.6
12	218.6
13	335.9
14	251.9
15	301.5
16	231.8
17	368.4
18	265.7
19	193.4
20	443.9
21	280.7
22	315.3
23	169.9
24	264.9
25	242.6
Average:	**259.1**
St. Dev:	**63.2**
St. Dev (%):	**24.4**

Material Variables Evaluation

Sample:	EB-SD-01
Client:	DOE
Coal:	Eagle Butte - 70% - 1mm
Biomass:	Sawdust - 30% - #4
Target Moisture:	15.0%
Date:	8/14/2013
Time	5:00:00 PM

Comments:	1068.38 g coal
	498.15 g biomass
	158.48 g water
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1500 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1300
Briquettes	47.67	42.18	5.49	0.130

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.92	0.66	1.07	0.95
2	9.73	0.68	1.08	0.95
3	9.60	0.55	1.06	0.94
4	9.65	0.84	1.10	0.97
5	9.88	0.69	1.08	0.95
6	9.19	0.54	1.06	0.94
7	10.06	1.01	1.11	0.98
8	9.56	0.82	1.09	0.97
9	9.82	0.73	1.08	0.96
10	9.80	0.61	1.07	0.94
		Average:	**1.08**	**0.95**
		St. Dev:	**0.02**	**0.01**
		St. Dev (%):	**1.52**	**1.52**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	189.67	134.12	70.71

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	191.2
2	202.0
3	169.9
4	208.5
5	224.5
6	128.3
7	190.2
8	181.8
9	200.4
10	205.6
11	210.5
12	253.8
13	184.6
14	170.8
15	146.7
16	195.9
17	183.1
18	219.0
19	198.7
20	208.9
21	201.5
22	221.9
23	168.1
24	177.9
25	224.7
Average:	**194.7**
St. Dev:	**26.5**
St. Dev (%):	**13.6**

A.3.4 Evaluation of Roll Press Operating Parameters

Machine Parameters Evaluation

Sample:	MR-CS-MP-08
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/13/2013
Time	2:00:00 PM

Comments:	2018.60 g coal
	553.50 g biomass
	0.00 g water
	Roll Force: 75 kN
	Roll Speed: 900 rpm - 30 hz
	Roll Torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0340
Briquettes	59.63	58.53	1.10	0.019

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	11.88	1.24	1.12	1.10
2	11.59	1.47	1.15	1.12
3	11.94	1.59	1.15	1.13
4	11.50	1.45	1.14	1.12
5	11.63	1.63	1.16	1.14
6	11.62	1.33	1.13	1.11
7	11.44	1.48	1.15	1.13
8	11.71	1.47	1.14	1.12
9	11.88	1.57	1.15	1.13
10	11.78	1.58	1.15	1.13
		Average:	**1.15**	**1.12**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.17**	**1.17**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	233.87	216.21	92.45

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	355.1
2	322.2
3	354.6
4	289.3
5	316.0
6	282.1
7	302.1
8	236.1
9	250.2
10	233.9
11	242.0
12	311.0
13	328.4
14	264.1
15	314.3
16	361.1
17	344.6
18	307.0
19	237.0
20	308.9
21	356.7
22	301.1
23	226.9
24	252.1
25	300.0
Average:	**295.9**
St. Dev:	**42.9**
St. Dev (%):	**14.5**

Machine Parameters Evaluation

Sample:	MR-CS-MP-05
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/13/2013
Time	3:00:00 PM

Comments:	1211.10 g coal
	332.16 g biomass
	0.00 g water
	Roll Force: 75 kN
	Roll Speed: 300 rpm - 10 hz
	Roll Torque: 600 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0350
Briquettes	43.53	42.50	1.03	0.024

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.95	0.60	1.07	1.05
2	8.97	0.84	1.10	1.08
3	8.54	0.66	1.08	1.06
4	8.61	0.54	1.07	1.04
5	8.98	0.87	1.11	1.08
6	8.90	0.85	1.11	1.08
7	8.38	0.52	1.07	1.04
8	8.92	0.79	1.10	1.07
9	8.42	0.82	1.11	1.08
10	8.48	0.43	1.05	1.03
		Average:	**1.09**	**1.06**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.88**	**1.88**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	176.87	113.64	64.25

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	181.3
2	220.8
3	215.7
4	165.8
5	210.7
6	195.0
7	216.5
8	212.3
9	198.8
10	188.2
11	163.0
12	233.9
13	204.4
14	207.5
15	217.7
16	172.8
17	272.1
18	207.2
19	227.6
20	217.0
21	273.0
22	211.6
23	196.4
24	170.7
25	196.6
Average:	**207.1**
St. Dev:	**27.3**
St. Dev (%):	**13.2**

Machine Parameters Evaluation	
Sample:	MR-CS-MP-14
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/13/2013
Time	4:00:00 PM

Comments:	1614.88 g coal
	442.80 g biomass
	0.00 g water
	Roll Force: 75 kN
	Roll Speed: 600 rpm - 20 hz
	Roll Torque: 1200 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0365
Briquettes	53.51	52.27	1.24	0.024

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.55	1.24	1.13	1.11
2	10.37	1.03	1.11	1.08
3	10.80	1.21	1.13	1.10
4	10.60	1.28	1.14	1.11
5	10.45	1.12	1.12	1.09
6	10.59	1.34	1.14	1.12
7	10.38	1.18	1.13	1.10
8	10.21	0.88	1.09	1.07
9	10.64	1.31	1.14	1.11
10	10.46	1.00	1.11	1.08
		Average:	**1.12**	**1.10**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.46**	**1.46**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	210.77	184.75	87.65

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	231.3
2	257.0
3	216.0
4	282.6
5	214.1
6	254.6
7	234.5
8	221.1
9	227.2
10	252.3
11	233.8
12	254.5
13	186.3
14	233.8
15	316.7
16	217.6
17	211.4
18	222.7
19	220.7
20	229.5
21	241.6
22	260.5
23	204.6
24	224.6
25	269.4
Average:	**236.7**
St. Dev:	**27.4**
St. Dev (%):	**11.6**

Machine Parameters Evaluation

Sample:	MR-CS-MP-07
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/14/2013
Time	9:00:00 AM

Comments:	1211.10 g coal
	332.16 g biomass
	0.00 g water
	Roll Force: 75 kN
	Roll Speed: 300 rpm - 10 hz
	Roll Torque: ~~1800~~ 1200 ft-lb
	1800 torque was not possible so 1200 was

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0375
Briquettes	29.01	28.22	0.79	0.028

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.07	0.92	1.10	1.07
2	9.80	1.04	1.12	1.09
3	9.93	1.05	1.12	1.09
4	10.06	1.17	1.13	1.10
5	9.88	1.11	1.13	1.10
6	9.62	0.85	1.10	1.07
7				
8				
9				
10				
		Average:	**1.12**	**1.09**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.25**	**1.25**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.76	160.98	84.39

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	204.2
2	210.7
3	251.4
4	256.4
5	237.0
6	233.5
7	215.3
8	219.5
9	283.1
10	254.2
11	230.6
12	284.0
13	292.4
14	310.4
15	202.8
16	248.6
17	175.8
18	241.4
19	217.4
20	243.1
21	274.7
22	
23	
24	
25	
Average:	**242.2**
St. Dev:	**33.6**
St. Dev (%):	**13.9**

Machine Parameters Evaluation

Sample:	MR-CS-MP-06
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/14/2013
Time	10:00:00 AM

Comments:	2018.60 g coal
	553.50 g biomass
	0.00 g water
	Roll Force: 75 kN
	Roll Speed: 900 rpm - 30 hz
	Roll Torque: 600 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0310
Briquettes	43.03	42.01	1.02	0.024

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.18	0.22	1.03	1.00
2	8.66	0.31	1.04	1.01
3	8.35	0.24	1.03	1.01
4	8.40	0.18	1.02	1.00
5	8.65	0.65	1.08	1.06
6	8.43	0.34	1.04	1.02
7	8.23	0.27	1.03	1.01
8	8.93	0.60	1.07	1.05
9	8.77	0.21	1.02	1.00
10	8.45	0.17	1.02	1.00
		Average:	**1.04**	**1.01**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**2.02**	**2.02**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	172.16	93.01	54.03

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	235.5
2	167.2
3	238.5
4	210.8
5	176.6
6	237.1
7	205.5
8	183.7
9	184.2
10	213.8
11	189.6
12	161.6
13	177.3
14	224.3
15	161.6
16	184.8
17	234.5
18	137.2
19	186.7
20	198.4
21	205.3
22	204.6
23	189.7
24	215.8
25	170.9
Average:	**195.8**
St. Dev:	**26.7**
St. Dev (%):	**13.6**

Machine Parameters Evaluation

Sample:	MR-CS-MP-01
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/14/2013
Time	11:00:00 AM

Comments:	1211.10 g coal
	332.16 g biomass
	0.00 g water
	Roll Force: 50 kN
	Roll Speed: 300 rpm - 10 hz
	Roll Torque: 1200 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0315
Briquettes	37.64	36.92	0.72	0.020

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	12.94	1.28	1.11	1.09
2	12.83	1.27	1.11	1.09
3	12.65	1.23	1.11	1.09
4	13.12	1.29	1.11	1.09
5	12.61	1.20	1.11	1.08
6	12.88	1.30	1.11	1.09
7	12.41	1.19	1.11	1.08
8	12.65	1.21	1.11	1.08
9				
10				
		Average:	**1.11**	**1.09**
		St. Dev:	**0.00**	**0.00**
		St. Dev (%):	**0.22**	**0.22**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	254.34	207.33	81.52

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	237.5
2	242.8
3	215.1
4	185.7
5	180.8
6	249.1
7	199.2
8	162.6
9	158.3
10	189.6
11	124.1
12	274.1
13	179.8
14	223.8
15	171.4
16	177.9
17	176.6
18	176.4
19	231.6
20	145.0
21	216.9
22	184.0
23	
24	
25	
Average:	**195.6**
St. Dev:	**36.8**
St. Dev (%):	**18.8**

Machine Parameters Evaluation

Sample:	MR-CS-MP-02
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/14/2013
Time	1:00:00 PM

Comments:	2018.60 g coal
	553.50 g biomass
	0.00 g water
	Roll Force: 50 kN
	Roll Speed: 900 rpm - 30 hz
	Roll Torque: 1200 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0310
Briquettes	65.12	63.62	1.50	0.024

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	12.59	1.13	1.10	1.07
2	12.25	1.05	1.09	1.07
3	12.18	1.05	1.09	1.07
4	12.02	0.93	1.08	1.06
5	12.87	1.18	1.10	1.08
6	12.78	1.01	1.09	1.06
7	12.51	1.16	1.10	1.08
8	13.09	1.20	1.10	1.08
9	13.00	1.12	1.09	1.07
10	12.99	1.09	1.09	1.07
		Average:	**1.09**	**1.07**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.58**	**0.58**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	254.12	207.09	81.49

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	212.4
2	250.5
3	172.3
4	219.8
5	171.8
6	253.4
7	262.3
8	231.5
9	247.0
10	221.2
11	221.6
12	212.4
13	174.3
14	201.8
15	257.5
16	238.9
17	190.4
18	181.7
19	185.7
20	244.8
21	196.6
22	213.9
23	186.0
24	205.9
25	183.4
Average:	**213.5**
St. Dev:	**28.8**
St. Dev (%):	**13.5**

Machine Parameters Evaluation	
Sample:	MR-CS-MP-09
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/14/2013
Time	2:00:00 PM

Comments:	1413.02 g coal
	387.45 g biomass
	0.00 g water
	Roll Force: 50 kN
	Roll Speed: 600 rpm - 20 hz
	Roll Torque: 600 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0325
Briquettes	59.28	57.98	1.30	0.022

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.94	0.94	1.09	1.07
2	11.49	0.90	1.08	1.06
3	11.59	0.95	1.09	1.07
4	11.38	0.78	1.07	1.05
5	11.30	0.80	1.08	1.05
6	11.44	0.94	1.09	1.07
7	10.91	0.57	1.06	1.03
8	11.12	0.88	1.09	1.06
9	11.21	0.71	1.07	1.04
10	11.30	0.73	1.07	1.05
		Average:	**1.08**	**1.05**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.14**	**1.14**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	226.77	159.45	70.31

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	174.3
2	141.2
3	146.1
4	134.9
5	161.9
6	170.0
7	160.5
8	149.3
9	129.2
10	137.6
11	174.3
12	135.6
13	203.8
14	180.7
15	165.1
16	193.8
17	158.1
18	180.5
19	178.4
20	154.7
21	220.3
22	194.5
23	134.4
24	206.9
25	149.7
Average:	**165.4**
St. Dev:	**25.2**
St. Dev (%):	**15.2**

Machine Parameters Evaluation

Sample:	MR-CS-MP-12
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/14/2013
Time	3:00:00 PM

Comments:	1413.02 g coal
	387.45 g biomass
	0.00 g water
	Roll Force: 100 kN
	Roll Speed: 600 rpm - 20 hz
	Roll Torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0325
Briquettes	52.35	51.28	1.07	0.021

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.31	1.60	1.18	1.16
2	10.12	1.63	1.19	1.17
3	10.42	1.60	1.18	1.16
4	10.15	1.56	1.18	1.16
5	10.23	1.48	1.17	1.15
6	10.21	1.49	1.17	1.15
7	10.43	1.64	1.19	1.16
8	10.05	1.54	1.18	1.16
9	10.46	1.56	1.18	1.15
10	10.34	1.54	1.18	1.15
		Average:	**1.18**	**1.16**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.60**	**0.60**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	206.49	193.49	93.70

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	287.6
2	263.3
3	307.6
4	313.5
5	331.2
6	256.9
7	306.5
8	345.6
9	295.5
10	279.7
11	339.6
12	275.0
13	325.4
14	291.7
15	248.1
16	352.1
17	304.8
18	312.0
19	293.2
20	238.5
21	296.6
22	266.9
23	294.4
24	290.4
25	282.0
Average:	**295.9**
St. Dev:	**29.3**
St. Dev (%):	**9.9**

Machine Parameters Evaluation

Sample:	MR-CS-MP-11
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/14/2013
Time	4:00:00 PM

Comments:	1413.02 g coal
	387.45 g biomass
	0.00 g water
	Roll Force: 50 kN
	Roll Speed: 600 rpm - 20 hz
	Roll Torque: ~~1800~~ 1200 ft-lb
	1800 torque was not possible so 1200 was

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0300
Briquettes	64.74	63.48	1.26	0.020

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	12.71	1.24	1.11	1.09
2	12.95	1.15	1.10	1.08
3	13.17	1.17	1.10	1.08
4	13.01	1.16	1.10	1.08
5	12.06	1.01	1.09	1.07
6	12.84	1.13	1.10	1.08
7	12.88	1.16	1.10	1.08
8	12.96	1.29	1.11	1.09
9	12.79	1.13	1.10	1.08
10	13.21	1.25	1.10	1.08
		Average:	**1.10**	**1.08**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.53**	**0.53**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	257.69	213.85	82.99

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	223.2
2	239.2
3	264.1
4	189.2
5	245.7
6	217.1
7	200.3
8	205.0
9	230.2
10	181.4
11	231.1
12	208.9
13	256.5
14	239.1
15	219.1
16	195.2
17	215.5
18	226.4
19	215.0
20	187.5
21	207.9
22	185.8
23	260.5
24	214.6
25	
Average:	**219.1**
St. Dev:	**23.6**
St. Dev (%):	**10.8**

Machine Parameters Evaluation	
Sample:	MR-CS-MP-15
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/14/2013
Time	5:00:00 PM

Comments:	1413.02 g coal
	387.45 g biomass
	0.00 g water
	Roll Force: 75 kN
	Roll Speed: 600 rpm - 20 hz
	Roll Torque: 1200 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0315
Briquettes	54.23	53.07	1.16	0.022

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.55	1.28	1.14	1.11
2	10.53	1.34	1.15	1.12
3	10.77	1.30	1.14	1.11
4	10.72	1.29	1.14	1.11
5	10.57	1.20	1.13	1.10
6	10.82	1.42	1.15	1.13
7	10.76	1.27	1.13	1.11
8	10.97	1.30	1.13	1.11
9	10.96	1.47	1.15	1.13
10	10.91	1.16	1.12	1.10
		Average:	**1.14**	**1.11**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.93**	**0.93**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	214.17	189.75	88.60

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	226.8
2	198.1
3	230.3
4	261.3
5	238.9
6	214.4
7	148.9
8	237.3
9	222.1
10	222.6
11	219.0
12	260.1
13	217.3
14	244.8
15	267.1
16	267.7
17	300.7
18	253.8
19	254.0
20	260.0
21	252.8
22	280.1
23	246.8
24	269.4
25	252.3
Average:	**241.9**
St. Dev:	**30.4**
St. Dev (%):	**12.6**

Machine Parameters Evaluation

Sample:	MR-CS-MP-13
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/19/2013
Time	2:00:00 PM

Comments:	1413.02 g coal
	387.45 g biomass
	0.00 g water
	Roll Force: 75 kN
	Roll Speed: 600 rpm - 20 hz
	Roll Torque: 1200 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0390
Briquettes	53.19	51.92	1.27	0.024

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.49	1.29	1.14	1.11
2	10.75	1.43	1.15	1.13
3	10.32	1.27	1.14	1.11
4	10.22	1.22	1.14	1.11
5	10.12	1.19	1.13	1.11
6	10.29	1.24	1.14	1.11
7	10.46	1.30	1.14	1.11
8	10.19	1.09	1.12	1.09
9	10.08	1.15	1.13	1.10
10	10.48	1.20	1.13	1.10
		Average:	**1.14**	**1.11**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.80**	**0.80**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	208.73	180.76	86.60

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	210.0
2	270.7
3	180.5
4	201.7
5	296.1
6	238.1
7	261.5
8	240.5
9	184.4
10	209.8
11	277.1
12	225.5
13	232.7
14	249.5
15	207.5
16	275.7
17	214.8
18	223.2
19	246.3
20	223.1
21	252.2
22	227.7
23	228.2
24	250.3
25	223.0
Average:	**234.0**
St. Dev:	**28.7**
St. Dev (%):	**12.2**

Machine Parameters Evaluation	
Sample:	MR-CS-MP-03
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/19/2013
Time	3:00:00 PM

Comments:	1211.10 g coal
	332.16 g biomass
	0.00 g water
	Roll Force: 100 kN
	Roll Speed: 300 rpm - 10 hz
	Roll Torque: 1200 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0345
Briquettes	46.70	45.48	1.22	0.027

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.34	1.21	1.15	1.12
2	9.22	1.33	1.17	1.14
3	9.21	1.13	1.14	1.11
4	9.44	1.08	1.13	1.10
5	9.41	1.17	1.14	1.11
6	9.57	1.15	1.14	1.11
7	9.49	1.24	1.15	1.12
8	9.33	1.09	1.13	1.10
9	9.39	1.18	1.14	1.11
10	9.18	1.41	1.18	1.15
		Average:	**1.15**	**1.12**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.42**	**1.42**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.29	158.61	84.69

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	237.6
2	273.3
3	217.2
4	211.6
5	284.5
6	207.6
7	198.4
8	234.5
9	295.5
10	228.8
11	224.1
12	248.1
13	255.4
14	241.3
15	219.8
16	201.4
17	247.7
18	226.5
19	254.1
20	264.5
21	191.4
22	248.3
23	261.0
24	271.9
25	201.1
Average:	**237.8**
St. Dev:	**28.3**
St. Dev (%):	**11.9**

Machine Parameters Evaluation

Sample:	MR-CS-MP-10
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/19/2013
Time	4:00:00 PM

Comments:	2018.60 g coal
	553.50 g biomass
	0.00 g water
	Roll Force: 100 kN
	Roll Speed: 600 rpm - 30 hz
	Roll Torque: 600 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0320
Briquettes	44.38	43.27	1.11	0.026

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	8.61	0.59	1.07	1.05
2	8.76	0.82	1.10	1.08
3	8.85	0.79	1.10	1.07
4	8.70	0.66	1.08	1.06
5	8.56	0.62	1.08	1.05
6	8.84	0.76	1.09	1.07
7	8.73	0.72	1.09	1.06
8	8.66	0.71	1.09	1.06
9	8.74	0.75	1.09	1.07
10	8.67	0.48	1.06	1.03
		Average:	**1.09**	**1.06**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.22**	**1.22**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	171.97	108.58	63.14

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	203.1
2	226.8
3	216.9
4	226.2
5	233.2
6	258.9
7	230.5
8	212.8
9	191.3
10	189.6
11	194.9
12	244.0
13	160.7
14	238.4
15	192.4
16	225.3
17	260.4
18	210.6
19	228.1
20	205.4
21	223.7
22	223.3
23	176.5
24	175.1
25	208.3
Average:	**214.3**
St. Dev:	**25.1**
St. Dev (%):	**11.7**

Machine Parameters Evaluation	
Sample:	MR-CS-MP-04
Client:	DOE
Coal:	McClure River - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Target Moisture:	3.00%
Date:	6/19/2013
Time	5:00:00 PM

Comments:	2018.60 g coal
	553.50 g biomass
	0.00 g water
	Roll Force: 100 kN
	Roll Speed: 900 rpm - 30 hz
	Roll Torque: 1200 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0325
Briquettes	47.74	46.51	1.23	0.026

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.02	1.08	1.14	1.11
2	9.43	1.19	1.14	1.11
3	9.23	1.18	1.15	1.12
4	8.98	0.93	1.12	1.09
5	9.45	1.27	1.16	1.13
6	9.26	0.95	1.11	1.09
7	9.44	1.32	1.16	1.13
8	9.14	0.93	1.11	1.08
9	9.37	1.18	1.14	1.11
10	9.43	1.26	1.15	1.12
		Average:	**1.14**	**1.11**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.60**	**1.60**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	185.32	157.57	85.03

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	289.3
2	262.7
3	247.3
4	300.9
5	200.0
6	183.4
7	261.6
8	292.8
9	225.9
10	236.6
11	310.1
12	252.1
13	253.8
14	267.1
15	253.4
16	283.3
17	275.0
18	267.0
19	261.7
20	267.0
21	274.8
22	240.2
23	241.7
24	230.0
25	277.0
Average:	**258.2**
St. Dev:	**29.3**
St. Dev (%):	**11.3**

A.3.5 Detailed Characterization of Optimum Briquettes

Comprehensive Briquette Evaluations

Sample:	EM-SD
Client:	DOE
Coal:	Emerald - 70% - minus 1 mm
Biomass:	Sawdust - 30% - minus 1.20 mm
Chemical:	None
Target moisture:	2.20%
Date:	9/24/2013
Time:	10:00:00 AM

Comments:
2843.40 g coal; 1202.40 g biomass; 42.20 g water
Roll force: 100 kN; Roll speed: 900 rpm; Roll torque: 1800 N-m
Attritability: 20 briq, 5 min, #4 sieve
Friability: 20 briq, 6 ft, 2 drops, #4 sieve
Elasticity: Hooke's Law (F=-kx), linear portion
Tensile strength: standard plunger, standing short

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0265
Briquettes	51.58	50.67	0.91	0.0180

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake (%)
1	51.11	55.34	4.23	8.28

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.10	1.41	1.16	1.14
2	10.13	1.39	1.16	1.14
3	10.10	1.29	1.15	1.13
4	10.48	1.53	1.17	1.15
5	10.09	1.26	1.14	1.12
6	10.07	1.19	1.13	1.11
7	10.17	1.24	1.14	1.12
8	10.51	1.43	1.16	1.14
9	10.06	1.28	1.15	1.13
10	10.17	1.37	1.16	1.14
		Average:	1.15	1.13
		St. Dev:	0.01	0.01
		St. Dev (%):	1.01	1.01

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	204.06	189.29	92.76
2	205.54	159.42	77.56
3	176.83	96.84	54.76
Total			39.40

Tumbled Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake (%)
1	189.29	205.54	16.25	8.58
2	159.42	176.83	17.41	10.92
Total				20.44

Friability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	204.26	198.26	97.06

Attritability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	203.15	197.89	97.41

Crushing Strength & Elasticity Tests

Measurement	Crushing Strength (lb$_f$)	Crushing force (1) (lb$_f$)	Briquette disp. (1) (in)	Crushing force (2) (lb$_f$)	Briquette disp. (2) (in)	Stiffness constant (lb$_f$/in)
1	354.4	123.8	0.2550	20.5	0.2330	4695
2	293.0	57.3	0.2430	22.3	0.2310	2917
3	402.9	173.2	0.2760	45.8	0.2450	4110
4	380.1	173.4	0.2730	73.9	0.2380	2843
5	332.0	148.5	0.2610	34.7	0.2380	4948
6	310.9	258.4	0.2850	92.7	0.2450	4143
7	374.2	246.0	0.2950	78.9	0.2570	4397
8	320.8	220.6	0.2800	69.0	0.2490	4890
9	383.1	232.4	0.2990	79.3	0.2730	5888
10	379.3	224.2	0.2910	72.5	0.2540	4100
11	376.2	222.5	0.2840	73.1	0.2540	4980
12	411.3	239.4	0.2920	77.7	0.2520	4043
13	314.0	260.7	0.2970	98.9	0.2600	4373
14	324.3	201.3	0.2910	72.3	0.2640	4778
15	324.4	277.1	0.3070	85.3	0.2680	4918
16	424.3	219.8	0.2980	65.0	0.2670	4994
17	370.5	293.6	0.2980	144.0	0.2640	4400
18	294.1	264.2	0.2790	81.0	0.2420	4951
19	414.0	248.5	0.3030	64.9	0.2680	5246
20	383.8	272.8	0.2950	104.1	0.2610	4962
21	388.4	260.2	0.3040	61.4	0.2710	6024
22	361.6	263.9	0.2890	70.0	0.2430	4215
23	352.3	305.9	0.3000	103.2	0.2590	4944
24	315.6	292.7	0.2960	84.5	0.2620	6124
25	348.3	296.5	0.2930	96.2	0.2460	4262
Average:	357.4					4646
St. Dev:	38.2					783
St. Dev (%):	10.7					16.9

Tensile Strength Test

Measurement	Tensile strength (lb$_f$)
1	68.4
2	61.9
3	54.8
4	83.9
5	56.0
6	56.6
7	48.4
8	62.7
9	57.7
10	61.0
11	38.2
12	58.8
13	58.8
14	55.6
15	40.2
16	55.1
17	89.0
18	67.2
19	83.8
20	52.1
21	42.9
22	34.0
23	53.4
24	44.2
25	51.6
Average:	57.5
St. Dev:	13.6
St. Dev (%):	23.7

Comprehensive Briquette Evaluations

Sample:	EB-CS
Client:	DOE
Coal:	Eagle Butte - 70% - minus 1 mm
Biomass:	Corn Stover - 30% - minus 3/16"
Chemical:	None
Target moisture:	18.50%
Date:	9/25/2013
Time:	9:00:00 AM

Comments: 2847.60 g coal; 1336.20 g biomass; 556.20 g water
Roll force: 100 kN; Roll speed: 900 rpm; Roll torque: 1800 N-m
Attritability: 20 briq, 5 min, #4 sieve
Friability: 20 briq, 6 ft, 2 drops, #4 sieve
Elasticity: Hooke's Law (F=-kx), linear portion
Tensile strength: standard plunger, standing short

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1770
Briquettes	48.76	41.92	6.84	0.1632

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake (%)
1	49.25	56.28	7.03	14.27

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.94	1.13	1.13	0.97
2	9.61	0.75	1.08	0.93
3	10.03	0.95	1.10	0.95
4	9.92	0.76	1.08	0.93
5	9.74	0.84	1.09	0.94
6	10.07	0.76	1.08	0.93
7	10.15	0.81	1.09	0.93
8	10.22	0.75	1.08	0.93
9	10.01	0.79	1.09	0.93
10	9.90	0.75	1.08	0.93
		Average:	1.09	0.94
		St. Dev:	0.02	0.01
		St. Dev (%):	1.38	1.38

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	195.82	178.30	91.05
2	216.34	109.13	50.44
3	142.62	23.96	16.80
Total			7.72

Tumbled Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake (%)
1	178.30	216.34	38.04	21.33
2	109.13	142.62	33.49	30.69
Total				58.57

Friability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	195.31	192.25	98.43

Attritability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	198.50	192.33	96.89

Crushing Strength & Elasticity Tests

Measurement	Crushing Strength (lb$_f$)	Crushing force (1) (lb$_f$)	Briquette disp. (1) (in)	Crushing force (2) (lb$_f$)	Briquette disp. (2) (in)	Stiffness constant (lb$_f$/in)
1	273.7	170.0	0.6140	85.3	0.5840	2823
2	235.1	136.2	0.5820	45.3	0.5430	2331
3	239.8	120.1	0.5960	39.9	0.5680	2864
4	266.3	171.3	0.6100	84.3	0.5800	2900
5	205.0	153.8	0.6010	90.5	0.5670	1862
6	271.6	169.5	0.6040	69.5	0.5480	1786
7	294.3	239.9	0.6280	97.5	0.5690	2414
8	292.8	156.2	0.6060	67.9	0.5620	2007
9	351.6	169.7	0.6070	63.3	0.5720	3040
10	294.4	211.8	0.6130	71.9	0.5650	2915
11	254.4	143.1	0.5640	39.6	0.5320	3234
12	256.3	138.9	0.5880	61.2	0.5560	2428
13	275.7	152.7	0.6030	50.0	0.5730	3423
14	290.9	220.3	0.6080	86.4	0.5730	3826
15	301.2	141.5	0.6010	63.1	0.5540	1668
16	299.3	194.5	0.6140	49.2	0.5790	4151
17	347.3	232.1	0.6220	91.9	0.5860	3894
18	228.9	175.2	0.6250	73.5	0.5890	2825
19	298.6	186.3	0.6020	43.2	0.5460	2555
20	282.3	124.1	0.5750	30.4	0.5460	3231
21	250.4	173.6	0.6020	64.8	0.5710	3510
22	279.3	165.1	0.6130	39.8	0.5590	2320
23	256.2	128.7	0.5680	23.9	0.5380	3493
24	292.6	149.8	0.5980	58.5	0.5490	1863
25	244.0	159.3	0.5990	34.4	0.5650	3674
Average:	275.3					2842
St. Dev:	33.7					711
St. Dev (%):	12.2					25.0

Tensile Strength Test

Measurement	Tensile strength (lb$_f$)
1	47.5
2	30.6
3	51.4
4	68.4
5	36.7
6	43.6
7	43.3
8	64.7
9	37.6
10	25.9
11	48.9
12	50.1
13	40.9
14	41.1
15	49.8
16	55.9
17	29.3
18	52.1
19	44.7
20	59.9
21	43.4
22	48.8
23	48.2
24	41.6
25	52.8
Average:	46.3
St. Dev:	10.2
St. Dev (%):	21.9

A.4 Water-Resistant Briquette Production

A.4.1 Conventional Binder Evaluations

Binder/Water Proofing Evaluation

Sample:	EM-CS-GXX-0.0
Client:	DOE
Coal:	Emerald - 80% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	None
Target moisture:	5.0%
Production date:	8/22/2013
Production time:	3:05:00 PM

Comments:	1219.20 g coal
	332.10 g biomass
	0.00 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0510
Briquettes	49.40	48.10	1.30	0.027

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	49.68	57.51	7.83	15.76

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.66	1.54	1.19	1.16
2	9.81	1.56	1.19	1.16
3	9.92	1.38	1.16	1.13
4	9.96	1.59	1.19	1.16
5	9.95	1.75	1.21	1.18
6	9.96	1.58	1.19	1.16
7	10.07	1.68	1.20	1.17
8	9.76	1.58	1.19	1.16
9	10.01	1.56	1.18	1.15
10	9.91	1.65	1.20	1.17
		Average:	**1.19**	**1.16**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.12**	**1.12**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	198.07	183.12	92.45

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	262.5
2	308.9
3	271.1
4	290.8
5	291.4
6	305.8
7	315.9
8	321.1
9	273.3
10	331.6
11	325.9
12	282.6
13	290.8
14	290.2
15	318.8
16	277.1
17	276.1
18	277.1
19	281.1
20	297.6
21	285.8
22	313.4
23	321.8
24	304.1
25	264.8
Average:	**295.2**
St. Dev:	**20.4**
St. Dev (%):	**6.9**

Binder/Water Proofing Evaluation

Sample:	EM-CS-PGWS-2.5
Client:	DOE
Coal:	Emerald - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	Pregelatinized wheat starch - 2.5%
Target moisture:	5.0%
Production date:	8/29/2013
Production time:	2:20:00 PM

Comments:	1259.84 g coal
	354.24 g biomass
	45.40 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0525
Briquettes	49.51	47.97	1.54	0.032

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	50.19	60.05	9.86	19.65

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.73	1.41	1.17	1.13
2	10.16	1.63	1.19	1.15
3	9.98	1.66	1.20	1.16
4	10.06	1.79	1.22	1.18
5	9.70	1.41	1.17	1.13
6	9.78	1.39	1.17	1.13
7	9.79	1.44	1.17	1.14
8	9.69	1.56	1.19	1.15
9	9.99	1.65	1.20	1.16
10	9.75	1.60	1.20	1.16
		Average:	**1.19**	**1.15**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.41**	**1.41**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	199.43	190.23	95.39

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	333.8
2	337.0
3	400.4
4	402.5
5	335.5
6	306.9
7	372.3
8	352.5
9	396.0
10	373.6
11	344.6
12	403.3
13	364.2
14	339.6
15	358.8
16	330.4
17	365.0
18	352.3
19	318.1
20	339.5
21	372.2
22	395.6
23	382.2
24	404.1
25	367.3
Average:	**361.9**
St. Dev:	**28.3**
St. Dev (%):	**7.8**

Binder/Water Proofing Evaluation

Sample:	EM-CS-PGWS-5.0
Client:	DOE
Coal:	Emerald - 75% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	Pregelatinized wheat starch - 5.0%
Target moisture:	5.0%
Production date:	8/29/2013
Production time:	2:40:00 PM

Comments:	1219.20 g coal
	354.24 g biomass
	90.80 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0495
Briquettes	50.11	48.46	1.65	0.034

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	50.19	61.06	10.87	21.66

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.12	1.77	1.21	1.17
2	9.86	1.67	1.20	1.16
3	9.70	1.63	1.20	1.16
4	9.71	1.59	1.20	1.16
5	9.91	1.61	1.19	1.15
6	10.04	1.73	1.21	1.17
7	9.89	1.55	1.19	1.15
8	10.08	1.75	1.21	1.17
9	9.91	1.57	1.19	1.15
10	10.04	1.51	1.18	1.14
		Average:	**1.20**	**1.16**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.96**	**0.96**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	199.15	191.22	96.02

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	398.1
2	404.0
3	489.8
4	425.3
5	457.0
6	450.1
7	387.0
8	399.9
9	370.0
10	476.8
11	366.8
12	399.1
13	422.2
14	432.5
15	360.9
16	400.7
17	332.8
18	384.8
19	403.0
20	465.2
21	386.0
22	471.3
23	337.1
24	349.3
25	372.2
Average:	**405.7**
St. Dev:	**44.0**
St. Dev (%):	**10.8**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G16-2.5
Client:	DOE
Coal:	Emerald - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	GP-G16 - 2.5%
Target moisture:	5.0%
Production date:	8/29/2013
Production time:	11:25:00 AM

Comments:	1574.80 g coal
	442.80 g biomass
	50.53 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0380
Briquettes	46.29	45.00	1.29	0.029

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	46.31	122.80	76.49	165.17

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.60	0.45	1.05	1.02
2	8.80	0.30	1.04	1.01
3	9.32	0.49	1.06	1.03
4	9.36	0.52	1.06	1.03
5	9.43	0.55	1.06	1.03
6	9.51	0.35	1.04	1.01
7	9.39	0.32	1.04	1.01
8	9.27	0.49	1.06	1.03
9	9.72	0.53	1.06	1.03
10	8.66	0.38	1.05	1.02
		Average:	**1.05**	**1.02**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.97**	**0.97**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	187.57	56.07	29.89

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	123.7
2	114.4
3	103.2
4	109.1
5	93.9
6	116.6
7	121.9
8	118.0
9	122.0
10	120.1
11	109.0
12	124.7
13	105.2
14	99.5
15	112.8
16	121.2
17	118.9
18	118.5
19	91.5
20	93.1
21	116.8
22	107.1
23	120.1
24	119.2
25	83.7
Average:	**111.4**
St. Dev:	**11.5**
St. Dev (%):	**10.3**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G16-5.0
Client:	DOE
Coal:	Emerald - 75% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	GP-G16 - 5.0%
Target moisture:	5.0%
Production date:	8/29/2013
Production time:	11:50:00 AM

Comments:	1524.00 g coal
	442.80 g biomass
	101.05 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0375
Briquettes	46.95	45.67	1.28	0.028

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	47.61	138.35	90.74	190.59

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.26	0.08	1.01	0.98
2	8.73	0.29	1.03	1.01
3	9.09	0.29	1.03	1.00
4	9.73	0.36	1.04	1.01
5	9.56	0.35	1.04	1.01
6	9.11	0.39	1.04	1.02
7	9.38	0.26	1.03	1.00
8	8.81	0.31	1.04	1.01
9	9.52	0.41	1.05	1.02
10	9.74	0.49	1.05	1.02
		Average:	**1.04**	**1.01**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.15**	**1.15**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	186.47	48.97	26.26

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	64.2
2	58.8
3	55.2
4	56.5
5	44.6
6	53.1
7	66.3
8	76.9
9	74.0
10	68.9
11	58.3
12	59.3
13	59.8
14	73.7
15	57.3
16	75.8
17	52.1
18	52.9
19	49.7
20	61.6
21	68.4
22	62.5
23	55.6
24	54.6
25	66.0
Average:	**61.0**
St. Dev:	**8.5**
St. Dev (%):	**14.0**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G88-2.5
Client:	DOE
Coal:	Emerald - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	GP-G88 - 2.5%
Target moisture:	5.0%
Production date:	8/29/2013
Production time:	10:00:00 AM

Comments:	1259.84 g coal
	354.24 g biomass
	40.00 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0485
Briquettes	49.49	48.06	1.43	0.030

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	49.25	52.38	3.13	6.36

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.82	1.49	1.18	1.14
2	9.75	1.55	1.19	1.15
3	9.86	1.38	1.16	1.13
4	9.91	1.39	1.16	1.13
5	9.76	1.35	1.16	1.13
6	9.69	1.14	1.13	1.10
7	9.83	1.48	1.18	1.14
8	10.00	1.42	1.17	1.13
9	9.81	1.02	1.12	1.08
10	9.60	1.23	1.15	1.11
		Average:	**1.16**	**1.13**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.90**	**1.90**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	196.11	177.41	90.46

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	258.9
2	264.1
3	261.1
4	257.5
5	265.5
6	256.8
7	281.9
8	261.5
9	274.6
10	291.9
11	276.8
12	314.0
13	328.2
14	230.0
15	285.1
16	231.3
17	281.3
18	267.2
19	239.5
20	229.1
21	243.7
22	264.6
23	250.3
24	254.0
25	269.3
Average:	**265.5**
St. Dev:	**23.8**
St. Dev (%):	**9.0**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G88-5.0
Client:	DOE
Coal:	Emerald - 75% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	GP-G88 - 5.0%
Target moisture:	5.0%
Production date:	8/29/2013
Production time:	11:00:00 AM

Comments:	1219.20 g coal
	354.24 g biomass
	80.00 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0450
Briquettes	47.76	46.50	1.26	0.027

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	48.02	51.38	3.36	7.00

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.67	1.48	1.18	1.15
2	9.76	1.34	1.16	1.13
3	9.79	1.35	1.16	1.13
4	9.61	1.21	1.14	1.11
5	9.55	1.21	1.15	1.11
6	9.58	1.37	1.17	1.14
7	9.51	1.31	1.16	1.13
8	9.76	1.35	1.16	1.13
9	9.65	1.29	1.15	1.12
10	9.51	1.22	1.15	1.12
		Average:	**1.16**	**1.13**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.96**	**0.96**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	192.85	173.87	90.16

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	249.5
2	238.9
3	264.1
4	243.0
5	232.1
6	248.5
7	231.5
8	265.2
9	211.0
10	249.1
11	199.0
12	258.6
13	283.1
14	191.5
15	334.4
16	285.7
17	252.6
18	235.3
19	235.1
20	229.2
21	188.0
22	217.2
23	201.6
24	299.0
25	256.1
Average:	**244.0**
St. Dev:	**34.2**
St. Dev (%):	**14.0**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G89-2.5
Client:	DOE
Coal:	Emerald - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	GP-G89 - 2.5%
Target moisture:	5.0%
Production date:	8/29/2013
Production time:	12:15:00 PM

Comments:	1259.84 g coal
	354.24 g biomass
	40.06 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0455
Briquettes	48.90	47.66	1.24	0.026

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	49.54	52.69	3.15	6.36

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.23	1.70	1.20	1.17
2	9.60	1.38	1.17	1.14
3	10.01	1.57	1.19	1.16
4	9.81	1.61	1.20	1.17
5	10.19	1.55	1.18	1.15
6	9.78	1.50	1.18	1.15
7	9.63	1.27	1.15	1.12
8	10.01	1.62	1.19	1.16
9	9.82	1.41	1.17	1.14
10	9.98	1.57	1.19	1.16
		Average:	**1.18**	**1.15**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.25**	**1.25**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	196.54	183.67	93.45

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	324.9
2	368.2
3	269.9
4	291.1
5	260.1
6	323.9
7	345.4
8	329.6
9	304.8
10	288.8
11	287.5
12	309.3
13	292.1
14	294.8
15	291.7
16	250.1
17	308.1
18	278.5
19	312.2
20	308.8
21	271.3
22	332.3
23	270.5
24	261.6
25	315.5
Average:	**299.6**
St. Dev:	**28.6**
St. Dev (%):	**9.5**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G89-5.0
Client:	DOE
Coal:	Emerald - 75% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	GP-G89 - 5.0%
Target moisture:	5.0%
Production date:	8/29/2013
Production time:	1:55:00 PM

Comments:	1219.20 g coal
	354.24 g biomass
	80.12 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb
	Difficult to sustain high torque

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0500
Briquettes	48.74	47.50	1.24	0.026

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	48.98	51.88	2.90	5.92

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.69	1.49	1.18	1.15
2	9.60	1.33	1.16	1.13
3	9.82	1.59	1.19	1.16
4	9.56	1.42	1.17	1.14
5	9.89	1.62	1.20	1.17
6	9.59	1.44	1.18	1.15
7	9.73	1.38	1.17	1.14
8	9.80	1.51	1.18	1.15
9	9.88	1.50	1.18	1.15
10	9.78	1.43	1.17	1.14
		Average:	**1.18**	**1.15**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.94**	**0.94**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	197.26	185.04	93.81

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	268.1
2	285.2
3	288.9
4	324.6
5	277.3
6	295.9
7	296.9
8	284.4
9	349.7
10	308.8
11	281.0
12	329.8
13	294.0
14	321.7
15	256.3
16	325.7
17	335.0
18	404.0
19	302.0
20	270.9
21	302.0
22	313.8
23	273.3
24	297.5
25	303.3
Average:	**303.6**
St. Dev:	**31.0**
St. Dev (%):	**10.2**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G90-2.5
Client:	DOE
Coal:	Emerald - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	GP-G90 - 2.5%
Target moisture:	5.0%
Production date:	8/22/2013
Production time:	3:05:00 PM

Comments:	1259.84 g coal
	354.24 g biomass
	40.06 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0480
Briquettes	49.10	47.72	1.38	0.029

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	48.75	51.57	2.82	5.78

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.69	1.33	1.16	1.13
2	9.80	1.45	1.17	1.14
3	10.04	1.49	1.17	1.14
4	9.69	1.40	1.17	1.14
5	9.93	1.49	1.18	1.14
6	9.77	1.54	1.19	1.15
7	9.93	1.47	1.17	1.14
8	9.83	1.43	1.17	1.14
9	9.81	1.54	1.19	1.15
10	10.15	1.51	1.17	1.14
		Average:	**1.17**	**1.14**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.69**	**0.69**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	197.86	178.68	90.31

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	290.7
2	250.8
3	291.6
4	326.0
5	287.8
6	335.5
7	293.4
8	277.5
9	293.2
10	366.4
11	261.2
12	252.6
13	256.5
14	245.6
15	242.0
16	293.8
17	320.5
18	255.8
19	246.3
20	287.9
21	271.6
22	278.5
23	261.8
24	282.8
25	257.0
Average:	**281.1**
St. Dev:	**31.0**
St. Dev (%):	**11.0**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G90-5.0
Client:	DOE
Coal:	Emerald - 75% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	GP-G90 - 5.0%
Target moisture:	5.0%
Production date:	8/29/2013
Production time:	9:40:00 AM

Comments:	1219.20 g coal
	354.24 g biomass
	80.12 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0490
Briquettes	48.93	47.83	1.10	0.023

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	48.36	50.15	1.79	3.70

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.62	1.44	1.18	1.15
2	9.80	1.41	1.17	1.14
3	9.71	1.40	1.17	1.14
4	9.80	1.51	1.18	1.16
5	9.80	1.43	1.17	1.14
6	9.82	1.31	1.15	1.13
7	9.54	1.33	1.16	1.14
8	9.71	1.35	1.16	1.14
9	9.78	1.16	1.13	1.11
10	9.57	1.31	1.16	1.13
		Average:	**1.16**	**1.14**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.13**	**1.13**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.23	172.21	88.66

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	298.0
2	330.7
3	250.5
4	261.5
5	290.2
6	250.6
7	243.1
8	258.3
9	239.5
10	302.7
11	312.3
12	282.0
13	249.7
14	244.7
15	262.2
16	297.1
17	274.9
18	321.1
19	292.3
20	300.7
21	214.9
22	251.6
23	312.8
24	257.8
25	295.4
Average:	**275.8**
St. Dev:	**30.0**
St. Dev (%):	**10.9**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G97-2.5
Client:	DOE
Coal:	Emerald - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	GP-G97 - 2.5%
Target moisture:	5.0%
Production date:	8/22/2013
Production time:	2:20:00 PM

Comments:	1259.84 g coal
	354.24 g biomass
	40.06 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0450
Briquettes	48.95	47.69	1.26	0.026

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	48.63	52.99	4.36	8.97

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.74	1.52	1.18	1.15
2	9.91	1.55	1.19	1.15
3	9.82	1.49	1.18	1.15
4	9.72	1.37	1.16	1.13
5	9.59	1.25	1.15	1.12
6	9.57	1.52	1.19	1.16
7	9.81	1.23	1.14	1.11
8	9.69	1.44	1.17	1.14
9	9.76	1.48	1.18	1.15
10	9.73	1.48	1.18	1.15
		Average:	**1.17**	**1.14**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.32**	**1.32**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.63	179.64	92.30

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	341.5
2	290.5
3	300.2
4	277.2
5	283.4
6	261.5
7	297.2
8	292.7
9	314.6
10	287.8
11	331.7
12	304.0
13	287.1
14	294.2
15	288.1
16	288.9
17	275.0
18	300.2
19	342.7
20	307.6
21	317.1
22	292.6
23	327.4
24	307.7
25	348.1
Average:	**302.4**
St. Dev:	**22.2**
St. Dev (%):	**7.3**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G97-5.0
Client:	DOE
Coal:	Emerald - 75% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	GP-G97 - 5.0%
Target moisture:	5.0%
Production date:	8/22/2013
Production time:	3:35:00 PM

Comments:	
	1219.20 g coal
	354.24 g biomass
	80.12 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0435
Briquettes	47.65	46.40	1.25	0.027

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	47.29	50.04	2.75	5.82

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.59	1.51	1.19	1.16
2	9.61	1.39	1.17	1.14
3	9.71	1.48	1.18	1.15
4	9.50	1.36	1.17	1.14
5	9.66	1.31	1.16	1.13
6	9.75	1.43	1.17	1.14
7	9.61	1.19	1.14	1.11
8	9.76	1.35	1.16	1.13
9	9.14	1.13	1.14	1.11
10	9.55	1.48	1.18	1.15
		Average:	**1.17**	**1.14**
		St. Dev:	**0.02**	**0.02**
		St. Dev (%):	**1.38**	**1.38**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.40	174.07	91.42

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	294.7
2	335.5
3	384.0
4	333.6
5	348.7
6	294.9
7	346.9
8	347.4
9	358.3
10	343.9
11	327.3
12	311.0
13	309.6
14	318.9
15	272.2
16	324.1
17	367.9
18	405.8
19	331.7
20	362.5
21	408.4
22	285.4
23	323.8
24	299.5
25	365.1
Average:	**336.0**
St. Dev:	**35.0**
St. Dev (%):	**10.4**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G98-2.5
Client:	DOE
Coal:	Emerald - 77.5% - 1mm
Biomass:	Corn stover - 20% - 3/16"
Binder:	GP-G98 - 2.5%
Target moisture:	5.0%
Production date:	8/22/2013
Production time:	2:20:00 PM

Comments:	1181.10 g coal
	332.10 g biomass
	37.58 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0490
Briquettes	48.45	47.16	1.29	0.027

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	48.29	51.38	3.09	6.40

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.64	1.56	1.19	1.16
2	9.61	1.52	1.19	1.16
3	9.32	1.28	1.16	1.13
4	10.09	1.56	1.18	1.15
5	9.94	1.58	1.19	1.16
6	9.89	1.53	1.18	1.15
7	9.71	1.52	1.19	1.15
8	9.54	1.37	1.17	1.14
9	9.97	1.38	1.16	1.13
10	9.89	1.53	1.18	1.15
		Average:	**1.18**	**1.15**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**1.03**	**1.03**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	194.52	177.04	91.01

Crushing Strength Tests

Measurement	Crushing Strength (lb$_f$)
1	261.7
2	265.4
3	349.9
4	336.4
5	287.7
6	359.9
7	245.7
8	285.5
9	195.2
10	325.8
11	348.9
12	269.9
13	239.0
14	194.2
15	328.0
16	288.4
17	317.2
18	284.8
19	316.3
20	345.4
21	294.4
22	261.2
23	289.5
24	295.8
25	328.0
Average:	**292.6**
St. Dev:	**44.8**
St. Dev (%):	**15.3**

Binder/Water Proofing Evaluation

Sample:	EM-CS-G98-5.0
Client:	DOE
Coal:	Emerald - 75% - 1mm
Biomass:	Corn stover - 10% - 3/16"
Binder:	GP-G98 - 5.0%
Target moisture:	5.0%
Production date:	8/22/2013
Production time:	3:35:00 PM

Comments:	1143.00 g coal
	332.10 g biomass
	75.15 g binder
	0.00 g water
	Cure time: 1 day
	Force: 100 kN
	Roll speed: 450 rpm - 15 hz
	Roll torque: 1800 ft-lb

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0435
Briquettes	48.11	46.83	1.28	0.027

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	47.84	50.44	2.60	5.43

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	9.56	1.28	1.15	1.12
2	9.30	1.21	1.15	1.12
3	9.62	1.17	1.14	1.11
4	9.55	1.33	1.16	1.13
5	9.65	1.35	1.16	1.13
6	9.52	1.26	1.15	1.12
7	9.45	1.27	1.16	1.12
8	9.48	1.21	1.15	1.12
9	9.53	1.33	1.16	1.13
10	9.50	1.20	1.14	1.11
		Average:	**1.15**	**1.12**
		St. Dev:	**0.01**	**0.01**
		St. Dev (%):	**0.71**	**0.71**

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	190.61	172.95	90.74

Crushing Strength Tests

Measurement	Crushing Strength (lb_f)
1	384.7
2	291.2
3	306.9
4	398.9
5	303.4
6	358.0
7	272.7
8	256.4
9	345.5
10	285.8
11	407.1
12	477.8
13	267.0
14	346.4
15	326.9
16	330.2
17	422.8
18	326.5
19	263.8
20	348.9
21	384.2
22	366.3
23	295.7
24	350.1
25	304.8
Average:	**336.9**
St. Dev:	**55.1**
St. Dev (%):	**16.4**

A.4.2 Preliminary Coating Evaluations

Chemical Coating Evaluation

Sample:	EM-CS-GXXC
Client:	DOE
Briquette ID:	EM-CS-GP
Chemical:	None
Production date:	9/11/2013
Production time:	3:00:00 PM

Comments:	Oven temp: 170-200 °C
	Resin temp: 150-160 °C
	Drip time: 10 min, flip, 5 min
	Cure time: 1 hour

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Briquettes	50.32	48.77	1.55	0.0318

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake (%)
1	49.52	58.03	8.51	17.18

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	198.85	183.10	92.08
2	205.86	133.65	64.92
3	157.18	51.15	32.54
Total			19.45

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake (%)
1	183.09	205.86	22.77	12.44
2	133.55	157.18	23.63	17.69
Total				32.33

Chemical Coating Evaluation

Sample:	EM-CS-G88C
Client:	DOE
Briquette ID:	EM-CS-GP
Chemical:	GP-G88
Production date:	9/13/2013
Production time:	2:00:00 PM

Comments:	Oven temp: 170-200 °C
	Resin temp: 150-160 °C
	Drip time: 10 min, flip, 5 min
	Cure time: 1 hour

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	9.89	10.44	0.55	5.56
2	9.84	10.53	0.69	7.01
3	10.07	10.79	0.72	7.15
4	9.81	10.56	0.75	7.65
5	9.90	10.57	0.67	6.77
			Average	6.83
			St. Dev:	0.78
			St. Dev (%):	11.38

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	52.88	53.58	0.70	1.32

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	198.88	218.61	19.73	9.92

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	218.61	215.98	98.80
2	217.24	214.20	98.60
3	215.35	212.85	98.84
Total			96.28

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	215.98	217.24	1.26	0.58
2	214.11	215.35	1.24	0.58
Total				1.17

Chemical Coating Evaluation

Sample:	EM-CS-G89C
Client:	DOE
Briquette ID:	EM-CS-GP
Chemical:	GP-G89
Production date:	9/12/2013
Production time:	3:00:00 PM

Comments:
Oven temp: 170-200 °C
Resin temp: 150-160 °C
Drip time: 10 min, flip, 5 min
Cure time: 1 hour

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	9.91	10.71	0.80	8.07
2	10.03	11.08	1.05	10.47
3	10.02	10.88	0.86	8.58
4	9.61	10.66	1.05	10.93
5	10.00	10.73	0.73	7.30
			Average	9.07
			St. Dev:	1.56
			St. Dev (%):	17.23

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	54.06	54.46	0.40	0.74

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	198.14	209.27	11.13	5.62

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	209.27	198.18	94.70
2	200.45	182.18	90.89
3	190.66	146.61	76.90
Total			66.18

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	198.17	200.45	2.28	1.15
2	182.07	190.66	8.59	4.72
Total				5.92

Chemical Coating Evaluation

Sample:	EM-CS-G90C
Client:	DOE
Briquette ID:	EM-CS-GP
Chemical:	GP-G90
Production date:	9/12/2013
Production time:	10:00:00 AM

Comments:
Oven temp: 170-200 °C
Resin temp: 150-160 °C
Drip time: 10 min, flip, 5 min
Cure time: 1 hour
Coating began to break off during tumbling
After two rounds of tumbling, bare
were exposed

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	10.02	10.72	0.70	6.99
2	10.13	11.00	0.87	8.59
3	9.87	10.76	0.89	9.02
4	9.80	10.69	0.89	9.08
5	9.94	11.06	1.12	11.27
			Average	8.99
			St. Dev:	1.53
			St. Dev (%):	17.03

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	54.24	54.72	0.48	0.88

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	197.35	214.62	17.27	8.75

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	214.62	208.29	97.05
2	209.07	206.46	98.75
3	207.64	201.52	97.05
Total			93.01

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	208.23	209.07	0.84	0.40
2	206.37	207.64	1.27	0.62
Total				1.02

Chemical Coating Evaluation

Sample:	EM-CS-G97C
Client:	DOE
Briquette ID:	EM-CS-GP
Chemical:	GP-G97
Production date:	9/11/2013
Production time:	12:00:00 PM

Comments:	
	Oven temp: 170-200 °C
	Resin temp: 150-160 °C
	Drip time: 10 min, flip, 5 min
	Cure time: 1 hour

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	9.89	10.49	0.60	6.07
2	9.79	10.33	0.54	5.52
3	9.88	10.40	0.52	5.26
4	9.65	10.30	0.65	6.74
5	9.91	10.48	0.57	5.75
			Average	5.87
			St. Dev:	0.57
			St. Dev (%):	9.70

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	52.00	52.51	0.51	0.98

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	197.36	213.10	15.74	7.98

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	213.10	210.69	98.87
2	212.07	210.70	99.35
3	212.08	210.81	99.40
Total			97.64

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	210.70	212.07	1.37	0.65
2	210.57	212.08	1.51	0.72
Total				1.37

Chemical Coating Evaluation

Sample:	EM-CS-G98C
Client:	DOE
Briquette ID:	EM-CS-GP
Chemical:	GP-G98
Production date:	9/11/2013
Production time:	9:00:00 AM

Comments:	
	Oven temp: 170-200 °C
	Resin temp: 150-160 °C
	Drip time: 10 min, flip, 5 min
	Cure time: 1 hour

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	10.03	10.55	0.52	5.18
2	9.85	10.41	0.56	5.69
3	9.92	10.53	0.61	6.15
4	10.08	10.63	0.55	5.46
5	9.98	10.62	0.64	6.41
			Average	5.78
			St. Dev:	0.50
			St. Dev (%):	8.68

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	52.73	53.28	0.55	1.04

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	198.86	211.79	12.93	6.50

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	211.79	208.25	98.33
2	209.64	208.02	99.23
3	209.97	208.26	99.19
Total			96.77

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	208.25	209.64	1.39	0.67
2	207.93	209.97	2.04	0.98
Total				1.66

Chemical Coating Evaluation

Sample:	EM-CS-PWC
Client:	DOE
Briquette ID:	EM-CS-GP
Chemical:	Paraffin wax
Production date:	9/15/2013
Production time:	12:00:00 PM

Comments:	Oven temp: 170-200 °C
	Resin temp: 150-160 °C
	Drip time: 10 min, flip, 5 min
	Cure time: 1 hour

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	9.80	9.90	0.10	1.02
2	9.95	10.10	0.15	1.51
3	10.15	10.32	0.17	1.64
4	10.14	10.29	0.15	1.48
5	9.88	10.06	0.18	1.82
			Average	1.49
			St. Dev:	0.30
			St. Dev (%):	19.93

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	50.67	51.00	0.33	0.65

Chemical Dosage Tests

Measurement	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	199.69	203.73	4.04	2.02

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	203.73	184.51	90.57
2	185.93	171.57	92.28
3	173.24	161.77	93.38
Total			78.04

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake %
1	184.49	185.93	1.44	0.78
2	171.51	173.24	1.73	1.01
Total				1.80

A.4.3 Detailed Coating Evaluations

Comprehensive Briquette Evaluations

Sample:	EM-SD-G97
Client:	DOE
Coal:	Emerald - 70% - minus 1 mm
Biomass:	Sawdust - 30% - minus 1.20 mm
Chemical:	GP-G97
Target moisture:	2.20%
Date:	9/24/2013
Time:	10:00:00 AM

Comments:
2843.40 g coal; 1202.40 g biomass; 42.20 g water
Roll force: 100 kN; Roll speed: 900 rpm; Roll torque: 1800 N-m
Attritability: 20 briq, 5 min, #4 sieve
Friability: 20 briq, 6 ft, 2 drops, #4 sieve
Elasticity: Hooke's Law (F=-kx), linear portion
Tensile strength: diametrical compression, standing tall
Oven temp: 170-200 °C; Resin temp: 150-160 °C
Drip time: 10 min, flip, 5 min; Cure time: 1 hour

Chemical Dosage Tests

Batch	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	503.08	549.51	46.43	9.23
2	504.82	555.11	50.29	9.96
3	507.03	556.63	49.60	9.78
4	507.27	556.62	49.35	9.73
5	506.06	558.69	52.63	10.40
6	313.15	344.29	31.14	9.94
			Average	9.84
			St. Dev:	0.35
			St. Dev (%):	3.54

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.0265
Briquettes	55.95	54.76	1.19	0.0217

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake (%)
1	55.75	56.29	0.54	0.97

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	10.79	1.35	1.14	1.12
2	10.71	1.35	1.14	1.12
3	10.94	1.32	1.14	1.11
4	10.84	1.33	1.14	1.12
5	10.82	1.24	1.13	1.11
6	10.97	1.31	1.14	1.11
7	10.72	1.19	1.12	1.10
8	10.94	1.26	1.13	1.11
9	10.89	1.18	1.12	1.10
10	11.01	1.22	1.12	1.10
		Average:	1.13	1.11
		St. Dev:	0.01	0.01
		St. Dev (%):	0.71	0.71

Crushing Strength & Elasticity Tests

Measurement	Crushing Strength (lb_f)	Crushing force (1) (lb_f)	Briquette disp. (1) (in)	Crushing force (2) (lb_f)	Briquette disp. (2) (in)	Stiffness constant (lb_f/in)
1	318.3	293.2	0.6020	133.8	0.5470	2898
2	328.9	274.5	0.5760	139.0	0.5420	3985
3	324.7	296.2	0.6160	148.9	0.5780	3876
4	399.5	325.4	0.5880	168.7	0.5560	4897
5	306.5	260.9	0.5940	129.3	0.5550	3374
6	289.5	258.1	0.5910	174.7	0.5740	4906
7	326.5	280.1	0.6060	193.6	0.5790	3204
8	337.5	289.7	0.6020	160.7	0.5700	4031
9	344.4	270.1	0.6060	177.1	0.5750	3000
10	294.2	232.2	0.5880	152.0	0.5540	2359
11	310.5	297.1	0.6100	206.1	0.5720	2395
12	277.8	223.7	0.5680	108.6	0.5320	3197
13	341.9	303.6	0.6300	195.5	0.5940	3003
14	305.0	263.4	0.6010	156.8	0.5750	4100
15	319.0	244.1	0.5860	153.9	0.5570	3110
16	358.2	301.7	0.6180	182.0	0.5930	4788
17	272.1	207.5	0.5830	99.3	0.5500	3279
18	304.4	249.6	0.6030	136.2	0.5710	3544
19	296.1	175.4	0.5640	70.2	0.5260	2768
20	297.6	192.9	0.5920	84.3	0.5310	1780
21	375.5	295.1	0.6010	172.5	0.5790	5573
22	287.6	254.9	0.6020	124.2	0.5480	2420
23	275.0	205.7	0.5780	68.5	0.5370	3346
24	273.2	212.1	0.5750	78.6	0.5380	3608
25	259.0	238.3	0.6020	148.2	0.5700	2816
Average:	312.9					3450
St. Dev:	33.9					908
St. Dev (%):	10.8					26.3

Comprehensive Briquette Evaluations

Sample:	EM-SD-G97
Client:	DOE
Coal:	Emerald - 70% - minus 1 mm
Biomass:	Sawdust - 30% - minus 1.20 mm
Chemical:	GP-G97
Target moisture:	2.20%
Date:	9/24/2013
Time:	10:00:00 AM

Comments:
2843.40 g coal; 1202.40 g biomass; 42.20 g water
Roll force: 100 kN; Roll speed: 900 rpm; Roll torque: 1800 N-m
Attritability: 20 briq, 5 min, #4 sieve
Friability: 20 briq, 6 ft, 2 drops, #4 sieve
Elasticity: Hooke's Law (F=-kx), linear portion
Tensile strength: diametrical compression, standing tall
Oven temp: 170-200 °C; Resin temp: 150-160 °C
Drip time: 10 min, flip, 5 min; Cure time: 1 hour

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	221.96	216.77	97.66
2	217.88	212.49	97.53
3	214.68	201.48	93.85
Total			89.39

Tumbled Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake (%)
1	216.77	217.88	1.11	0.51
2	212.49	214.68	2.19	1.03
Total				1.55

Friability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	220.71	219.19	99.31

Attritability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	220.46	219.34	99.49

Tensile Strength Test

Measurement	Tensile strength (lb_f)
1	103.9
2	96.7
3	74.0
4	98.5
5	125.4
6	97.4
7	113.3
8	93.6
9	118.0
10	101.1
11	95.5
12	139.3
13	106.6
14	122.6
15	89.4
16	94.4
17	112.9
18	75.9
19	120.7
20	90.1
21	85.6
22	77.4
23	96.0
24	101.5
25	130.6
Average:	102.4
St. Dev:	17.0
St. Dev (%):	16.6

Comprehensive Briquette Evaluations

Sample:	EB-CS-G97
Client:	DOE
Coal:	Eagle Butte - 70% - minus 1 mm
Biomass:	Corn Stover - 30% - minus 3/16"
Chemical:	GP-G97
Target moisture:	18.50%
Date:	9/26/2013
Time:	10:00:00 AM

Comments:
2847.60 g coal; 1336.20 g biomass; 556.20 g water
Roll force: 100 kN; Roll speed: 900 rpm; Roll torque: 1800 N-m
Attritability: 20 briq, 5 min, #4 sieve
Friability: 20 briq, 6 ft, 2 drops, #4 sieve
Elasticity: Hooke's Law (F=-kx), linear portion
Tensile strength: diametrical compression, standing tall
Oven temp: 170-200 °C; Resin temp: 150-160 °C
Drip time: 10 min, flip, 5 min; Cure time: 1 hour

Chemical Dosage Tests

Batch	Initial Mass (g)	Coated Mass (g)	Chemical Mass (g)	Chemical Dosage %
1	490.77	557.53	66.76	13.60
2	493.87	563.13	69.26	14.02
3	496.08	574.09	78.01	15.73
4	495.13	565.75	70.62	14.26
5	495.46	561.14	65.68	13.26
6	494.53	572.54	78.01	15.77
			Average	14.44
			St. Dev:	0.98
			St. Dev (%):	6.77

Water Content Tests

Measurement	Wet Mass (g)	Dry Mass (g)	Water Mass (g)	Water Content --
Feed				0.1760
Briquettes	56.87	50.29	6.58	0.1308

Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake (%)
1	55.81	56.31	0.50	0.90

Dry Density Tests

Measurement	Mass in Air (g)	Mass in Water (g)	Wet Density (g/cm^3)	Dry Density (g/cm^3)
1	11.48	0.91	1.09	0.96
2	11.17	0.91	1.09	0.96
3	11.81	0.94	1.09	0.96
4	11.32	0.94	1.09	0.96
5	10.97	0.63	1.06	0.94
6	11.01	0.91	1.09	0.96
7	11.00	0.55	1.05	0.93
8	11.33	0.97	1.09	0.97
9	11.18	0.75	1.07	0.95
10	11.41	1.09	1.11	0.98
		Average:	1.08	0.96
		St. Dev:	0.02	0.01
		St. Dev (%):	1.48	1.48

Crushing Strength & Elasticity Tests

Measurement	Crushing Strength (lb$_f$)	Crushing force (1) (lb$_f$)	Briquette disp. (1) (in)	Crushing force (2) (lb$_f$)	Briquette disp. (2) (in)	Stiffness constant (lb$_f$/in)
1	290.0	142.8	0.4720	81.4	0.4470	2456
2	292.1	161.9	0.4700	91.3	0.4290	1722
3	251.2	150.7	0.4650	62.2	0.4260	2269
4	247.3	152.6	0.4770	96.7	0.4460	1803
5	282.1	151.1	0.4480	59.3	0.4030	2040
6	383.3	129.0	0.4750	52.3	0.4160	1300
7	297.6	116.9	0.4720	28.7	0.4110	1446
8	303.3	98.6	0.4500	34.9	0.4090	1554
9	259.3	159.1	0.4820	68.1	0.4340	1896
10	283.6	113.7	0.4640	29.8	0.4090	1525
11	284.7	156.7	0.4690	45.9	0.4130	1979
12	316.9	93.5	0.4630	42.4	0.4280	1460
13	338.3	134.0	0.4590	55.6	0.4040	1425
14	260.8	110.8	0.4530	23.0	0.3900	1394
15	314.8	123.7	0.4670	63.0	0.4310	1686
16	272.7	156.2	0.4890	71.3	0.4390	1698
17	277.1	105.2	0.4360	42.0	0.4110	2528
18	291.9	83.8	0.4370	28.7	0.4170	2755
19	299.6	91.6	0.4420	49.4	0.4090	1279
20	297.6	170.5	0.4760	20.4	0.3950	1853
21	262.4	159.1	0.4830	35.5	0.4280	2247
22	251.2	115.5	0.4660	36.7	0.4270	2021
23	214.2	109.4	0.4470	30.0	0.3940	1498
24	231.1	143.5	0.4510	40.9	0.3810	1466
25	334.6	181.5	0.4940	78.5	0.4370	1807
Average:	285.5					1804
St. Dev:	36.2					402
St. Dev (%):	12.7					22.3

Comprehensive Briquette Evaluations

Sample:	EB-CS-G97
Client:	DOE
Coal:	Eagle Butte - 70% - minus 1 mm
Biomass:	Corn Stover - 30% - minus 3/16"
Chemical:	GP-G97
Target moisture:	18.50%
Date:	9/26/2013
Time:	10:00:00 AM

Comments:
2847.60 g coal; 1336.20 g biomass; 556.20 g water
Roll force: 100 kN; Roll speed: 900 rpm; Roll torque: 1800 N-m
Attritability: 20 briq, 5 min, #4 sieve
Friability: 20 briq, 6 ft, 2 drops, #4 sieve
Elasticity: Hooke's Law (F=-kx), linear portion
Tensile strength: diametrical compression, standing tall
Oven temp: 170-200 °C; Resin temp: 150-160 °C
Drip time: 10 min, flip, 5 min; Cure time: 1 hour

Mechanical Durability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	226.28	220.91	97.63
2	221.81	218.97	98.72
3	220.11	216.21	98.23
Total			94.67

Tumbled Water Uptake Tests

Measurement	Dry Mass (g)	Wet Mass (g)	Water Mass (g)	Water Uptake (%)
1	220.91	221.81	0.90	0.41
2	218.97	220.11	1.14	0.52
Total				0.93

Friability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	225.50	224.43	99.53

Attritability Tests

Measurement	Initial Mass of Briquettes (g)	Mass Retained on Screen (g)	Mass Retained on Screen (%)
1	227.24	226.08	99.49

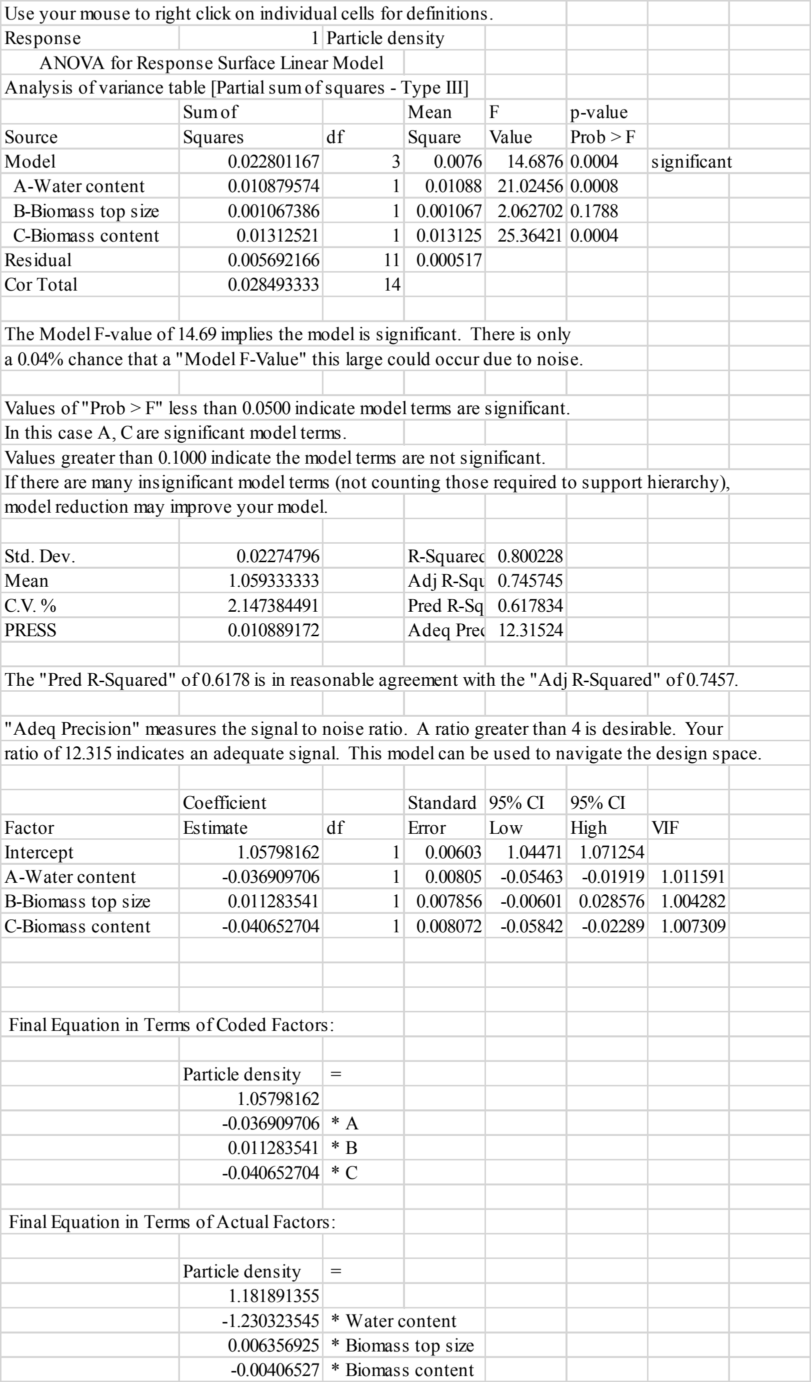
Tensile Strength Test

Measurement	Tensile strength (lb_f)
1	83.4
2	151.0
3	127.8
4	134.4
5	74.8
6	92.4
7	101.8
8	150.4
9	79.4
10	177.7
11	148.4
12	174.6
13	95.2
14	48.5
15	86.8
16	139.6
17	98.6
18	81.6
19	128.7
20	77.9
21	74.8
22	149.3
23	85.1
24	145.0
25	93.9
Average:	112.0
St. Dev:	35.5
St. Dev (%):	31.7

Appendix B. Mathematical Models

B.1 EM-SG Model

B.1.1 Particle Density Model



Use your mouse to right click on individual cells for definitions.

Response	1	Particle density

ANOVA for Response Surface Linear Model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.022801167	3	0.0076	14.6876	0.0004	significant
A-Water content	0.010879574	1	0.01088	21.02456	0.0008	
B-Biomass top size	0.001067386	1	0.001067	2.062702	0.1788	
C-Biomass content	0.01312521	1	0.013125	25.36421	0.0004	
Residual	0.005692166	11	0.000517			
Cor Total	0.028493333	14				

The Model F-value of 14.69 implies the model is significant. There is only
a 0.04% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant.
In this case A, C are significant model terms.
Values greater than 0.1000 indicate the model terms are not significant.
If there are many insignificant model terms (not counting those required to support hierarchy),
model reduction may improve your model.

Std. Dev.	0.02274796	R-Squarec	0.800228
Mean	1.059333333	Adj R-Squ	0.745745
C.V. %	2.147384491	Pred R-Sq	0.617834
PRESS	0.010889172	Adeq Prec	12.31524

The "Pred R-Squared" of 0.6178 is in reasonable agreement with the "Adj R-Squared" of 0.7457.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your
ratio of 12.315 indicates an adequate signal. This model can be used to navigate the design space.

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	1.05798162	1	0.00603	1.04471	1.071254	
A-Water content	-0.036909706	1	0.00805	-0.05463	-0.01919	1.011591
B-Biomass top size	0.011283541	1	0.007856	-0.00601	0.028576	1.004282
C-Biomass content	-0.040652704	1	0.008072	-0.05842	-0.02289	1.007309

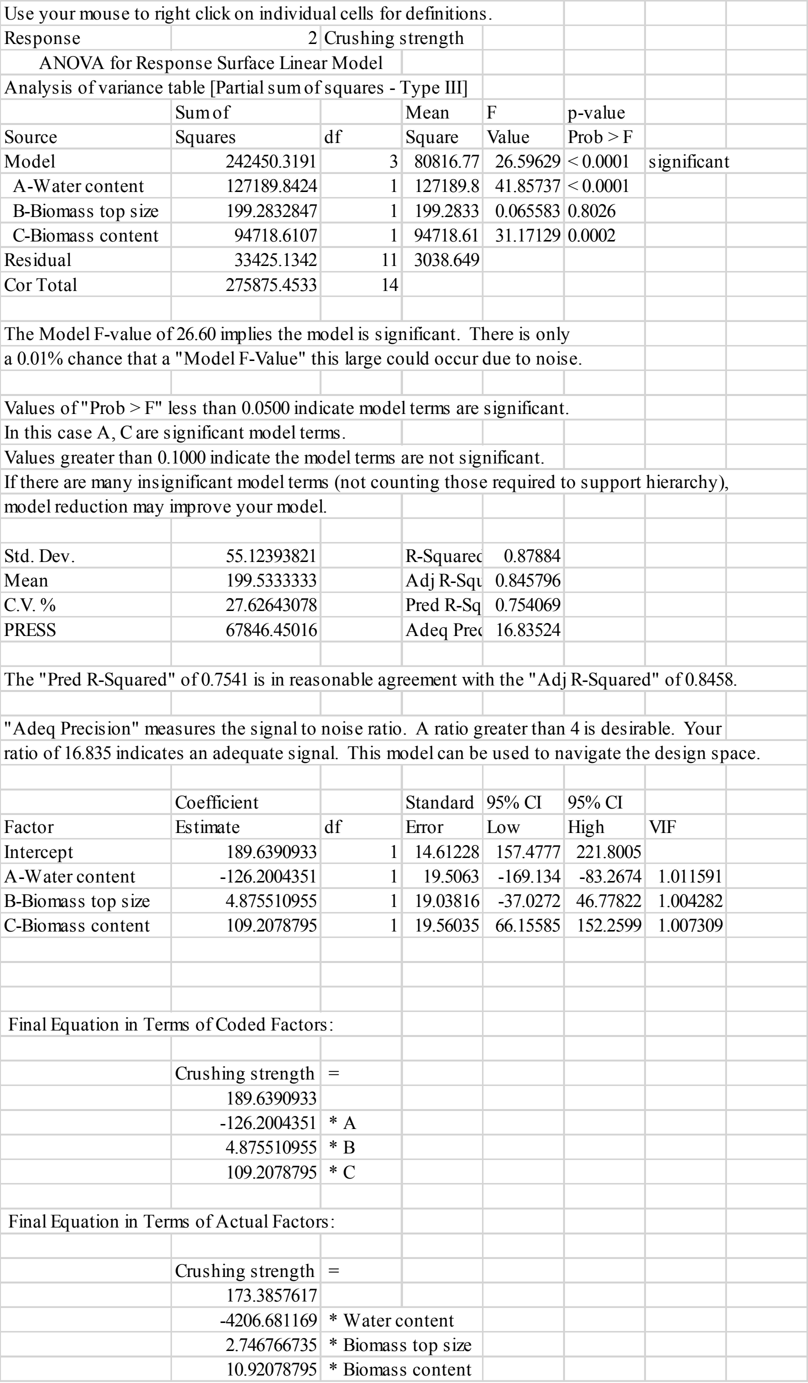
Final Equation in Terms of Coded Factors:

Particle density	=
1.05798162	
-0.036909706	* A
0.011283541	* B
-0.040652704	* C

Final Equation in Terms of Actual Factors:

Particle density	=
1.181891355	
-1.230323545	* Water content
0.006356925	* Biomass top size
-0.00406527	* Biomass content

B.1.2 Crushing Strength Model

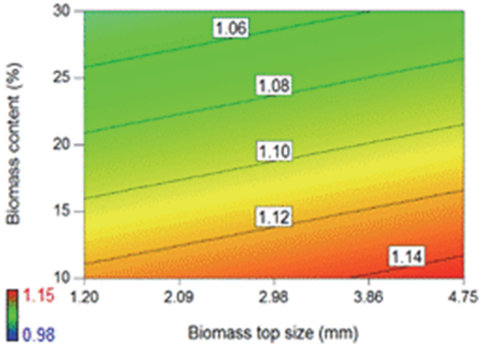
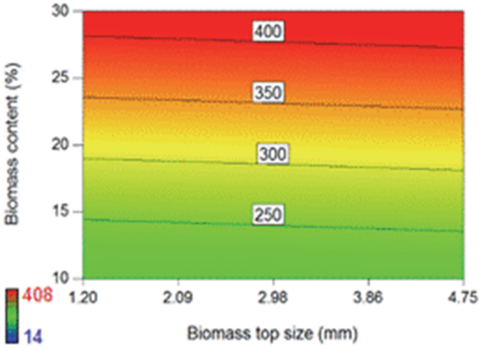
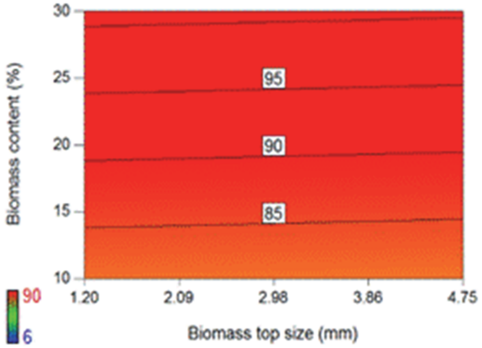
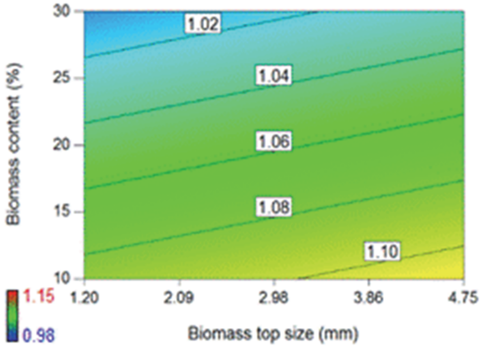
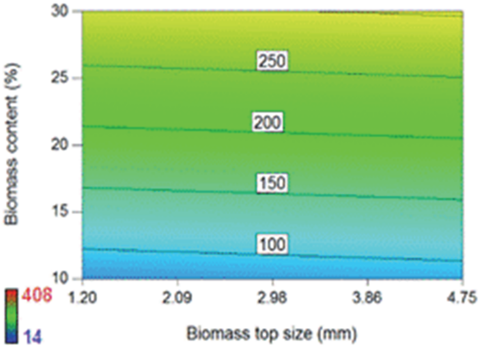
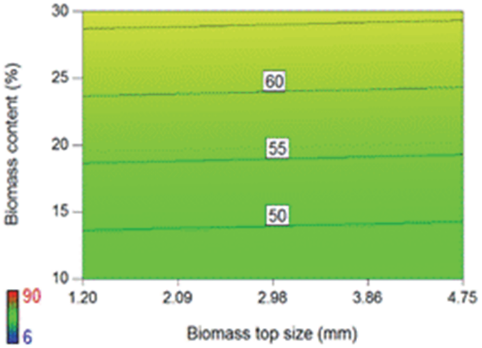
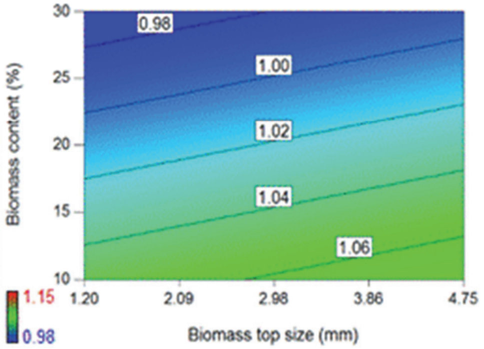
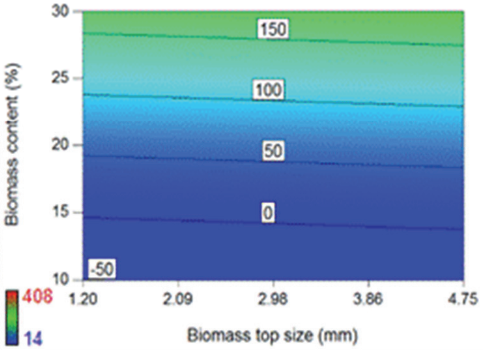
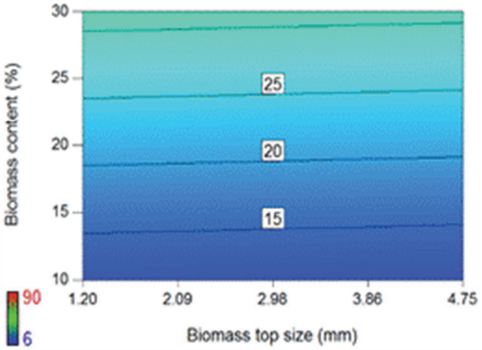


Use your mouse to right click on individual cells for definitions.							
Response	2	Crushing strength					
ANOVA for Response Surface Linear Model							
Analysis of variance table [Partial sum of squares - Type III]							
	Sum of		Mean	F	p-value		
Source	Squares	df	Square	Value	Prob > F		
Model	242450.3191	3	80816.77	26.59629	< 0.0001	significant	
A-Water content	127189.8424	1	127189.8	41.85737	< 0.0001		
B-Biomass top size	199.2832847	1	199.2833	0.065583	0.8026		
C-Biomass content	94718.6107	1	94718.61	31.17129	0.0002		
Residual	33425.1342	11	3038.649				
Cor Total	275875.4533	14					
The Model F-value of 26.60 implies the model is significant. There is only							
a 0.01% chance that a "Model F-Value" this large could occur due to noise.							
Values of "Prob > F" less than 0.0500 indicate model terms are significant.							
In this case A, C are significant model terms.							
Values greater than 0.1000 indicate the model terms are not significant.							
If there are many insignificant model terms (not counting those required to support hierarchy),							
model reduction may improve your model.							
Std. Dev.	55.12393821		R-Squarec	0.87884			
Mean	199.5333333		Adj R-Squ	0.845796			
C.V. %	27.62643078		Pred R-Sq	0.754069			
PRESS	67846.45016		Adeq Prec	16.83524			
The "Pred R-Squared" of 0.7541 is in reasonable agreement with the "Adj R-Squared" of 0.8458.							
"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your							
ratio of 16.835 indicates an adequate signal. This model can be used to navigate the design space.							
	Coefficient		Standard	95% CI	95% CI		
Factor	Estimate	df	Error	Low	High	VIF	
Intercept	189.6390933	1	14.61228	157.4777	221.8005		
A-Water content	-126.2004351	1	19.5063	-169.134	-83.2674	1.011591	
B-Biomass top size	4.875510955	1	19.03816	-37.0272	46.77822	1.004282	
C-Biomass content	109.2078795	1	19.56035	66.15585	152.2599	1.007309	
Final Equation in Terms of Coded Factors:							
	Crushing strength	=					
	189.6390933						
	-126.2004351	* A					
	4.875510955	* B					
	109.2078795	* C					
Final Equation in Terms of Actual Factors:							
	Crushing strength	=					
	173.3857617						
	-4206.681169	* Water content					
	2.746766735	* Biomass top size					
	10.92078795	* Biomass content					

B.1.3 Mechanical Durability Model

Response	3	Mechanical durability					
ANOVA for Response Surface Linear Model							
Analysis of variance table [Partial sum of squares - Type III]							
	Sum of		Mean	F	p-value		
Source	Squares	df	Square	Value	Prob > F		
Model	11077.63789	3	3692.546	32.6465	< 0.0001	significant	
A-Water content	9687.306228	1	9687.306	85.64731	< 0.0001		
B-Biomass top size	0.870660776	1	0.870661	0.007698	0.9317		
C-Biomass content	785.8871181	1	785.8871	6.948177	0.0232		
Residual	1244.176484	11	113.107				
Cor Total	12321.81437	14					
The Model F-value of 32.65 implies the model is significant. There is only							
a 0.01% chance that a "Model F-Value" this large could occur due to noise.							
Values of "Prob > F" less than 0.0500 indicate model terms are significant.							
In this case A, C are significant model terms.							
Values greater than 0.1000 indicate the model terms are not significant.							
If there are many insignificant model terms (not counting those required to support hierarchy),							
model reduction may improve your model.							
Std. Dev.	10.63517527		R-Squarec	0.899027			
Mean	59.01533333		Adj R-Squ	0.871488			
C.V. %	18.02103737		Pred R-Sq	0.825413			
PRESS	2151.232328		Adeq Prec	16.7288			
The "Pred R-Squared" of 0.8254 is in reasonable agreement with the "Adj R-Squared" of 0.8715.							
"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your							
ratio of 16.729 indicates an adequate signal. This model can be used to navigate the design space.							
	Coefficient		Standard	95% CI	95% CI		
Factor	Estimate	df	Error	Low	High	VIF	
Intercept	56.02383857	1	2.819177	49.81887	62.22881		
A-Water content	-34.82861077	1	3.763391	-43.1118	-26.5454	1.011591	
B-Biomass top size	-0.322262068	1	3.673071	-8.40664	7.762113	1.004282	
C-Biomass content	9.947556164	1	3.773818	1.641438	18.25367	1.007309	
Final Equation in Terms of Coded Factors:							
	Mechanical durability	=					
	56.02383857						
	-34.82861077	* A					
	-0.322262068	* B					
	9.947556164	* C					
Final Equation in Terms of Actual Factors:							
	Mechanical durability	=					
	94.71654024						
	-1160.953692	* Water content					
	-0.181556095	* Biomass top size					
	0.994755616	* Biomass content					

B.1.4 Model Graphs

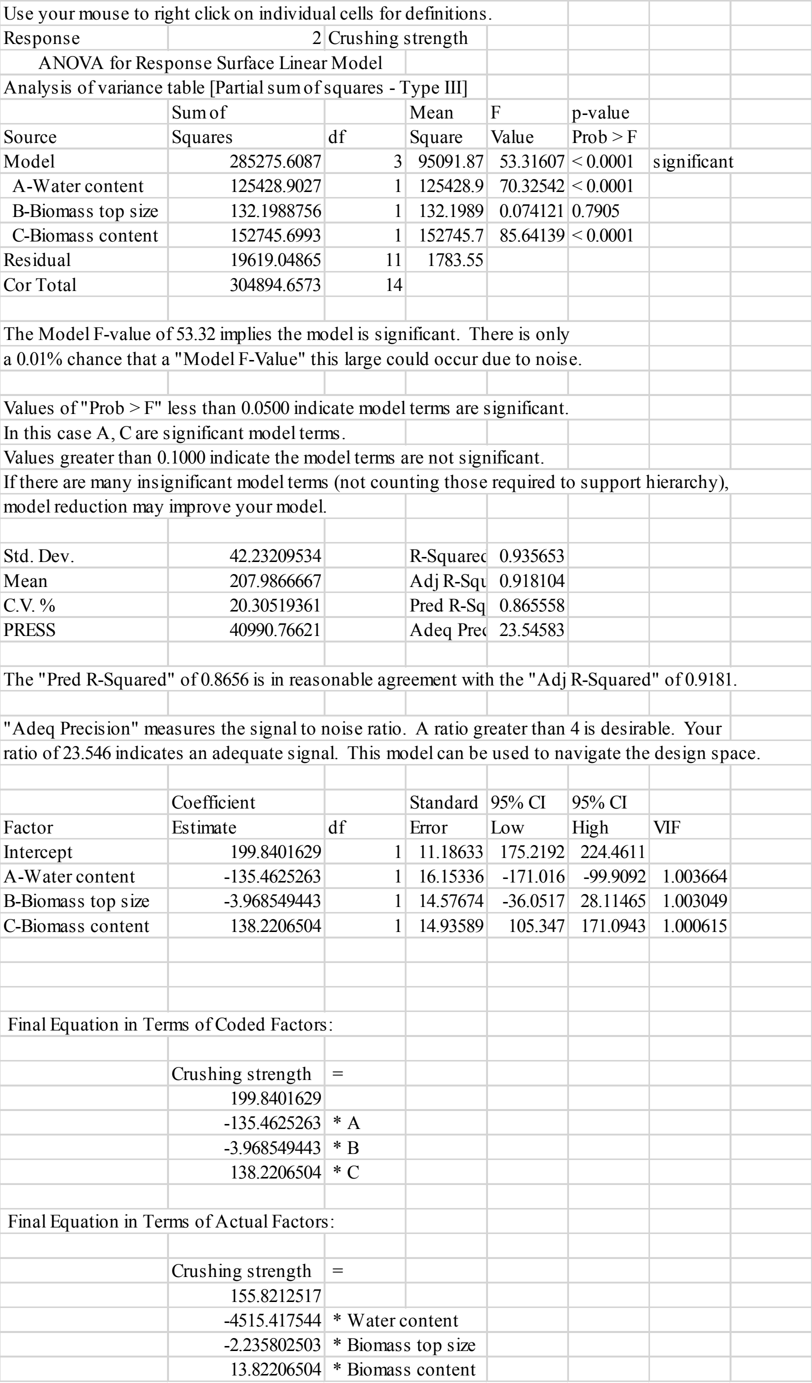
Water Content	Particle Density (g/cm^3)	Crushing Strength (lb$_f$)	Mechanical Durability (%)
0.02			
0.05			
0.08			

B.2 EM-MC Model

B.2.1 Particle Density Model

Response	1	Particle density					
ANOVA for Response Surface Linear Model							
Analysis of variance table [Partial sum of squares - Type III]							
	Sum of		Mean	F	p-value		
Source	Squares	df	Square	Value	Prob > F		
Model	0.020546812	3	0.006849	29.5848	< 0.0001	significant	
A-Water content	0.005146391	1	0.005146	22.23045	0.0006		
B-Biomass top size	2.92358E-05	1	2.92E-05	0.126288	0.7290		
C-Biomass content	0.015746156	1	0.015746	68.01739	< 0.0001		
Residual	0.002546521	11	0.000232				
Cor Total	0.023093333	14					
The Model F-value of 29.58 implies the model is significant. There is only							
a 0.01% chance that a "Model F-Value" this large could occur due to noise.							
Values of "Prob > F" less than 0.0500 indicate model terms are significant.							
In this case A, C are significant model terms.							
Values greater than 0.1000 indicate the model terms are not significant.							
If there are many insignificant model terms (not counting those required to support hierarchy),							
model reduction may improve your model.							
Std. Dev.	0.015215187		R-Squarec	0.889729			
Mean	1.097333333		Adj R-Squ	0.859655			
C.V. %	1.386560202		Pred R-Sq	0.786177			
PRESS	0.004937874		Adeq Prec	17.81544			
The "Pred R-Squared" of 0.7862 is in reasonable agreement with the "Adj R-Squared" of 0.8597.							
"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your							
ratio of 17.815 indicates an adequate signal. This model can be used to navigate the design space.							
	Coefficient		Standard	95% CI	95% CI		
Factor	Estimate	df	Error	Low	High	VIF	
Intercept	1.096100877	1	0.00403	1.087231	1.104971		
A-Water content	-0.02743922	1	0.00582	-0.04025	-0.01463	1.003664	
B-Biomass top size	0.001866274	1	0.005252	-0.00969	0.013425	1.003049	
C-Biomass content	-0.044378815	1	0.005381	-0.05622	-0.03254	1.000615	
Final Equation in Terms of Coded Factors:							
	Particle density	=					
	1.096100877						
	-0.02743922	* A					
	0.001866274	* B					
	-0.044378815	* C					
Final Equation in Terms of Actual Factors:							
	Particle density	=					
	1.227462562						
	-0.914640679	* Water content					
	0.001051422	* Biomass top size					
	-0.004437882	* Biomass content					

B.2.2 Crushing Strength Model

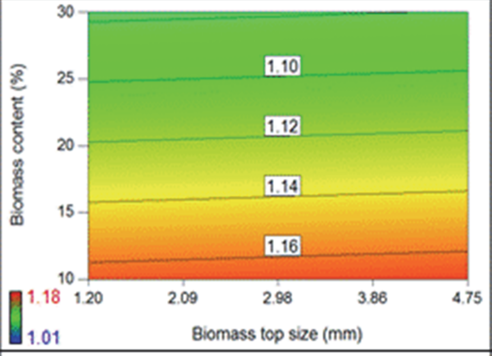
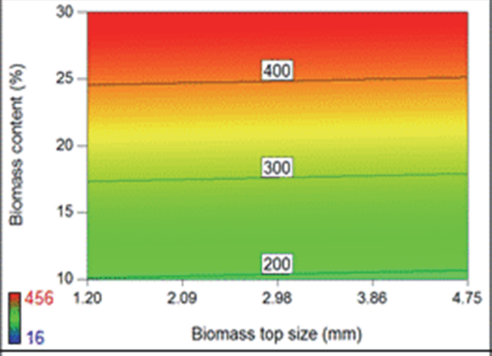
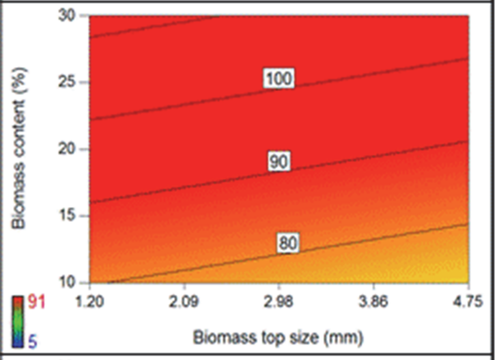
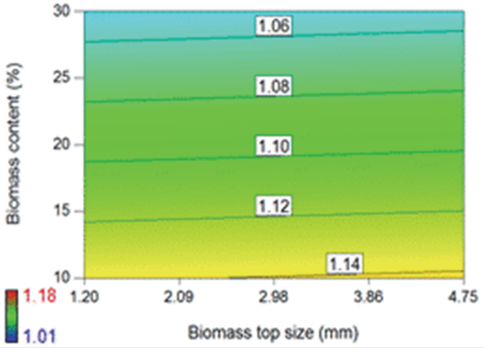
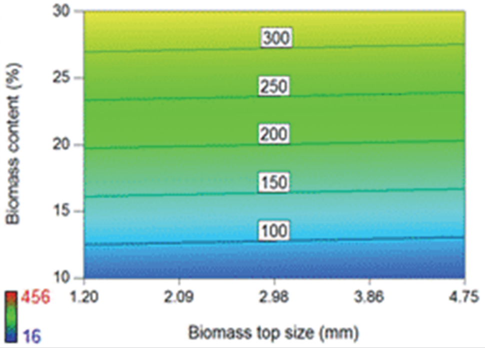
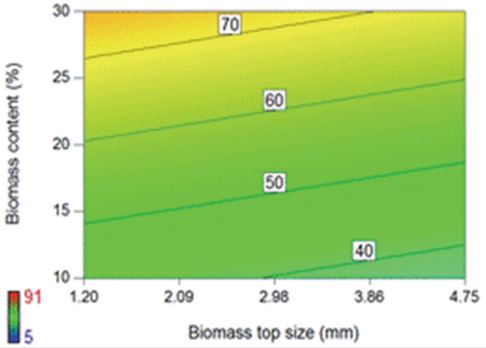
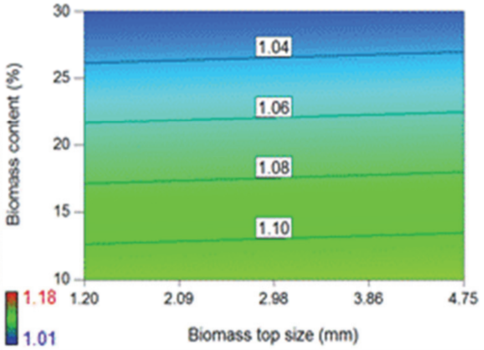
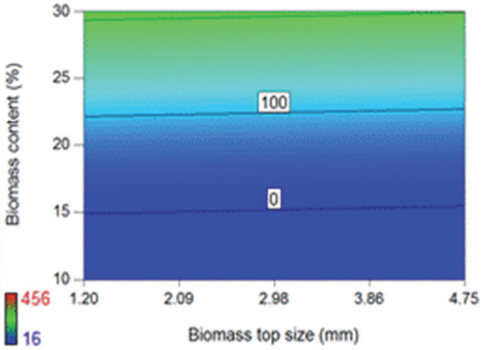
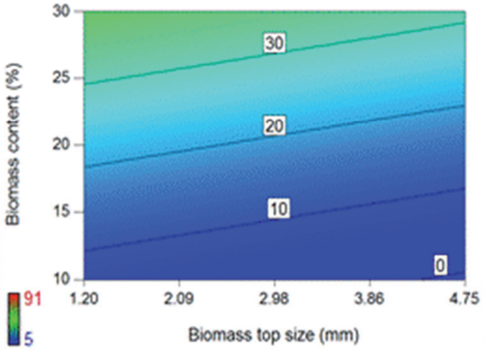


Use your mouse to right click on individual cells for definitions.							
Response	2	Crushing strength					
ANOVA for Response Surface Linear Model							
Analysis of variance table [Partial sum of squares - Type III]							
	Sum of		Mean	F	p-value		
Source	Squares	df	Square	Value	Prob > F		
Model	285275.6087	3	95091.87	53.31607	< 0.0001	significant	
A-Water content	125428.9027	1	125428.9	70.32542	< 0.0001		
B-Biomass top size	132.1988756	1	132.1989	0.074121	0.7905		
C-Biomass content	152745.6993	1	152745.7	85.64139	< 0.0001		
Residual	19619.04865	11	1783.55				
Cor Total	304894.6573	14					
The Model F-value of 53.32 implies the model is significant. There is only							
a 0.01% chance that a "Model F-Value" this large could occur due to noise.							
Values of "Prob > F" less than 0.0500 indicate model terms are significant.							
In this case A, C are significant model terms.							
Values greater than 0.1000 indicate the model terms are not significant.							
If there are many insignificant model terms (not counting those required to support hierarchy),							
model reduction may improve your model.							
Std. Dev.	42.23209534		R-Squarec	0.935653			
Mean	207.9866667		Adj R-Squ	0.918104			
C.V. %	20.30519361		Pred R-Sq	0.865558			
PRESS	40990.76621		Adeq Prec	23.54583			
The "Pred R-Squared" of 0.8656 is in reasonable agreement with the "Adj R-Squared" of 0.9181.							
"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your							
ratio of 23.546 indicates an adequate signal. This model can be used to navigate the design space.							
	Coefficient		Standard	95% CI	95% CI		
Factor	Estimate	df	Error	Low	High	VIF	
Intercept	199.8401629	1	11.18633	175.2192	224.4611		
A-Water content	-135.4625263	1	16.15336	-171.016	-99.9092	1.003664	
B-Biomass top size	-3.968549443	1	14.57674	-36.0517	28.11465	1.003049	
C-Biomass content	138.2206504	1	14.93589	105.347	171.0943	1.000615	
Final Equation in Terms of Coded Factors:							
	Crushing strength	=					
	199.8401629						
	-135.4625263	* A					
	-3.968549443	* B					
	138.2206504	* C					
Final Equation in Terms of Actual Factors:							
	Crushing strength	=					
	155.8212517						
	-4515.417544	* Water content					
	-2.235802503	* Biomass top size					
	13.82206504	* Biomass content					

B.2.3 Mechanical Durability Model

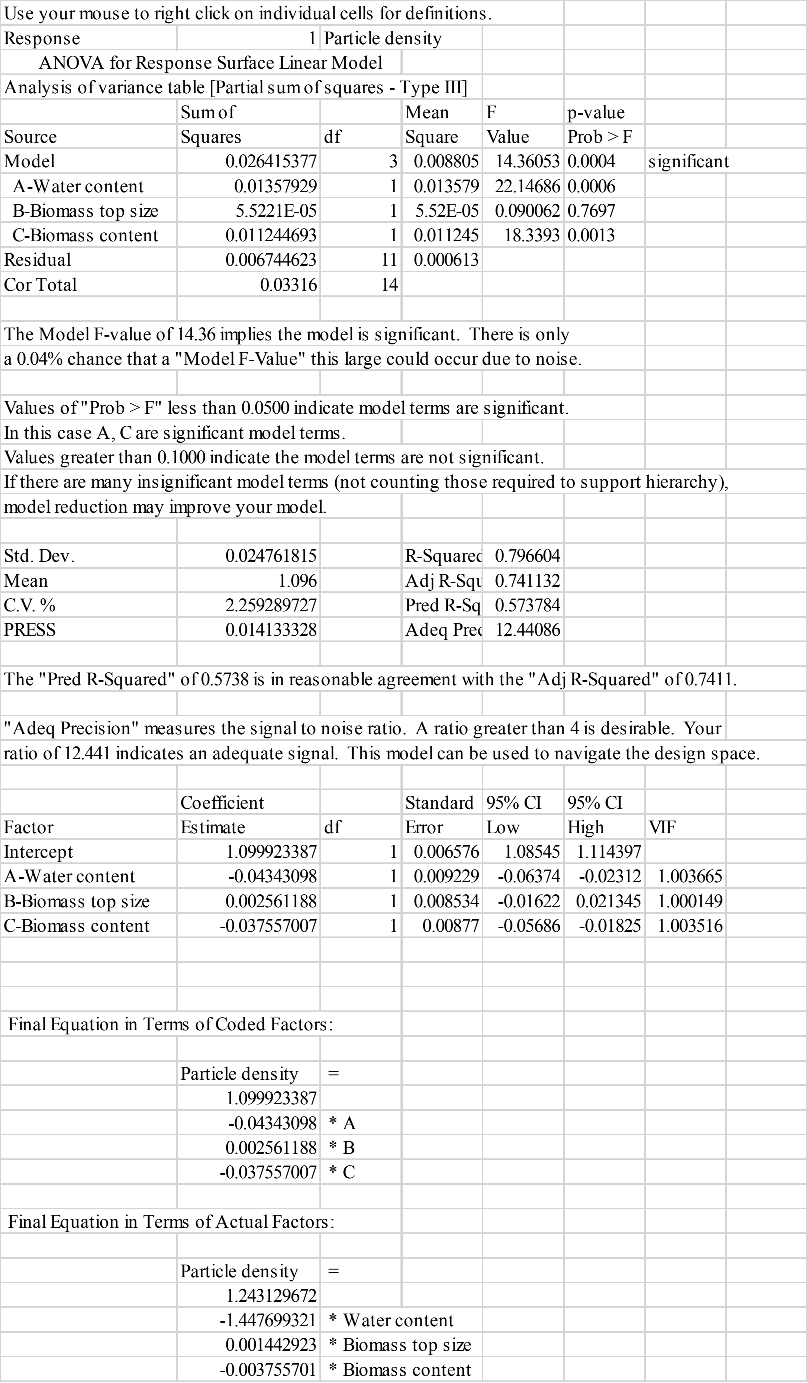
Use your mouse to right click on individual cells for definitions.							
Response	3	Mechanical durability					
ANOVA for Response Surface Linear Model							
Analysis of variance table [Partial sum of squares - Type III]							
	Sum of		Mean	F	p-value		
Source	Squares	df	Square	Value	Prob > F		
Model	11957.08044	3	3985.693	32.08396	< 0.0001	significant	
A-Water content	9625.412059	1	9625.412	77.48246	< 0.0001		
B-Biomass top size	116.0219322	1	116.0219	0.933951	0.3546		
C-Biomass content	2074.024161	1	2074.024	16.69544	0.0018		
Residual	1366.496804	11	124.227				
Cor Total	13323.57724	14					
The Model F-value of 32.08 implies the model is significant. There is only							
a 0.01% chance that a "Model F-Value" this large could occur due to noise.							
Values of "Prob > F" less than 0.0500 indicate model terms are significant.							
In this case A, C are significant model terms.							
Values greater than 0.1000 indicate the model terms are not significant.							
If there are many insignificant model terms (not counting those required to support hierarchy),							
model reduction may improve your model.							
Std. Dev.	11.14571587		R-Squarec	0.897438			
Mean	58.512		Adj R-Squ	0.869466			
C.V. %	19.04859835		Pred R-Sq	0.811102			
PRESS	2516.793937		Adeq Prec	17.00645			
The "Pred R-Squared" of 0.8111 is in reasonable agreement with the "Adj R-Squared" of 0.8695.							
"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your							
ratio of 17.006 indicates an adequate signal. This model can be used to navigate the design space.							
	Coefficient		Standard	95% CI	95% CI		
Factor	Estimate	df	Error	Low	High	VIF	
Intercept	55.84564782	1	2.952248	49.34779	62.3435		
A-Water content	-37.52580561	1	4.263128	-46.9089	-28.1427	1.003664	
B-Biomass top size	-3.717816595	1	3.847033	-12.1851	4.749445	1.003049	
C-Biomass content	16.10628362	1	3.941817	7.430404	24.78216	1.000615	
Final Equation in Terms of Coded Factors:							
	Mechanical durability	=					
	55.84564782						
	-37.52580561	* A					
	-3.717816595	* B					
	16.10628362	* C					
Final Equation in Terms of Actual Factors:							
	Mechanical durability	=					
	92.40735999						
	-1250.860187	* Water content					
	-2.094544561	* Biomass top size					
	1.610628362	* Biomass content					

B.2.4 Model Graphs

Water Content	Particle Density (g/cm^3)	Crushing Strength (lb$_f$)	Mechanical Durability (%)
0.02			
0.05			
0.08			

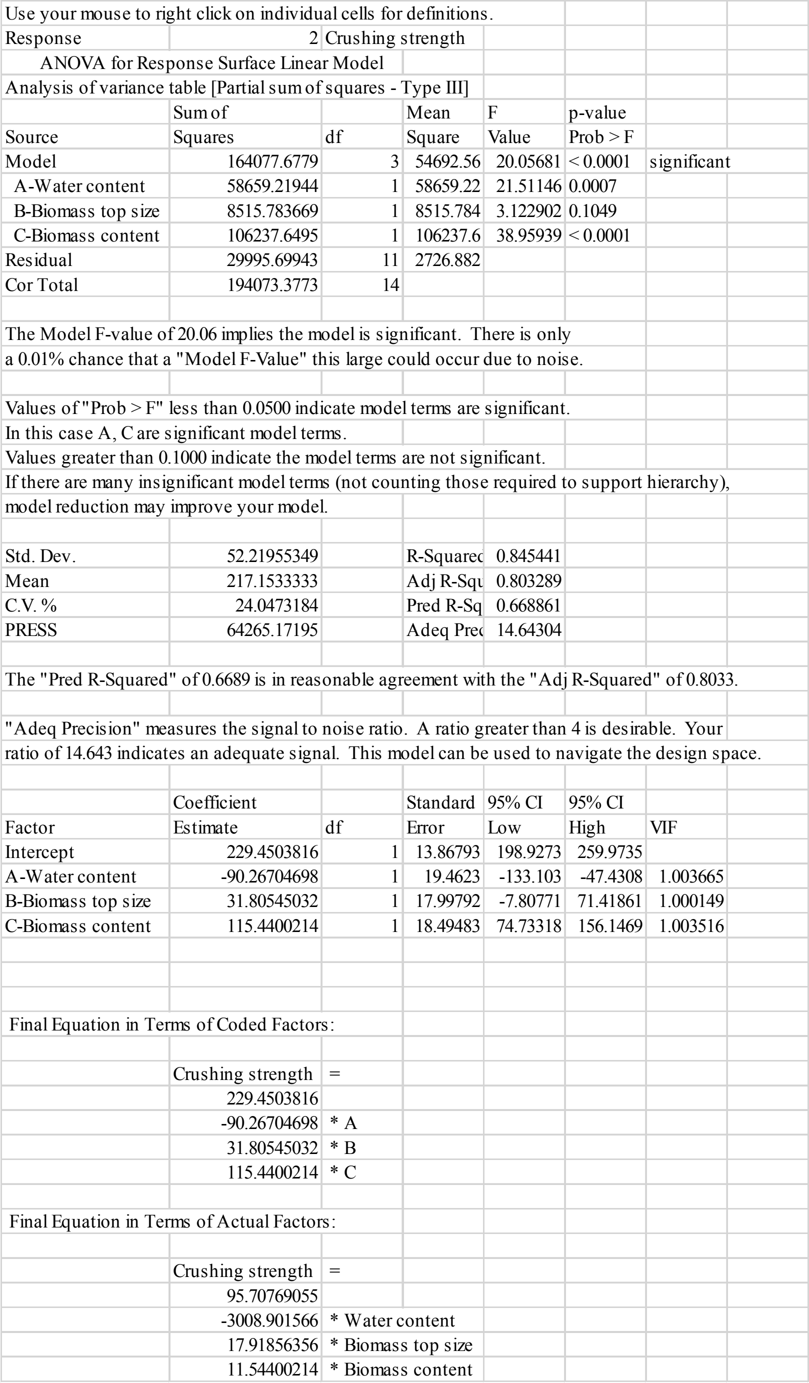
B.3 EM-WS Model

B.3.1 Particle Density Model



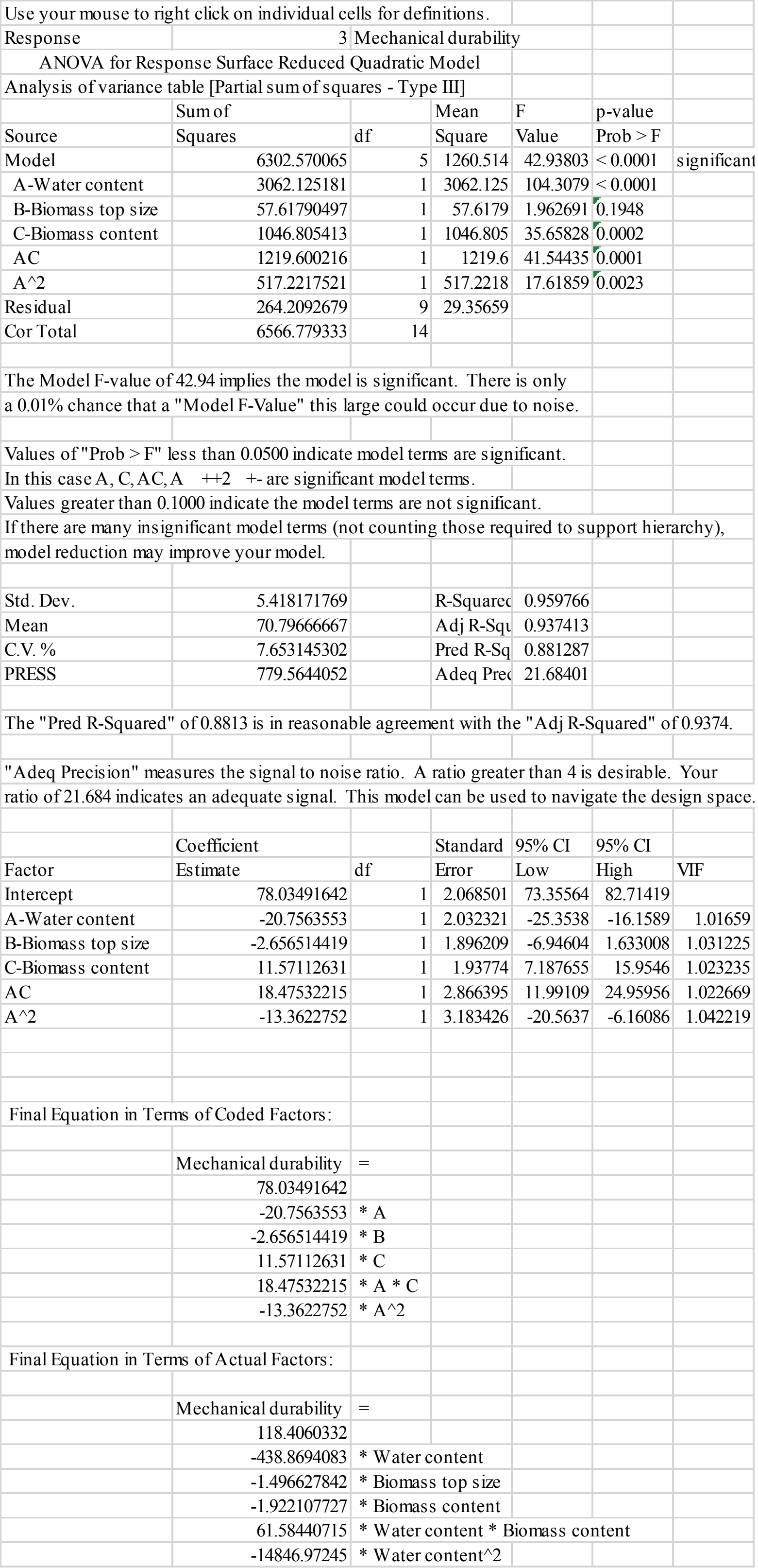
Use your mouse to right click on individual cells for definitions.							
Response	1	Particle density					
ANOVA for Response Surface Linear Model							
Analysis of variance table [Partial sum of squares - Type III]							
	Sum of		Mean	F	p-value		
Source	Squares	df	Square	Value	Prob > F		
Model	0.026415377	3	0.008805	14.36053	0.0004	significant	
A-Water content	0.01357929	1	0.013579	22.14686	0.0006		
B-Biomass top size	5.5221E-05	1	5.52E-05	0.090062	0.7697		
C-Biomass content	0.011244693	1	0.011245	18.3393	0.0013		
Residual	0.006744623	11	0.000613				
Cor Total	0.03316	14					
The Model F-value of 14.36 implies the model is significant. There is only							
a 0.04% chance that a "Model F-Value" this large could occur due to noise.							
Values of "Prob > F" less than 0.0500 indicate model terms are significant.							
In this case A, C are significant model terms.							
Values greater than 0.1000 indicate the model terms are not significant.							
If there are many insignificant model terms (not counting those required to support hierarchy),							
model reduction may improve your model.							
Std. Dev.	0.024761815		R-Squarec	0.796604			
Mean	1.096		Adj R-Squ	0.741132			
C.V. %	2.259289727		Pred R-Sq	0.573784			
PRESS	0.014133328		Adeq Prec	12.44086			
The "Pred R-Squared" of 0.5738 is in reasonable agreement with the "Adj R-Squared" of 0.7411.							
"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your							
ratio of 12.441 indicates an adequate signal. This model can be used to navigate the design space.							
	Coefficient		Standard	95% CI	95% CI		
Factor	Estimate	df	Error	Low	High	VIF	
Intercept	1.099923387	1	0.006576	1.08545	1.114397		
A-Water content	-0.04343098	1	0.009229	-0.06374	-0.02312	1.003665	
B-Biomass top size	0.002561188	1	0.008534	-0.01622	0.021345	1.000149	
C-Biomass content	-0.037557007	1	0.00877	-0.05686	-0.01825	1.003516	
Final Equation in Terms of Coded Factors:							
	Particle density	=					
	1.099923387						
	-0.04343098	* A					
	0.002561188	* B					
	-0.037557007	* C					
Final Equation in Terms of Actual Factors:							
	Particle density	=					
	1.243129672						
	-1.447699321	* Water content					
	0.001442923	* Biomass top size					
	-0.003755701	* Biomass content					

B.3.2 Crushing Strength Model



Use your mouse to right click on individual cells for definitions.							
Response	2	Crushing strength					
ANOVA for Response Surface Linear Model							
Analysis of variance table [Partial sum of squares - Type III]							
	Sum of		Mean	F	p-value		
Source	Squares	df	Square	Value	Prob > F		
Model	164077.6779	3	54692.56	20.05681	< 0.0001	significant	
A-Water content	58659.21944	1	58659.22	21.51146	0.0007		
B-Biomass top size	8515.783669	1	8515.784	3.122902	0.1049		
C-Biomass content	106237.6495	1	106237.6	38.95939	< 0.0001		
Residual	29995.69943	11	2726.882				
Cor Total	194073.3773	14					
The Model F-value of 20.06 implies the model is significant. There is only							
a 0.01% chance that a "Model F-Value" this large could occur due to noise.							
Values of "Prob > F" less than 0.0500 indicate model terms are significant.							
In this case A, C are significant model terms.							
Values greater than 0.1000 indicate the model terms are not significant.							
If there are many insignificant model terms (not counting those required to support hierarchy),							
model reduction may improve your model.							
Std. Dev.	52.21955349		R-Squarec	0.845441			
Mean	217.1533333		Adj R-Squ	0.803289			
C.V. %	24.0473184		Pred R-Sq	0.668861			
PRESS	64265.17195		Adeq Prec	14.64304			
The "Pred R-Squared" of 0.6689 is in reasonable agreement with the "Adj R-Squared" of 0.8033.							
"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your							
ratio of 14.643 indicates an adequate signal. This model can be used to navigate the design space.							
	Coefficient		Standard	95% CI	95% CI		
Factor	Estimate	df	Error	Low	High	VIF	
Intercept	229.4503816	1	13.86793	198.9273	259.9735		
A-Water content	-90.26704698	1	19.4623	-133.103	-47.4308	1.003665	
B-Biomass top size	31.80545032	1	17.99792	-7.80771	71.41861	1.000149	
C-Biomass content	115.4400214	1	18.49483	74.73318	156.1469	1.003516	
Final Equation in Terms of Coded Factors:							
	Crushing strength	=					
	229.4503816						
	-90.26704698	* A					
	31.80545032	* B					
	115.4400214	* C					
Final Equation in Terms of Actual Factors:							
	Crushing strength	=					
	95.70769055						
	-3008.901566	* Water content					
	17.91856356	* Biomass top size					
	11.54400214	* Biomass content					

B.3.3 Mechanical Durability Model



Use your mouse to right click on individual cells for definitions.

Response 3 Mechanical durability

ANOVA for Response Surface Reduced Quadratic Model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	6302.570065	5	1260.514	42.93803	< 0.0001	significant
A-Water content	3062.125181	1	3062.125	104.3079	< 0.0001	
B-Biomass top size	57.61790497	1	57.6179	1.962691	0.1948	
C-Biomass content	1046.805413	1	1046.805	35.65828	0.0002	
AC	1219.600216	1	1219.6	41.54435	0.0001	
A^2	517.2217521	1	517.2218	17.61859	0.0023	
Residual	264.2092679	9	29.35659			
Cor Total	6566.779333	14				

The Model F-value of 42.94 implies the model is significant. There is only
a 0.01% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant.
In this case A, C, AC, A ++2 +- are significant model terms.
Values greater than 0.1000 indicate the model terms are not significant.
If there are many insignificant model terms (not counting those required to support hierarchy),
model reduction may improve your model.

Std. Dev.	5.418171769	R-Squarec	0.959766
Mean	70.79666667	Adj R-Squ	0.937413
C.V. %	7.653145302	Pred R-Sq	0.881287
PRESS	779.5644052	Adeq Prec	21.68401

The "Pred R-Squared" of 0.8813 is in reasonable agreement with the "Adj R-Squared" of 0.9374.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your
ratio of 21.684 indicates an adequate signal. This model can be used to navigate the design space.

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	78.03491642	1	2.068501	73.35564	82.71419	
A-Water content	-20.7563553	1	2.032321	-25.3538	-16.1589	1.01659
B-Biomass top size	-2.656514419	1	1.896209	-6.94604	1.633008	1.031225
C-Biomass content	11.57112631	1	1.93774	7.187655	15.9546	1.023235
AC	18.47532215	1	2.866395	11.99109	24.95956	1.022669
A^2	-13.3622752	1	3.183426	-20.5637	-6.16086	1.042219

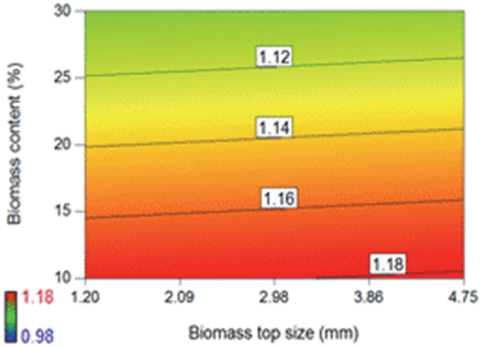
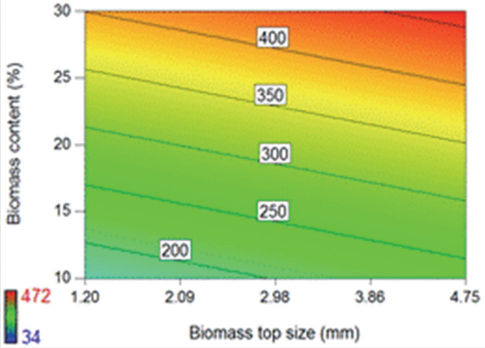
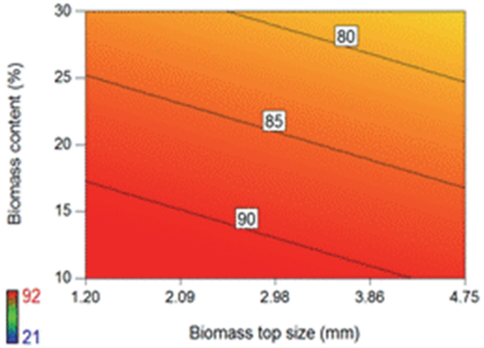
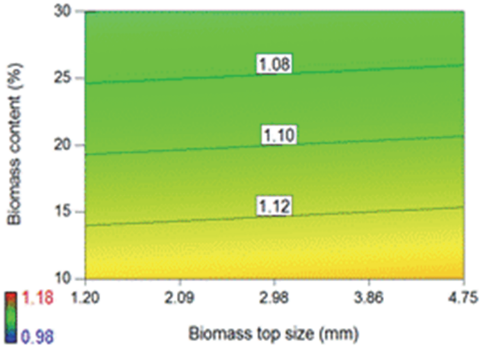
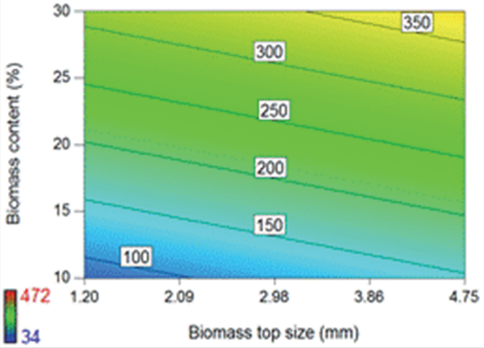
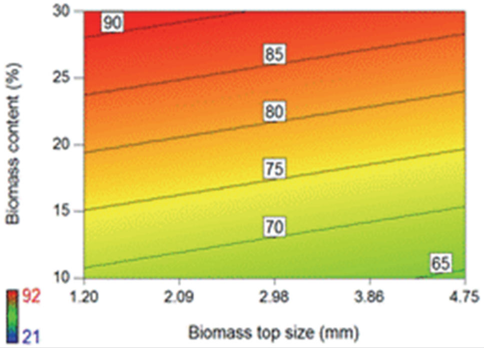
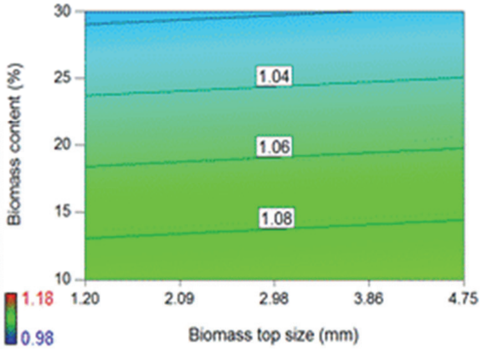
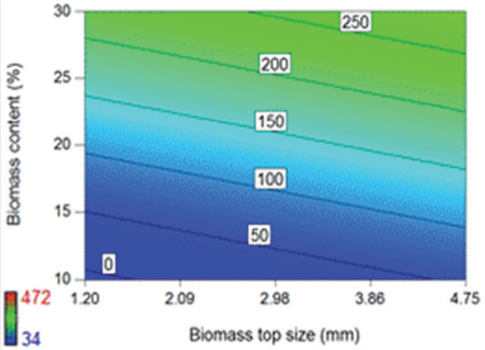
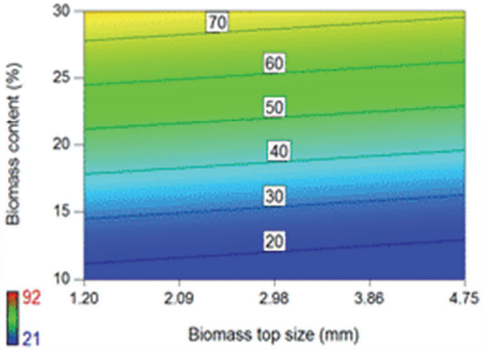
Final Equation in Terms of Coded Factors:

Mechanical durability =
78.03491642
-20.7563553 * A
-2.656514419 * B
11.57112631 * C
18.47532215 * A * C
-13.3622752 * A^2

Final Equation in Terms of Actual Factors:

Mechanical durability =
118.4060332
-438.8694083 * Water content
-1.496627842 * Biomass top size
-1.922107727 * Biomass content
61.58440715 * Water content * Biomass content
-14846.97245 * Water content^2

B.3.4 Model Graphs

Water Content	Particle Density (g/cm^3)	Crushing Strength (lb$_f$)	Mechanical Durability (%)
0.02			
0.05			
0.08			

B.4 EM-SD Model

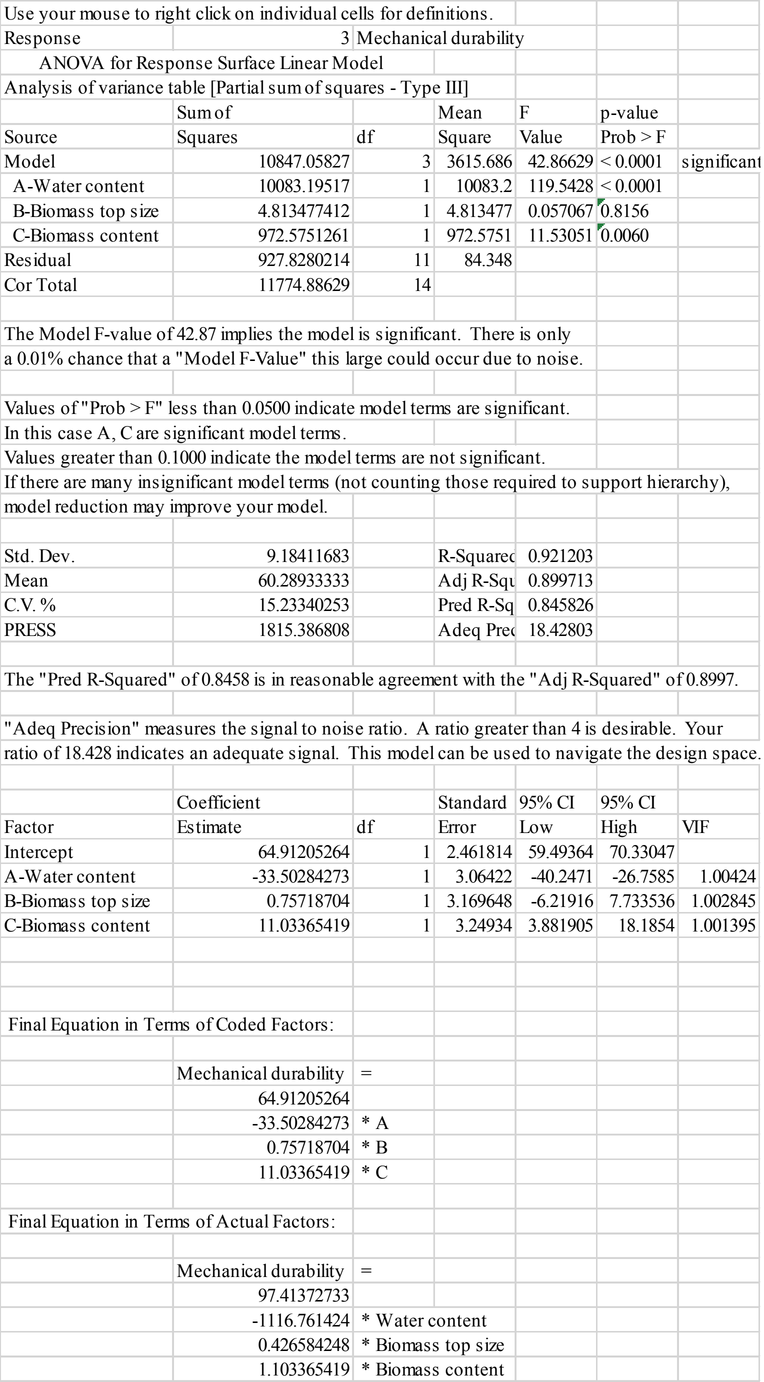
B.4.1 Particle Density Model

Use your mouse to right click on individual cells for definitions.							
Response	1	Particle density					
ANOVA for Response Surface Linear Model							
Analysis of variance table [Partial sum of squares - Type III]							
	Sum of		Mean	F	p-value		
Source	Squares	df	Square	Value	Prob > F		
Model	0.036113858	3	0.012038	18.75741	0.0001	significant	
A-Water content	0.028452389	1	0.028452	44.33421	< 0.0001		
B-Biomass top size	0.002407903	1	0.002408	3.751969	0.0788		
C-Biomass content	0.005102399	1	0.005102	7.950503	0.0167		
Residual	0.007059476	11	0.000642				
Cor Total	0.043173333	14					
The Model F-value of 18.76 implies the model is significant. There is only							
a 0.01% chance that a "Model F-Value" this large could occur due to noise.							
Values of "Prob > F" less than 0.0500 indicate model terms are significant.							
In this case A, C are significant model terms.							
Values greater than 0.1000 indicate the model terms are not significant.							
If there are many insignificant model terms (not counting those required to support hierarchy),							
model reduction may improve your model.							
Std. Dev.	0.02533319		R-Squarec	0.836485			
Mean	1.061333333		Adj R-Squ	0.79189			
C.V. %	2.38692116		Pred R-Sq	0.700943			
PRESS	0.0129113		Adeq Prec	13.26808			
The "Pred R-Squared" of 0.7009 is in reasonable agreement with the "Adj R-Squared" of 0.7919.							
"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your							
ratio of 13.268 indicates an adequate signal. This model can be used to navigate the design space.							
	Coefficient		Standard	95% CI	95% CI		
Factor	Estimate	df	Error	Low	High	VIF	
Intercept	1.071548878	1	0.006791	1.056603	1.086495		
A-Water content	-0.056278426	1	0.008452	-0.07488	-0.03768	1.00424	
B-Biomass top size	0.016935312	1	0.008743	-0.00231	0.036179	1.002845	
C-Biomass content	-0.025272312	1	0.008963	-0.045	-0.00555	1.001395	
Final Equation in Terms of Coded Factors:							
	Particle density	=					
	1.071548878						
	-0.056278426	* A					
	0.016935312	* B					
	-0.025272312	* C					
Final Equation in Terms of Actual Factors:							
	Particle density	=					
	1.187506342						
	-1.87594752	* Water content					
	0.009541021	* Biomass top size					
	-0.002527231	* Biomass content					

B.4.2 Crushing Strength Model

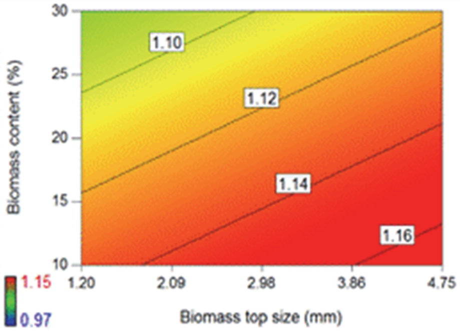
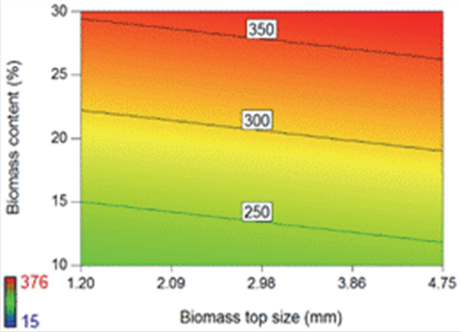
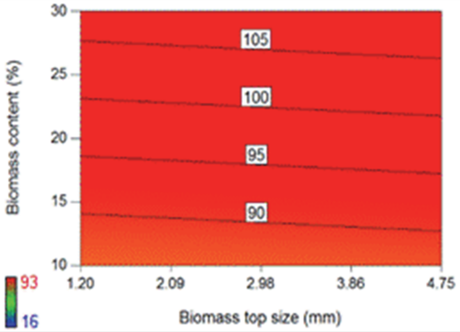
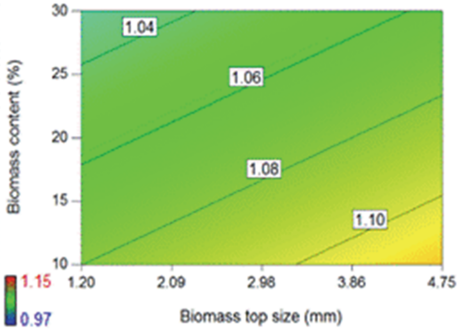
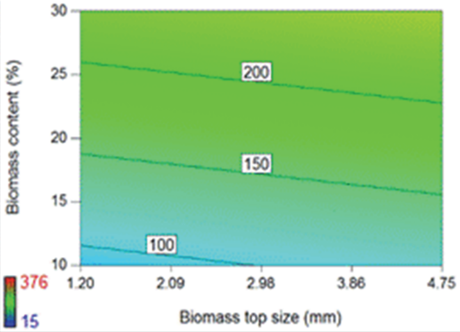
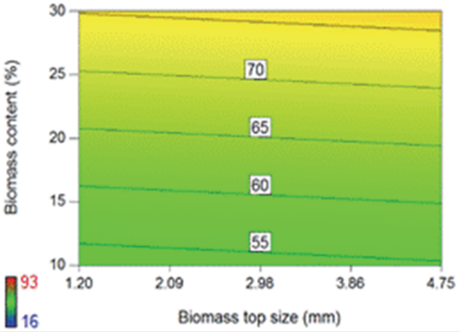
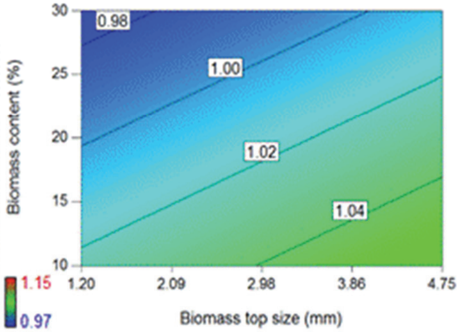
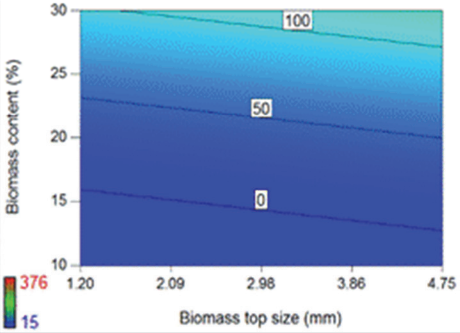
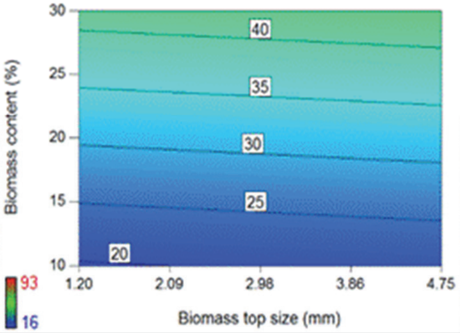
Use your mouse to right click on individual cells for definitions.							
Response	2	Crushing strength					
ANOVA for Response Surface Linear Model							
Analysis of variance table [Partial sum of squares - Type III]							
	Sum of		Mean	F	p-value		
Source	Squares	df	Square	Value	Prob > F		
Model	185655.4159	3	61885.14	75.89205	< 0.0001	significant	
A-Water content	152614.7869	1	152614.8	187.1572	< 0.0001		
B-Biomass top size	1041.119518	1	1041.12	1.276764	0.2825		
C-Biomass content	38362.87511	1	38362.88	47.04582	< 0.0001		
Residual	8969.800083	11	815.4364				
Cor Total	194625.216	14					
The Model F-value of 75.89 implies the model is significant. There is only							
a 0.01% chance that a "Model F-Value" this large could occur due to noise.							
Values of "Prob > F" less than 0.0500 indicate model terms are significant.							
In this case A, C are significant model terms.							
Values greater than 0.1000 indicate the model terms are not significant.							
If there are many insignificant model terms (not counting those required to support hierarchy),							
model reduction may improve your model.							
Std. Dev.	28.55584653		R-Squarec	0.953912			
Mean	150.46		Adj R-Squ	0.941343			
C.V. %	18.97902867		Pred R-Sq	0.906917			
PRESS	18116.35415		Adeq Prec	26.6346			
The "Pred R-Squared" of 0.9069 is in reasonable agreement with the "Adj R-Squared" of 0.9413.							
"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your							
ratio of 26.635 indicates an adequate signal. This model can be used to navigate the design space.							
	Coefficient		Standard	95% CI	95% CI		
Factor	Estimate	df	Error	Low	High	VIF	
Intercept	169.7256215	1	7.654431	152.8783	186.5729		
A-Water content	-130.3409492	1	9.52747	-151.311	-109.371	1.00424	
B-Biomass top size	11.13586602	1	9.855275	-10.5554	32.82718	1.002845	
C-Biomass content	69.29682924	1	10.10306	47.06015	91.53351	1.001395	
Final Equation in Terms of Coded Factors:							
	Crushing strength	=					
	169.7256215						
	-130.3409492	* A					
	11.13586602	* B					
	69.29682924	* C					
Final Equation in Terms of Actual Factors:							
	Crushing strength	=					
	229.7025394						
	-4344.698306	* Water content					
	6.273727335	* Biomass top size					
	6.929682924	* Biomass content					

B.4.3 Mechanical Durability Model



Use your mouse to right click on individual cells for definitions.						
Response	3	Mechanical durability				
ANOVA for Response Surface Linear Model						
Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob > F	
Model	10847.05827	3	3615.686	42.86629	< 0.0001	significant
A-Water content	10083.19517	1	10083.2	119.5428	< 0.0001	
B-Biomass top size	4.813477412	1	4.813477	0.057067	0.8156	
C-Biomass content	972.5751261	1	972.5751	11.53051	0.0060	
Residual	927.8280214	11	84.348			
Cor Total	11774.88629	14				
The Model F-value of 42.87 implies the model is significant. There is only						
a 0.01% chance that a "Model F-Value" this large could occur due to noise.						
Values of "Prob > F" less than 0.0500 indicate model terms are significant.						
In this case A, C are significant model terms.						
Values greater than 0.1000 indicate the model terms are not significant.						
If there are many insignificant model terms (not counting those required to support hierarchy),						
model reduction may improve your model.						
Std. Dev.	9.18411683		R-Squarec	0.921203		
Mean	60.28933333		Adj R-Squ	0.899713		
C.V. %	15.23340253		Pred R-Sq	0.845826		
PRESS	1815.386808		Adeq Prec	18.42803		
The "Pred R-Squared" of 0.8458 is in reasonable agreement with the "Adj R-Squared" of 0.8997.						
"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your						
ratio of 18.428 indicates an adequate signal. This model can be used to navigate the design space.						
	Coefficient		Standard	95% CI	95% CI	
Factor	Estimate	df	Error	Low	High	VIF
Intercept	64.91205264	1	2.461814	59.49364	70.33047	
A-Water content	-33.50284273	1	3.06422	-40.2471	-26.7585	1.00424
B-Biomass top size	0.75718704	1	3.169648	-6.21916	7.733536	1.002845
C-Biomass content	11.03365419	1	3.24934	3.881905	18.1854	1.001395
Final Equation in Terms of Coded Factors:						
	Mechanical durability	=				
	64.91205264					
	-33.50284273	* A				
	0.75718704	* B				
	11.03365419	* C				
Final Equation in Terms of Actual Factors:						
	Mechanical durability	=				
	97.41372733					
	-1116.761424	* Water content				
	0.426584248	* Biomass top size				
	1.103365419	* Biomass content				

B.4.4 Model Graphs

Water Content	Particle Density (g/cm³)	Crushing Strength (lb$_f$)	Mechanical Durability (%)
0.02			
0.05			
0.08			

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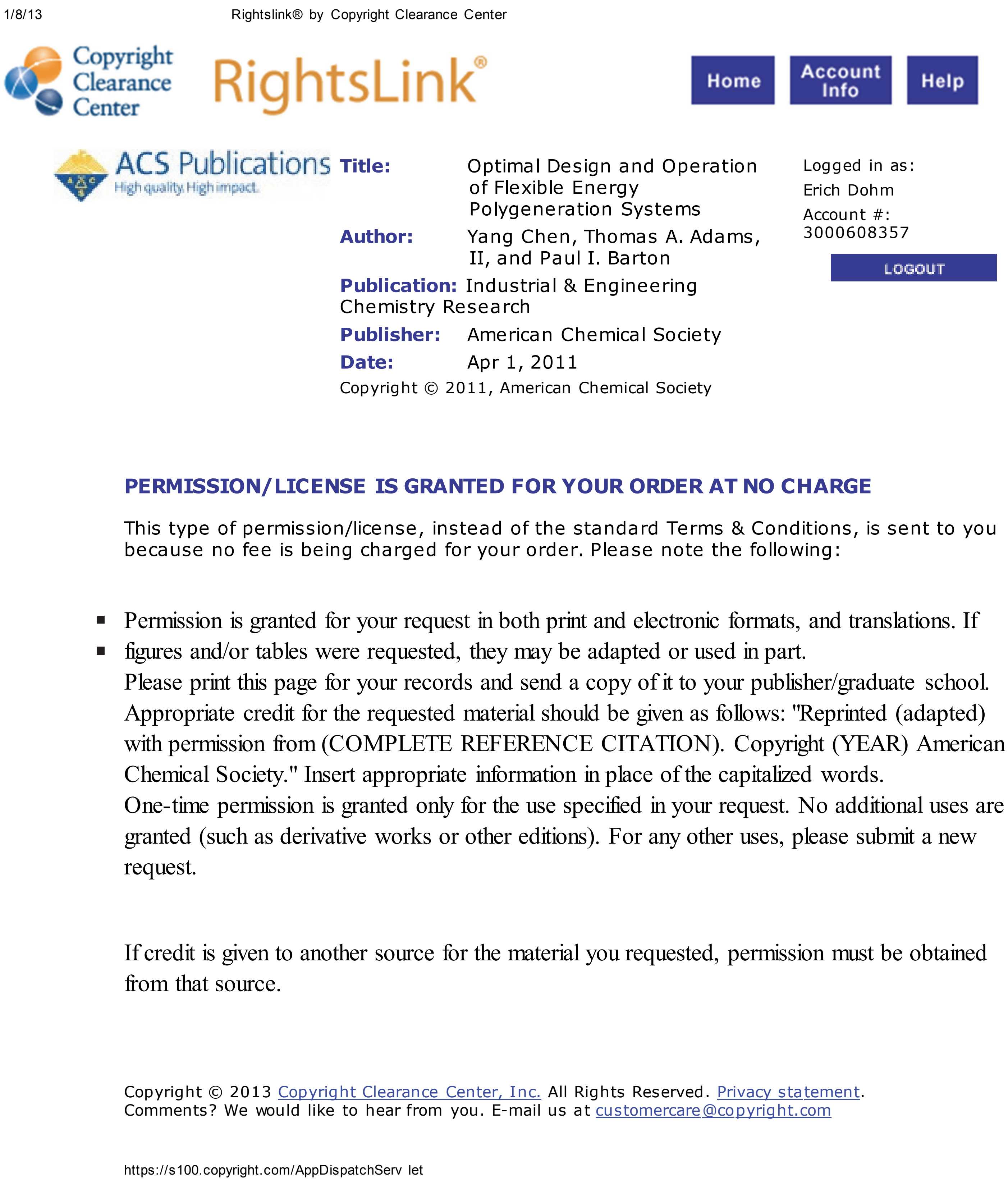

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