Solid Waste Biodegradation Enhancements and the Evaluation of Analytical Methods Used to Predict Waste Stability

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Thesis submitted to the Faculty of Virginia Polytechnic Institute and State University in partial fulfillment for the degree of

Master of Science

in

Environmental Science and Engineering

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May 2, 2002
Blacksburg, Virginia

Keywords: Solid Waste, Biodegradation, Landfill, Bioreactor

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ABSTRACT

Conventional landfills are built to dispose of the increasing amount of municipal solid waste (MSW) generated each year. A relatively new type of landfill, called a bioreactor landfill, is designed to optimize the biodegradation of the contained waste to stabilized products. Landfills with stabilized waste pose little threat to the environment from ozone depleting gases and groundwater contamination. Limited research has been done to determine the importance of biodegradation enhancement techniques and the analytical methods that are used to characterize waste stability. The purpose of this research was to determine the effectiveness of several biodegradation enhancements and to evaluate the analytical methods which predict landfill stability.

In the first part of this study leachate recirculation, and moisture and temperature management were found to significantly affect the biodegradation of MSW. Leachate recirculation, increased moisture, and higher temperatures increased the first order degradation rates of cellulose and volatile solids. Of the three enhancements, temperature was shown to have the biggest impact on the biodegradation of waste, but sufficient moisture is critical for degradation. Plastic material was also shown to significantly impact the measurements for volatile solids and lignin, which is important if these measurements are used to establish waste stability.

In the second part of the study the analytical methods used to characterize waste were evaluated to determine if relationships existed between the methods and which methods were the best predictors of waste stability. Volatile solids and cellulose were found to be the best parameters to monitor waste in landfills. These parameters correlate well with each other, age of the waste, and other parameters. Volatile solids and cellulose are also relatively easy to determine, quick, and show little variation.

ACKNOWLEDGEMENTS

I would like to thank Dr. John Novak for providing me with a great research opportunity and allowing me to work at my own pace with little supervision. I would also like to thank Doug Goldsmith for helping with samples, setting up the columns, and being a member on my committee. Thanks also to Greg Evanylo for being a committee member.

Thanks to everyone in Patton Hall who had to smell the rotten odors when leachate leaked onto the lab floor, and everyone in Durham Hall that also had to smell the samples. Thanks to Julie Petruska and Jody Smiley for help in the labs and with all the analytical equipment. Thanks to all the students who were a part of the research project and worked together- Brad Shearer, Borbala Boda, and Rajendra Vaidya. Thanks to Mike Buchanan who taught me the analytical tests and how many interesting things can be found in landfill trash. Thanks also to Waste Management, Inc. for providing funding. The research project would not have been possible without it.

Special thanks to my parents, Tom and Karen, who provided me with the best education opportunities, and my two older brothers, Matt and Erin, who always set an example for me, good or bad. Lastly, thanks to Gina Ebbett who has shown me there are other things in life besides hunting and fishing.

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CHAPTER 1

Introduction

Most of the municipal solid waste (MSW) generated in the United States each year is placed in landfills. Municipal landfills pose numerous threats to humans and the environment because of the production of leachate and gases generated from the high amount of biodegradable material in the contained waste. Leachate can cause groundwater and surface water contamination, and the gases emitted can cause odor problems, adverse human health effects, explosion hazards, and are considered ozone depleting.

Since most of the problems associated with landfills are so severe, monitoring of landfills must be done during the active filling and for some time after the final closure of the site. The cost of monitoring and long term care of the landfill can be very high. Leachate that is produced must be collected and stored, or treated if it is to be discharged from the site. Gas must also be controlled if it is to be recovered as a potential source of energy (Reinhart and Townsend 1998).

A relatively new form of landfill, called a bioreactor landfill, is being used to optimize and accelerate the biodegradation MSW**.** Bioreactors and accelerated waste degradation have several advantages over conventional landfills. Increased methane production can result when biological reactions in the landfill are accelerated. Methane is a very valuable energy source and bioreactors have the potential to produce high amounts of the gas in a very short period of time, which could possibly be collected. Leachate strength can also be lowered by recirculation leading to reduced treatment costs and less potential for soil and groundwater contamination. Therefore, enhanced degradation will lead to a reduction in long-term care of the landfill and reduced costs for operation and monitoring (Barlaz et al. 1990).

Enhancements that can be use to increase biological degradation in landfill bioreactors include leachate recirculation, moisture, temperature, nutrients, buffers, sludge addition, shredding, and lift design. Limited research has been done to determine the effectiveness of applying these techniques to accelerate the biodegradation of MSW. Also, little research has been done to determine when MSW is sufficiently degraded.

The research presented in the following chapters is divided into three sections. The first section is a literature review which discusses background information on MSW and past research performed on various aspects of landfills and degradation of solid waste. The second section discusses lab-scale research performed on MSW. In this research, three enhancements techniques were studied to determine their effectiveness in accelerating the biodegradation of MSW. The techniques that were chosen to be part of this research were leachate recirculation, moisture and temperature management. These three enhancements were chosen because of their potential to increase degradation and also for the ease of applying these techniques to the lab scale materials.

An additional part of the lab scale research was to determine the impact of plastic material on the analytical measurements used in the waste management industry to monitor landfills. Plastic material is generally considered to be non-biodegradable in landfill environments and should therefore not affect the quality of leachate or the amount of gas produced. But, if the measurements used to determine the amount of biodegradable material left in landfills are affected by plastics, then the measurements need to take this into account.

The third section discusses research performed on full-scale landfills. In the past the measurements that have been used to monitor landfills and predict stability of refuse have been volatile solids, cellulose, biochemical methane potential (BMP), and the cellulose/ lignin ratio. The purpose of this research was to determine if relationships existed between these parameters so that the simplest and most cost efficient measurements could be used in the future by the waste management industry. It was also the object of this research to determine at what point waste could be considered sufficiently stabilized so that it poses no further threat to human or environmental health.

CHAPTER 2

Literature Review

Landfill Bioreactor Introduction

Bioreactor landfills are constructed like most of today's sanitary landfill, being equipped with liners, leachate collection systems, and gas management systems. The main difference in the bioreactor landfills is that they are operated and closely controlled to accelerate the biological activity that degrades and stabilizes waste. Acceleration is accomplished by the addition of water to bring the moisture content to an approximate range of 35 to 50 percent.

Leachate recirculation is the fundamental process used in bioreactor landfills to treat the contained waste (Reinhart and Townsend 1998). The U.S. EPA reported that more than 200 landfills use leachate recirculation as a means of leachate management (Reinhart and Carson 1993). Leachate is produced in landfills as a result of water entering and moving through solid waste and may contain dissolved or suspended material associated with the waste, as well as byproducts of biological and chemical reactions. Leachate may also contain hazardous and toxic constituents that are found in the waste (Reinhart and Townsend 1998).

Leachate recirculation has had limited acceptance in some areas because of the excessive head on the bottom liner, clogging of drainage systems, and leachate breakouts to the soil and groundwater (Warith and Sharma 1998). Before liners were required for landfills leachate would migrate from the waste and contaminate the underlying soil and groundwater (Reinhart and Townsend 1998).

Landfill gas is also generated by landfills due to the biological decomposition of the waste and contains approximately 50 percent methane. Problems associated with landfill gas include explosion hazards, toxins such as mercury, odors, and ozone depletion from the greenhouse gas of methane. Approximately 50 to 70 percent of municipal solid waste (MSW) is biodegradable which can lead to high amounts of gas being generated (Reinhart and Townsend 1998).

Bioreactors and accelerated waste degradation have several advantages over conventional landfills. Increased methane production can result when biological reactions in the landfill are accelerated. Methane is a very valuable energy source and bioreactors have the potential to produce high amounts of the gas in a very short period of time. Leachate strength can also be lowered by recirculation leading to reduced treatment costs and less potential for soil and groundwater contamination. The settlement time of the landfill can also be greatly reduced allowing for reuse of the area. Therefore, enhanced degradation

will lead to a reduction in long-term care of the landfill and reduced costs for operation and monitoring (Barlaz et al. 1990).

Waste Physical Properties and Composition

Landfill waste is very heterogeneous and biological degradation takes place in microenvironments within the landfill (Ham et al. 1993). The composition of municipal refuse includes food, garden and yard trimmings, paper products, plastics, textiles, rubber, leather, wood, glass, metals, dirt, and ash (Barlaz et al. 1990). Density of wastes can vary from 800 to 1400 lb/yd^3 depending on compaction (Reinhart and Townsend 1998).

Paper and paper-related products are the biggest constituents in MSW averaging about 40 percent of the total mass (Barlaz et al. 1990). These paper products contain holocellulose, which is the sum of cellulose and hemicellulose, and lignin. Together, holocellulose and lignin is called lignocellulose and accounts for the major part of biomass. Degradation of lignocellulose is essential for operation of the global carbon cycle (Tuomela et al. 2000).

Cellulose is a polymer of the 6-carbon sugar glucose and hemicellulose is a polymer of 5 and 6-carbon sugars. Typically, holocellulose is the main degradable component of MSW (Baldwin et al. 1998). Cellulose and hemicellulose accounts for 91 percent of the methane potential of MSW (Barlaz et al. 1989).

Lignin is a recalcitrant polymer and paper may contain up to 20 percent of lignin. Lignin is an important cell wall constituent in plants and provides strength and resistance to degradation (Tuomela et al. 2000). Lignin is usually measured gravimetrically by ignition of acid-insoluble material. This lignin is referred to as Klason lignin (Baldwin et al. 1998). Lignin may only slowly degrade under anaerobic conditions and physically surrounds much of the cellulose in refuse components that come from biomass (Eleazer et al. 1997). Lignin is considered to have no methane potential because it is recalcitrant under the anaerobic conditions required to produce methane (Young and Frazer 1987). Municipal refuse typically contains 40 to 50% cellulose, 10 to 15% lignin, and 12% hemicellulose (Barlaz et al. 1990).

Since lignin is thought to be recalcitrant and surrounds much of the cellulose in nature it would be suspected that it could interfere with the degradation of cellulose and hemicellulose. Some studies have shown this to be false. Eleazer et al. (1997) showed that the lignin concentration does not always reflect the degree that lignin inhibits cellulose bioavailability, and even the most lignified materials, such as leaves and branches, can be degraded. Others, such as Barlaz et al. (1989), believe 100 percent of the cellulose and hemicellulose cannot be degraded because some fraction is surrounded by lignin and is not available for anaerobic degradation.

A ratio of cellulose to lignin has been used in research to determine stability of MSW. As mentioned before, cellulose and lignin both occur in paper products with cellulose expected to be able to degrade in anaerobic environments and lignin recalcitrant. The lignin can be used as an internal standard since it changes very little as the waste degrades. Usually fresh refuse has cellulose to lignin ratio of about 4, with the ratio falling to about 0.2 as the refuse becomes stabilized (Sulfita et al. 1992). The decline in the cellulose to lignin ratio with age shows the refuse is degrading and can be used to measure the relative decomposition age (Ham et al. 1993).

Methane production from the decomposition of MSW has been well documented but the yield (m^3/lb) and the time for its onset has been very unpredictable in landfills. As mentioned before, cellulose and hemicellulose account for 91% of the methane potential for MSW. The rest of the potential is accounted for in the organic nitrogen and sugars. Results from studies show that methane potential of refuse can be at least 152 to 170 L/kg dry refuse (Barlaz et al. 1989).

MSW also contains a number of unmeasured organics, including rubber, leather, and plastics. Generally these organics are not biodegradable under anaerobic conditions and will therefore not produce any methane (Eleazer et al. 1997). The measurement of organic constituents in refuse is fairly accurate and in some studies only 8% was unaccounted for (Ham et al. 1993). The unaccounted amount may be the result of organics like plastics, rubber, and leather. Plastic increased from 3% of MSW in the early 1970s to 6.5% in 1986 (Barlaz et al. 1990). It can be assumed that plastic has increased even more since 1986 and may account for approximately 10% of MSW in 2002 (Kelly et al. 2002).

Decomposition Phases and Bacterial Groups

Many studies have shown that stabilization of waste in a landfill environment proceeds in five distinct phases. Leachate and gas composition vary from one phase to another and reflect the chemical and biological changes that are taking place inside the landfill. A graphical depiction of these changes is shown in Figure 2.1 (Reinhart and Townsend 1998).

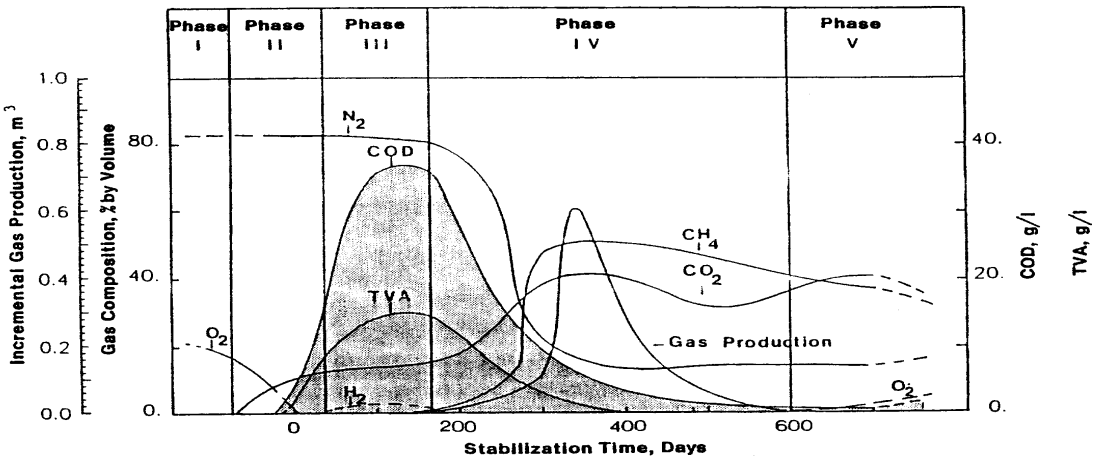

Figure 2.1 Graphical depiction of changes in landfill characteristics with age.

Phase I, called the initial adjustment phase, includes the initial placement of refuse and the collection of moisture. Usually an acclimation period is noticed until sufficient moisture develops to support microbial activity. Enough oxygen is usually present for aerobic decomposition to occur and produce carbon dioxide.

In Phase II, called the transition phase, the field capacity is reached and a change from aerobic to anaerobic conditions occurs. Reducing conditions begin to be established and a shift from oxygen as an electron acceptor to nitrates and sulfates is seen. Measurable amounts of chemical oxygen demand (COD) and volatile organic acids (VOA) can be found in the leachate.

Phase III, the acid formation phase, is when high amounts of VOAs are produced by the hydrolysis of the waste followed by the biological conversion of these intermediates to acids. This causes the pH to drop, typically between 5 or 6, and the mobilization of metals in the landfill to increase from their increased solubility at the low pH.

In Phase IV, the methane fermentation phase, the intermediate acids are converted by methanogenic bacteria to methane and carbon dioxide. Also, sulfate is reduced to sulfide. Since the organic acids are consumed, the pH increases and further supports the methanogenic bacteria. Metals become insoluble because of the increase in pH and are precipitated into the solid phase. In conventional landfills this phase is often very long and can last for decades. Bioreactor landfills can greatly decrease the time of this phase by accelerating the biodegradation. The increased methane production from bioreactors will allow more gas to be collected efficiently, which means less emission of ozone depleting compounds.

Phase V, the maturation phase, sees little available substrate for microbial activity and gas production drops significantly. Leachate strength remains constant and at low concentrations. Atmospheric gases begin to permeate the remaining waste and recalcitrant materials are slowly degraded. Phase V can also last for several years or even

decades. Although the amount of gas produced is much less than the previous phase, methane is still generated at a steady rate from the biodegradation of remaining material (Reinhart and Townsend 1998).

There are three main groups of bacteria that dominate the stabilization of MSW in landfills. The first group, referred to as the hydrolytic and fermentative microorganisms, convert polymers such as carbohydrates, proteins, and fats to sugars, amino acids, fatty acids, and glycerol. These products are then fermented to short chain carboxylic acids, carbon dioxide, and hydrogen. Acetate and alcohol are also produced by these microorganisms.

The second group of bacteria are the acetogens which ferment the alcohols and carboxylic acids of the first group to acetate, carbon dioxide, and hydrogen. Methanogens, the third group of microorganisms, then convert the acetate and hydrogen into methane gas and carbon dioxide.

All three groups of bacteria are essential for the stabilization of MSW. If the activity of the acid forming bacteria exceed that of the acetogens and methanogens, then a buildup of acid will occur causing an imbalance in the ecosystem with a drop in pH and inhibition of further methanogenesis (Barlaz et al. 1990).

Enhancements to Biological Degradation

Parameters that can be used to increase biological degradation include leachate recirculation, moisture, temperature, nutrients, buffers, sludge addition, shredding, and lift design.

Leachate recirculation enhances microbial degradation and improves leachate quality by providing a high moisture content for microbial activity and giving better contact between insoluble substrates, soluble nutrients and microorganisms. But if the rate of hydrolysis is greater than the rate of the conversion of acidic compounds to methane and carbon dioxide, then carboxylic acids will accumulate and cause a significant drop in pH. Some studies have shown that buffering is needed in addition to the leachate recycle so that this buildup will not occur and microbial degradation can be enhanced to produce more methane from MSW (Barlaz et al. 1990).

Moisture is one of the most important parameters that affects MSW degradation within landfills (Baldwin et al. 1998). The benefits of increased moisture in a landfill include limiting oxygen transport from the atmosphere, facilitating exchange of substrates, nutrients, buffer, dilution of inhibitors, and spreading microorganisms throughout the waste (Warith and Sharma 1998). Barlaz et al. (1990) indicated that moisture stimulates the growth of anaerobic microorganisms and stimulates methane production. In a landfill

the lack of contact between substrate, microorganism, and growth factors limits biodegradation. As the moisture content is increased, the amount of contact increases and biodegradation can occur easier (Warith and Sharma 1998).

It is widely known that temperature has a significant effect on microbial degradation. The most used equation describing the effect of temperature is the van't Hoff-Arrhenius equation (Metcalf and Eddy 1991)

$$k_t = k_{20} \times \theta^{(T-20)}$$

where k_t = degradation rate constant at a particular temperature; k_{20} = degradation rate constant at 20°C (0.23 is a typical value); θ = constant of 1.056 for temperatures between 20 and 30°C; and T= temperature for which *k* is desired. An example shows that if the temperature is increased from 22°C to 30°C then the rate constant increases from 0.25 to 0.40, a 60% increase (Baldwin et al. 1998).

Hartz et al. (1982) found that 41°C was the optimum for the production of methane and methane production would cease somewhere between 48 and 55°C. In deep landfills with moderate water flux, a temperature of 30 to 45°C can be expected and the increased temperature is attributed to microbial reactions and the insulating effects of the waste (Warith and Sharma 1998).

Microorganisms require nutrients such as sulfur, calcium, magnesium, potassium, iron, zinc, copper, cobalt, molybdate, selenium, nitrogen, and phosphorus to participate in anaerobic decomposition. In most cases these nutrients are found in landfills but the heterogeneous nature of the waste may limit their availability. Nutrients, especially nitrogen and phosphorus, can be added to landfills by the addition of municipal sewage sludge. The optimal ratios between organic matter (expressed as chemical oxygen demand), nitrogen, and phosphorus has been reported as 100:0.44:0.08 (Warith and Sharma 1998).

Sludge addition can also serve as a source of microorganism inoculum, although all the organisms needed for refuse methanogenesis are present in fresh waste. Old refuse can also be used as a source of inoculum for fresh refuse. Old refuse has been shown to stimulate methanogenesis in fresh refuse and may also serve as a dilutant against toxic compounds (Barlaz et al. 1990). Barlaz et al. (1989) found that when leachate was recycled with buffer, nutrients and sludge, the rate of methane production was higher than with no addition, and should therefore achieve the greatest waste stabilization.

Well- mixed, shredded refuse with a small particle size should allow greater contact between substrate, microorganisms, and moisture. However, Barlaz et al. (1990) found that refuse with a size of 250-350 mm produced 32% more methane after 90 days than refuse with a size of 100-150 mm. The reason stated for the increase in methane production was that the small particle size caused the rate of hydrolysis to be too fast and resulted in an accumulation of organic acids and a drop in pH. These conditions then limited methane production.

Lift design can also play an important part in the decomposition of MSW. Ham and Bookter (1982) concluded that the lift thickness is an important factor which affects leachate composition. Refuse built up in 2-m lifts were shown to degrade slower than refuse in 1.3-m lifts, and elevated leachate strength was longer in time for the thicker lifts. They also found that daily cover has an adverse effect on the enhancement of biological degradation. Methane concentration was increased and the production of methane was delayed by the presence of soil cover. The cover reduces the flow of gas out of the landfill and interferes with biological processes occurring in the waste.

Other Landfill Bioreactor Issues

Three other abiotic factors in a landfill that affect degradation and methane gas production are oxygen, pH, and inhibitors. Methanogenic bacteria are very sensitive to the presence of oxygen. Gas recovery pumping in a landfill may cause enough vacuum in a landfill to force air into the waste. Generally, only the first 1 m of the landfill is aerobic due to the rapid consumption of oxygen by aerobic bacteria.

Methanogenic bacteria are also sensitive to pH and generally function at their maximum within a narrow range of 6 to 8. If conditions are not right for the growth of methanogens then acidic conditions can result from the accumulation of organic acids and hydrogen produced by acetogenic bacteria. The result is a decrease in pH below 6 and a large decline in methane production.

Carbon dioxide, salt ions, sulfide, heavy metals, and many other specific compounds are potential inhibitors of methane production. While many cations are stimulatory at low levels, higher amounts may inhibit anaerobic decomposition (Warith and Sharma 1998).

While the waste in landfill undergoes decomposition a portion of the mass is lost to gas. The resulting landfill mass will therefore settle, decreasing the volume of the waste material (Reinhart and Townsend 1998). Very little information exists about the settlement of waste in landfills. One theory about settlement is that it occurs in three distinct phases: the initial compression or settlement when the load is applied, primary compression when water and gas is dissipated from void spaces, and secondary compression from biological decay and creep of the refuse (Warith and Sharma 1998).

The point at which degradation is sufficiently complete and the waste considered stable is not clearly defined or noted by any research. The best indicators seem to be leachate quality, gas quantity, and waste composition. Low leachate strength (COD below 1000 mg/l) and gas production of less than 5 percent of the peak value may be acceptable to show stabilization. Waste cellulose/lignin ratio of less than 0.2, a biochemical methane potential of less than 45 ml/mg dry refuse, and a dark soil-like appearance to the waste may also mark sufficient stabilization (Reinhart and Townsend 1998). Low cellulose and low volatile solids may also be possible points of stabilization.

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CHAPTER 3

EFFECTS OF ENHANCEMENT TECHNIQUES ON THE BIOLOGICAL STABILIZATION OF MUNICIPAL SOLID WASTE AND THE IMPACT OF PLASTIC ON MEASUREMENTS TO DETERMINE WASTE STABILITY

Ryan J. Kelly[1]; John T. Novak, M.ASCE[2]; Bradley D. Shearer[3]

Abstract

In this lab-scale study, three enhancements techniques were applied to the biodegradation of municipal solid waste (MSW). The enhancements were leachate recirculation, moisture, and temperature management. Leachate recirculation, which was possible from the addition of water, was shown to increase the first order degradation rates of volatile solids, cellulose, cellulose/lignin ratio, and lignin by 44%, 105%, 118%, and 50 %, respectively. Increased temperature significantly affected the degradation of volatile solids and cellulose, and correlated well with the settlement of MSW. Moisture correlated well with the degradation of volatile solids and cellulose and amounts above 20% were shown to be very important in the biodegradation of MSW. Plastic material was found to affect the measurements of volatile solids and lignin and should be accounted for when these measurements are to be used to predict remaining biodegradable matter in MSW. An average of 10% plastics was found in MSW samples and may be an appropriate amount to deduct from the volatile solids and cellulose measurements.

Introduction

Municipal landfills have been built to dispose of the increasing amount of solid waste generated each year. Municipal solid waste (MSW) in landfills is gradually converted by microorganisms into stabilized material and gas. The period of waste stabilization can take many decades and is dependent on the waste composition and the landfill

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environment. “Bioreactor landfills” are now built to optimize conditions for biological activity and accelerate the stabilization of the landfilled waste. Landfills with stabilized waste pose less threat to the environment and future contamination.

The techniques that are used to enhance the biological stabilization of waste in bioreactors include leachate recirculation, nutrients, inoculum, buffers, waste shredding, lift design, temperature and moisture control. The advantages of accelerating the degradation of landfill waste are reduced gas emissions after closure of the landfill, reduced leachate strength during operation and after closure of the landfill, and accelerated settlement of the landfill (Warith and Sharma 1998).

Leachate recirculation enhances microbial degradation and improves leachate quality by providing a high moisture content for microbial activity and giving better contact between insoluble substrates, soluble nutrients and microorganisms. Some studies have shown that buffering is needed in addition to the leachate recycle so that the buildup of organic acids will not occur and microbial degradation can be enhanced to produce more methane from MSW (Barlaz et al. 1990).

Moisture is one of the most important parameters that affects MSW degradation within landfills (Baldwin et al. 1998). The benefits of increased moisture in a landfill include limiting oxygen transport from the atmosphere, facilitating exchange of substrates, nutrients, buffer, dilution of inhibitors, and spreading microorganisms throughout the waste (Warith and Sharma 1998). Barlaz et al. (1990) also indicated that moisture stimulates the growth of anaerobic microorganisms and stimulates methane production.

It is widely known that temperature has a significant effect on microbial reactions. The most used equation describing the effect of temperature is the van’t Hoff-Arrhenius equation (Metcalf and Eddy 1991)

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where k_t = degradation rate constant at a particular temperature; k_{20} = degradation rate constant at 20^{o}C (0.23 is a typical value); θ = constant of 1.056 for temperatures between 20 and 30^{o}C; and T= temperature for which k is desired. An example shows that if the temperature is increased from 22^{o}C to 30^{o}C then the rate constant increases from 0.25 to 0.40, a 60% increase (Baldwin et al. 1998). Hartz et al. (1982) found that 41^{o}C was the optimum for the production of methane and methane production would cease somewhere between 48 and 55^{o}C. In deep landfills with moderate water flux 30 to 45^{o}C can be expected and is attributed to microbial reactions and the insulating effects of the waste (Warith and Sharma 1998).

While the waste in landfill undergoes decomposition a portion of the mass is lost to gas. The resulting landfill mass will therefore settle, decreasing the volume of the waste material (Reinhart and Townsend 1998). Settlement occurs in three distinct phases: the initial compression or settlement when the load is applied, primary compression when water and gas is dissipated from void spaces, and secondary compression from biological

decay and creep of the refuse (Warith and Sharma 1998). The faster settlement occurs the faster the landfill site can be reused or reclaimed.

The composition of municipal refuse includes food, garden and yard trimmings, paper products, plastics, textiles, rubber, leather, wood, glass, metals, dirt, and ash. Paper and paper-related products are the biggest constituents in MSW averaging about 40 percent of the total mass (Barlaz et al. 1990). These paper products contain holocellulose, which is the sum of cellulose and hemicellulose, and lignin (Tuomela et al. 2000). MSW also contains a number of unmeasured organics, including rubber, leather, and plastics. Plastic increased from 3% of MSW in the early 1970s to 6.5% in 1986 (Barlaz et al. 1990). It can be assumed that plastic has increased even more since 1986 and may account for almost 10% of MSW in 2000 (McBean et al. 1995).

The purpose of this study was to see the effects of several of the enhancement techniques on the biological stabilization of MSW and the effect of plastic material on the analytical measurements used to determine the stability of refuse. The enhancements that were chosen for the study include leachate recirculation and moisture and temperature management. Understanding these techniques is critical for the optimization of waste stabilization and the successful operation of bioreactor landfills. The understanding of the impact of plastics is also critical if accurate stability measurements are to be made on MSW.

Methods and Materials

Columns

Seven columns were filled with refuse from the Metro landfill, Wisconsin. Each column was 8 feet in length, 18 inches in diameter, and made of 1-inch thick high-density polyethylene (HDPE). Each column had four sampling ports located at 1, 3, 5, and 7 feet along its length. A five-gallon sealed plastic bucket was used as a reservoir for leachate and contained a submersible pump with a floating switch to recirculate the leachate. Flexible plastic tubing was attached to the top of each column to vent any gas produced.

Temperature management was accomplished by running hot water around the outside of each column. Each column was wrapped with approximately 60 feet of ½ inch soft copper tubing connecting to a 50 gallon electric water heater. The columns were further insulated with 3-inch fiberglass wrap to help retain heat.

Approximately 275 lbs of steel weight were placed on a perforated plated located on top of the refuse inside each column. The perforations in the plates allowed leachate to be recirculated through the waste. Two wires were attached to each plate on opposite edges and strung through the top of each column. The lengths of the wires were used as a measurement of waste settlement.

Sampling

Approximately 100 grams of waste was sampled at each of the four sampling ports located along the length of each column. Special attention was made to remove waste from the outer edge and middle of each sampling port to give a representative sample. A composite sample was prepared by thoroughly mixing each of the four sub-samples together.

Analytical Parameters:

pH

A slurry was prepared by adding approximately 250 milliliters of deionized water to 100 grams of waste. The pH meter was calibrated with pH 7 standard and another standard (e.g., pH 4) expected to bracket slurry pH values. The pH was recorded if it fell within the bracketed standards. If not, the pH meter was recalibrated and the sample reanalyzed.

Moisture

Moisture content was determined by modified Standard Method 2540-B (APHA 1992). Each sample of solid waste was dried in an aluminum pan at 105^0C to a constant weight after cooling under desiccation. Moisture content is determined by weight loss from the original sample and expressed as a percent.

Laboratory Sample Preparation

Oven dried (105^0 C) MSW was reduced to a particle size less than 1/8" in a bench top glass and stainless steel blender. Further grinding in a Wiley Mill with a 10-mesh screen achieved a powder-like consistency. Non-grindables such as rocks, nails, etc. were removed before processing.

Volatile Solids

The volatile solids procedure followed a modified version of Standard Methods APHA Method 2440-E. Samples were dried once again at 105^0 C to a constant weight and held in a desiccator. Approximately two grams of dried MSW were placed in pre-weighed aluminum pans and inserted into a muffle furnace at 550°C for 20 minutes. Samples were removed and allowed to cool in a desiccator to a constant weight. The percent weight loss from ignition yields the total amount of volatile matter.

Cellulose and Lignin

The cellulose and lignin analysis followed ASTM E 1758-95^{e1}. A sample size of 300 mg dry, milled MSW was used for this measurement. The cellulose was hydrolyzed into glucose monomers in two stages using sulfuric acid. The samples were digested in three milliliters of 72% sulfuric acid in a water bath at 45^oC for two hours. Samples were then

transferred to 250 mL septa bottles using 84 mL of nanopure water and autoclaved for one hour at 121^{o}C and 15 psi. The samples were subsequently filtered using standard TSS glass fiber filters. The volatile suspended solids (combusted at 550^{0}C) remaining after hydrolysis was considered lignin. The filtrate was then neutralized using $CaCO_3$ powder directly. The glucose was quantified using a HPLC with a refractive index detector (RID) and HPX-87C carbohydrate column.

Temperature

Temperature measurements were taken by inserting a thermocouple probe into the waste at each sampling port. Temperature readings were made at the edge and center of the waste to determine if variations existed from heating the outside of each column.

Plastics

All plastic material from each column sample was identified by sight, removed by hand, and weighed. Both the plastic and non-plastic portions of the samples were dried to determine moisture and then split into two equal parts by weight. One part plastic and one part non-plastic samples were thoroughly mixed to give a representative sample of original column solid waste and the percent plastic material on a dry weight basis calculated. The remaining portion of non-plastic sample was also retained and properly labeled as containing no plastic.

Results and Discussion

Table 3.1 shows the average temperature and average moisture of each of the seven columns and whether leachate was recirculated. (Note that the columns are not numbered in order of 1 through 7. Originally 12 columns were part of the study but five columns were not sampled due to inconsistencies in the waste placed in the columns. Some columns contained a large amount of wood and construction material). Only three of the seven columns had enough moisture above the waste's field capacity to produce leachate. Column 12 was used as a control in the study. No additional moisture was added to the waste and no temperature adjustments were made to the column.

Figure 3.1 shows the percent of volatile solids, cellulose, and lignin plotted against the date when samples were taken from the control column 12. This column shows very little if any degradation of waste over eight months of monitoring. Column 2 shows how moisture and/or increased temperature can increase the degradation of refuse (Figure 3.2). Volatile solids and cellulose were significantly degraded in Column 2 as seen in the first-order degradation rates. Lignin also showed degradation but at a slower rate.

Leachate recirculation had a significant effect on the degradation of the waste. Table 3.2 shows the average first order degradation rates of volatile solids, cellulose, cellulose/lignin ratio, and lignin. Leachate recirculation increased the first order rates by 44%, 105%, 118%, and 50%, respectively.

The columns were kept at room temperature until July 16, 2001 when heat was first added by circulating hot water around the outside of each column. Heat was continually added from this date until the last samples were removed in February 2002. Sampling was also performed for more then one year before the first addition of heat. A comparison of first-order degradation rates in Table 3.3 shows that the increase in temperature in July 2001 had a significant effect. In most of the columns the volatile solids were degraded faster when the waste was heated. Cellulose was degraded faster in all the columns after the addition of heat.

The effect of increased temperature can also be seen in Figure 3.3a which shows the degradation of cellulose in the three hottest columns (#1, 2, and 4), all with temperatures over 100 ^{0}F. The first-order degradation rates in these columns are all relatively high. Figure 3.3b shows the degradation of cellulose in three columns with temperatures between 90 and 100 ^{0}F (Columns #2,10,11). On average, the first-order degradation rates of these columns are less than the rates for the columns with temperatures above 100 ^{0}F.

Figure 3.4 shows the temperature of each column plotted against the first-order degradation rates of several parameters. Temperature is moderately correlated with the degradation rate of cellulose as seen by the R^2 value of 0.57. The first order rates for volatile solids and lignin seem to be less well correlated with temperature.

Figure 3.5 shows the average moisture of each column plotted against the rates of volatile solids and cellulose. In this figure the moisture is normalized to the amount of cellulose present in the waste and expressed as gram of water to gram of cellulose. Most inorganic material retains very little if any moisture, so most of the water in the waste is contained in the organic fraction. Waste that seems to have low moisture overall may in fact contain adequate amounts for biodegradation if the organic fraction is small and most of the moisture is contained there. Since cellulose is the largest fraction of the organic material in most wastes it was used to normalize the moisture. In the figure, cellulose shows a good correlation with moisture. As the amount of water to the amount of cellulose increases, the degradation rate increases. Volatile solids degradation also correlates with moisture. The first order rates for cellulose and volatile solids were higher in all the columns compared to the control column which had 20.4 % moisture overall, or 0.65 gram of water per gram of cellulose.

Interactions between the enhancement techniques may have had an effect on the correlations between moisture and the first order degradation rates. Some columns with lower moistures had high temperatures and leachate recirulation. This is seen in Column 4, which had 35.5 % moisture overall and 3.38 grams of water per gram of cellulose, an average temperature of 102.85 ^{0}F (39.4 ^{0}C), and leachate recirculation. Figure 3.5 shows that the first order rates of cellulose and volatile solids in Column 4 were the highest for all columns. Again, this column had an average moisture of only 35.5 % overall.

Columns 2, 3, and 11 all had overall moisture contents of approximately 42 percent. Figure 3.6 shows the first-order rates for volatile solids and cellulose plotted against the

temperature of each of these columns. As the temperature increases the first-order degradation rate for cellulose and volatile solids generally increases showing the effect of temperature without the interference of the effect of moisture.

Moisture is not always distributed equally throughout the waste in the columns. Channeling of water often occurs and some sections of the column may contain high amounts of moisture, while other parts have very little. Column 4 had an overall moisture content of only 35.5% but still produced enough leachate to be recirculated. Columns 2, 10, and 11 all had overall moisture contents greater than column 4 but produced no leachate that could be recirculated. The unequal spatial distribution of moisture in Column 4 could account for the high degradation rates of cellulose and volatile solids. Some sections of the column have high moisture and fast degradation, while others sections have very low moisture. Overall, the column still had relatively low moisture in the waste.

Plastics are generally non-biodegradable and so it is important to determine how they affect measurements, such as volatile solids, cellulose, and lignin that are used to determine the remaining portion of biodegradable material in a landfill. Since plastic material is combustible at 550 ^{0}C, any amount in a sample of MSW should be detected in the measurement of volatile solids. The effect of plastic material on the volatile solids measurement can be seen in Figure 3.7, which shows the percent of cellulose plotted against the percent of volatile solids for each sample. In this figure the percent of plastics, determined by hand collection and weighing, is shown for each sample and is approximately an average of 10 percent of the weight as indicated by the intercept of the trendline. Data from the same samples are plotted on the graph but the plastics were removed by hand. The samples without plastics show that the trendline for the cellulose and volatile solids is shifted down by 10 percent, confirming that plastics are detected in the volatile solids measurement.

The effect of plastic on the lignin measurement can be seen in Figure 3.8, which shows the percent of lignin plotted against the percent of cellulose. The samples with plastics removed show an average of 10 percent less lignin as seen by the downward shift of the trendline. Referring back to Figure 3.7 again shows these samples contained an average of 10 percent plastic material. This gives more evidence of the impact of plastics on the measurements used to determine waste stability.

Table 3.4 shows the total settlement of waste in each column (Note: Column 2 has no settlement data). Total settlement ranged from 1.25 to 5 inches. Settlement is plotted against the first order degradation rates in Figure 3.9. Although there is some trend the figure shows almost no correlation between the rates and settlement. Again, interaction of the enhancements could be the result of the poor correlations.

Figure 3.10 shows settlement plotted with moisture. Waste with higher moisture should have the ability to compact to higher densities and settlement may be the result of only moisture content. The figure shows a weak correlation between moisture and settlement. When settlement is plotted against temperature in Figure 3.11 a good correlation can be

seen. Again, temperature is shown to have a significant effect on the degradation of waste, therefore the degradation rates should be correlated with settlement but was not seen in the data.

Summary and Conclusions

In this study, leachate recirculation, moisture content, and temperature were all important for the enhanced biodegradation of MSW. Moisture correlated well with the first order degradation rates but not with the settlement of the waste. It was shown that amounts above 20% are necessary to accelerate biodegradation. Leachate recirculation did show that it increases the first order degradation rate, but leachate recirculation is only possible when enough water is added to the waste. This shows again that moisture does have a significant impact on degradation.

Temperature seems to have the biggest impact on the biodegradation of solid waste. It correlated well with the degradation of cellulose and the total settlement of waste, and increases of only 10^0F were shown to significantly affect the first order degradation rates. The acceleration of biodegradation is not possible with only increased temperatures. Moisture is also a critical element that is needed. Moisture may be easier to control in bioreactor landfills and may be sufficient to achieve the desired effect. In conclusion:

- Leachate recirculation, possible because of the addition of water to MSW, significantly increases the first order degradation rates for cellulose, volatile solids, lignin, and the cellulose lignin ratio.
- Temperature significantly affects the degradation rates and settlement of MSW.
- Moisture content was shown to correlate with the first order degradation rates but not with the settlement of MSW. Amounts above 20% are very important for the biodegradation of MSW.
- Plastic material affects the measurements of volatile solids and lignin. Therefore, it is important to account for plastics if these measurements are used to predict remaining biodegradable material. Samples of MSW contained an average of 10% plastic, which may be appropriate to deduct from volatile solids and lignin measurements.

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Column #	Ave. Temp. (°F)	Ave. Temp. (°C)	Ave. Moisture %	Lechate Recirc.
1	108.7	42.6	50.5	yes
2	105.75	41	42.9	no
3	98.65	37	42.7	yes
4	102.85	39.4	35.5	yes
10	94.45	34.7	37.0	no
11	90.75	32.6	42.1	no
12	75.85	24.4	20.4	no

Table 3.1. Temperature, moisture, and leachate recirculating conditions for seven columns.

First Order Rate (day^{-1})

	VS	Cellulose	C/L	Lignin
w/ recirculation	0.000867	0.0019	0.001633	0.0003
w/o recirculation	0.0006	0.000925	0.00075	0.0002

Table 3.2. First order degradation rates for columns with and without leachate recirculation.

	VS rate (day^{-1})		Cellulose Rate (day^{-1})	
Column #	Before Heating	After Heating	Before Heating	After heating
1	0.0005	0.0005	0.0011	0.0013
2	0.0003	0.0012	0.0005	0.0022
3	0	0.0006	0	0.0017
4	0	0.0015	0.001	0.0027
10	0.0004	0.0002	0.0003	0.0006
11	0.0007	0.0008	0	0.0013
12	0.0002	0.0002	0	0

Table 3.3. Volatile solids and cellulose degradation rates for seven columns before and after heating.

Column #	Total Settlement (inch)
1	5
2	-
3	2.375
4	3.6875
10	1.953
11	1.25
12	1.895

Table 3.4. Total settlement of each of the seven columns.

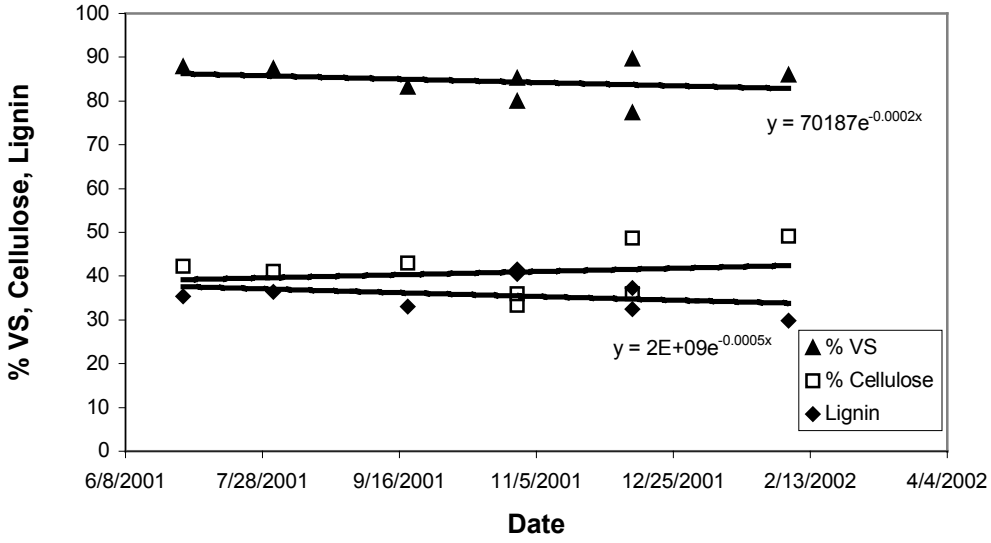

Figure 3.1. Control column (#12). No heat or moisture added.

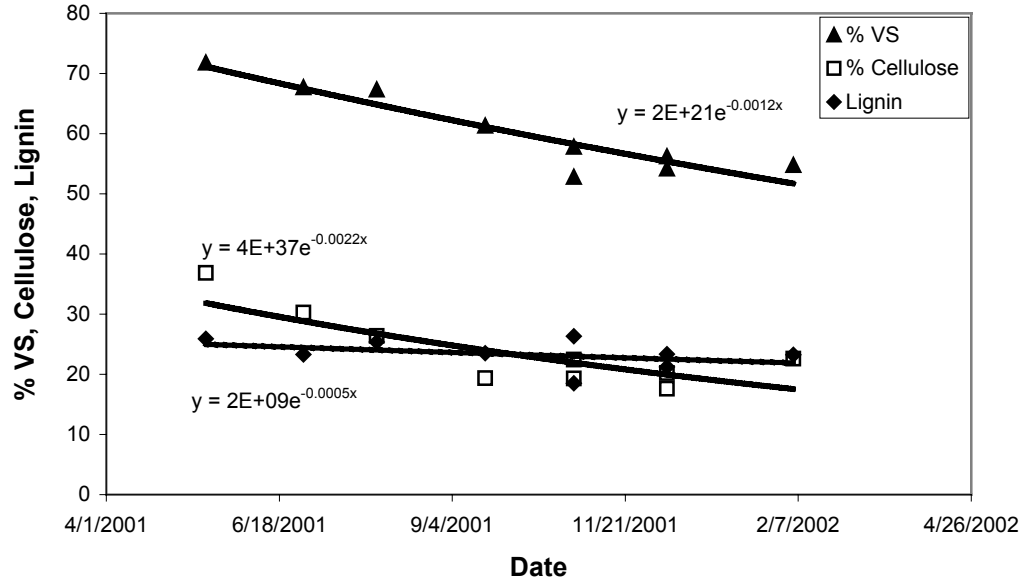

Figure 3.2. Column 2 at 105.75 ^{0}F and 42.9% moisture.

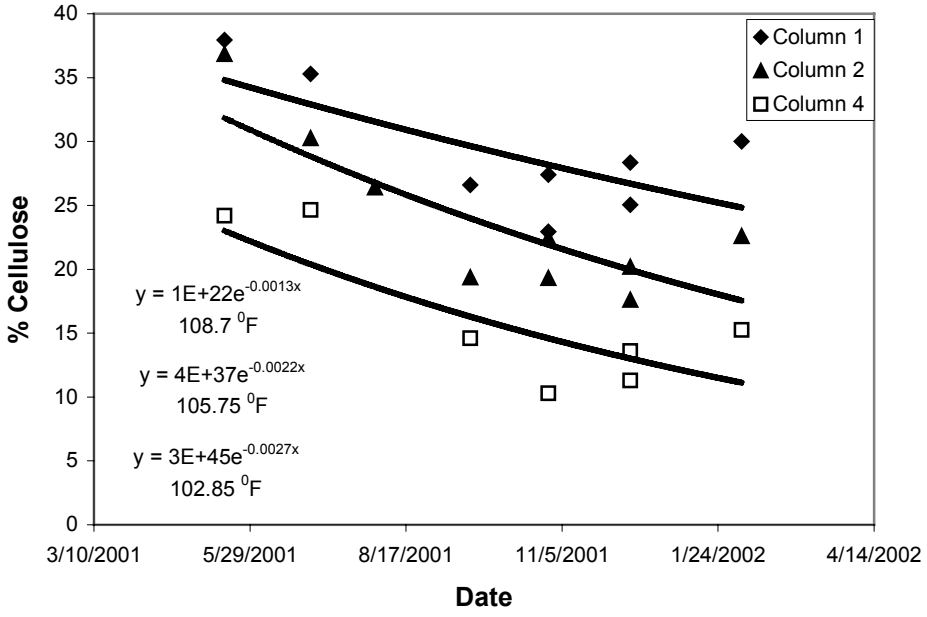

Figure 3.3a. Cellulose degradation for three columns over 100 ^{0}F.

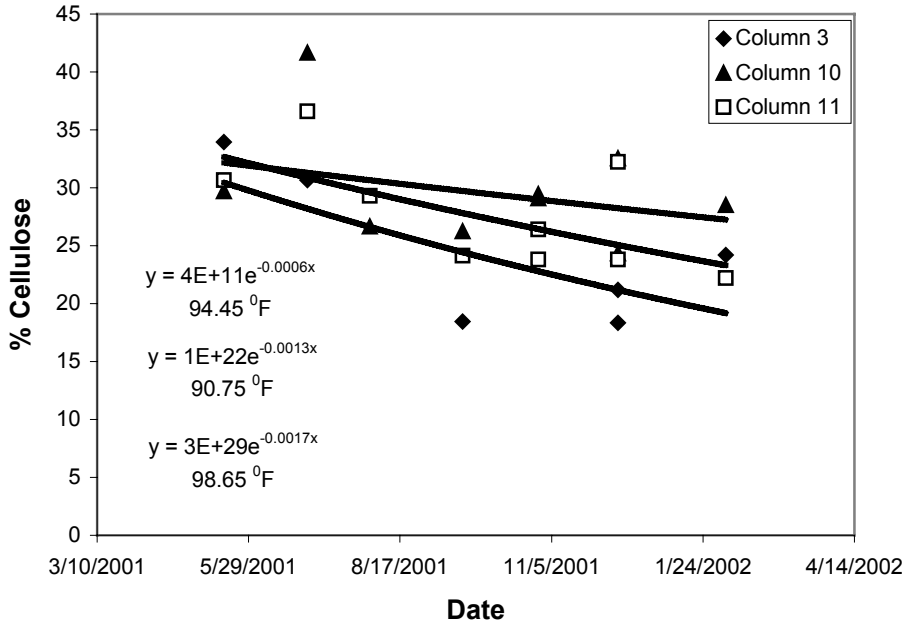

Figure 3.3b. Cellulose degradation for three columns under 100 ^{0}F.

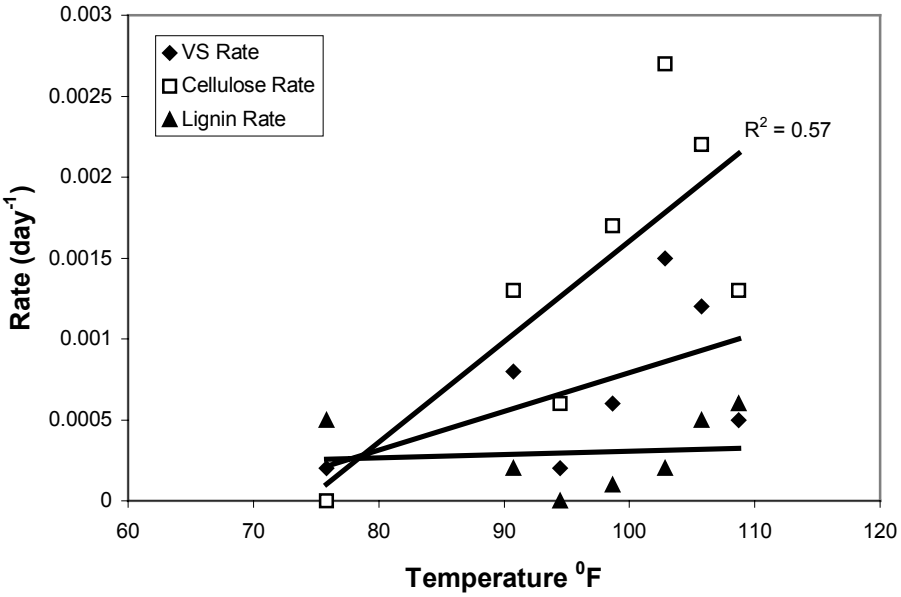

Figure 3.4. Temperature plotted against degradation rates of volatile solids, cellulose, and lignin

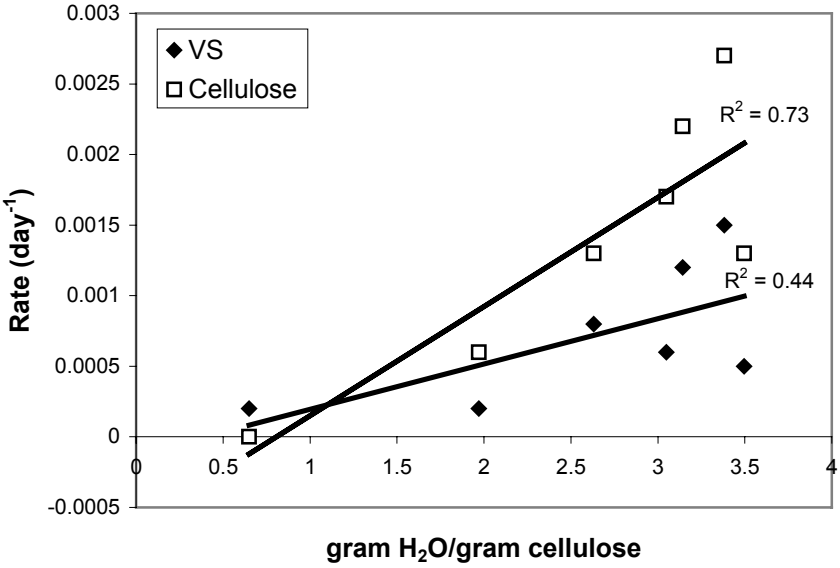

Figure 3.5. Moisture plotted against degradation rates of volatile solids and cellulose. Moisture is normalized to the amount of cellulose present in the MSW.

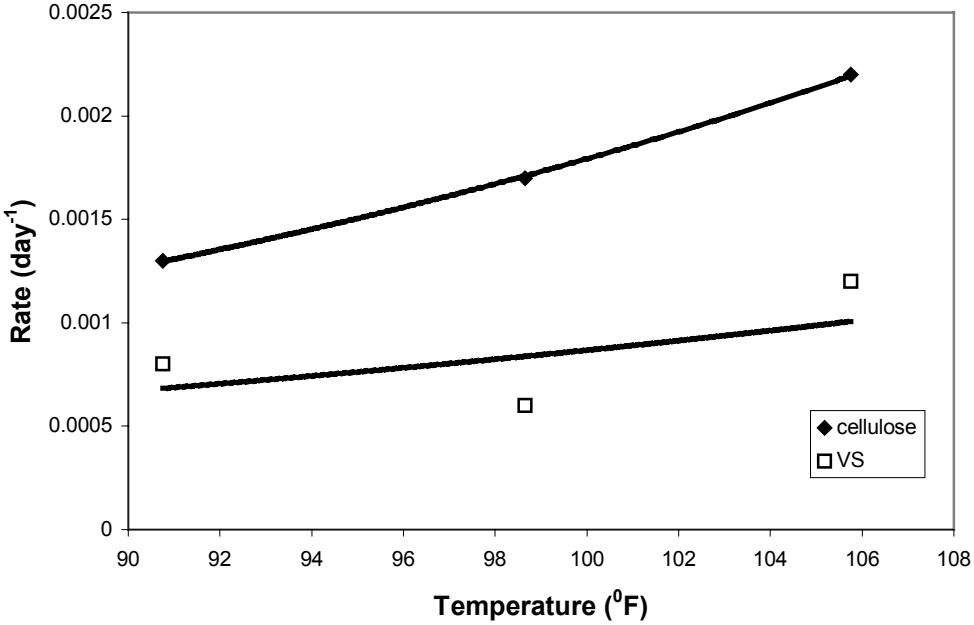

Figure 3.6. Temperature plotted with degradation rates for volatile solids and cellulose for columns with 42% moisture.

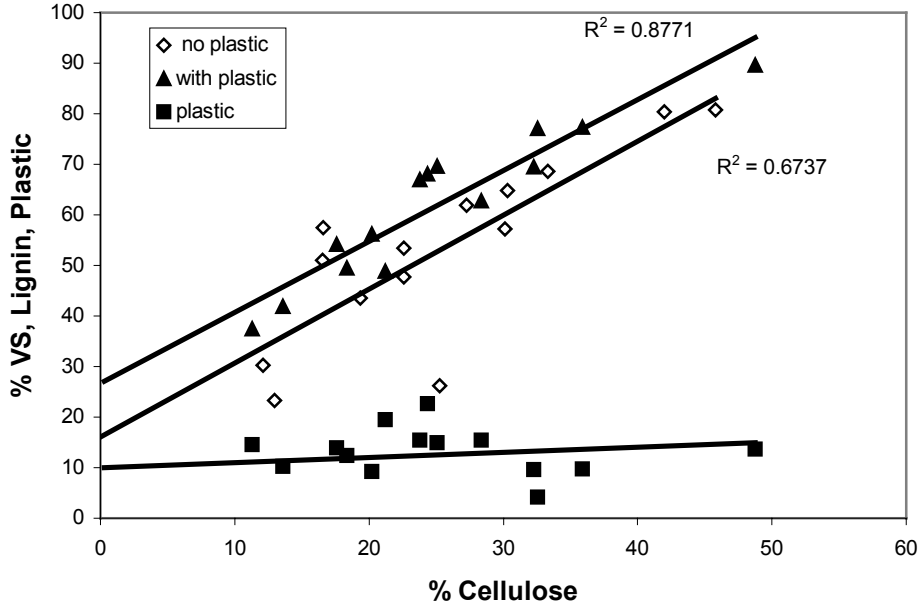

Figure 3.7. Cellulose plotted with volatile solids for samples with and without plastic.

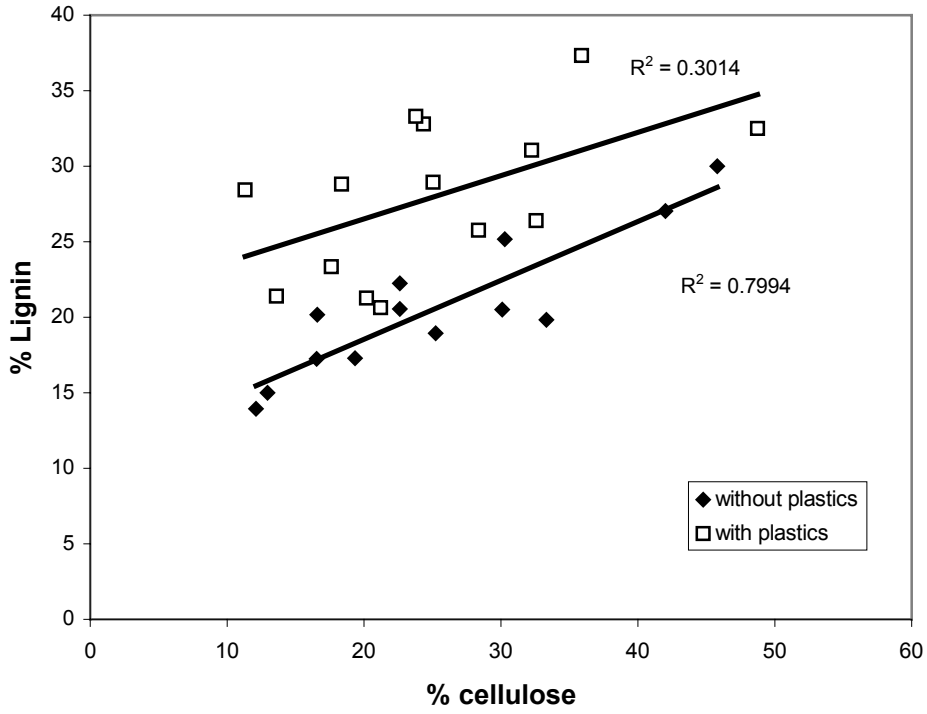

Figure 3.8. Cellulose plotted with lignin for samples with and without plastic.

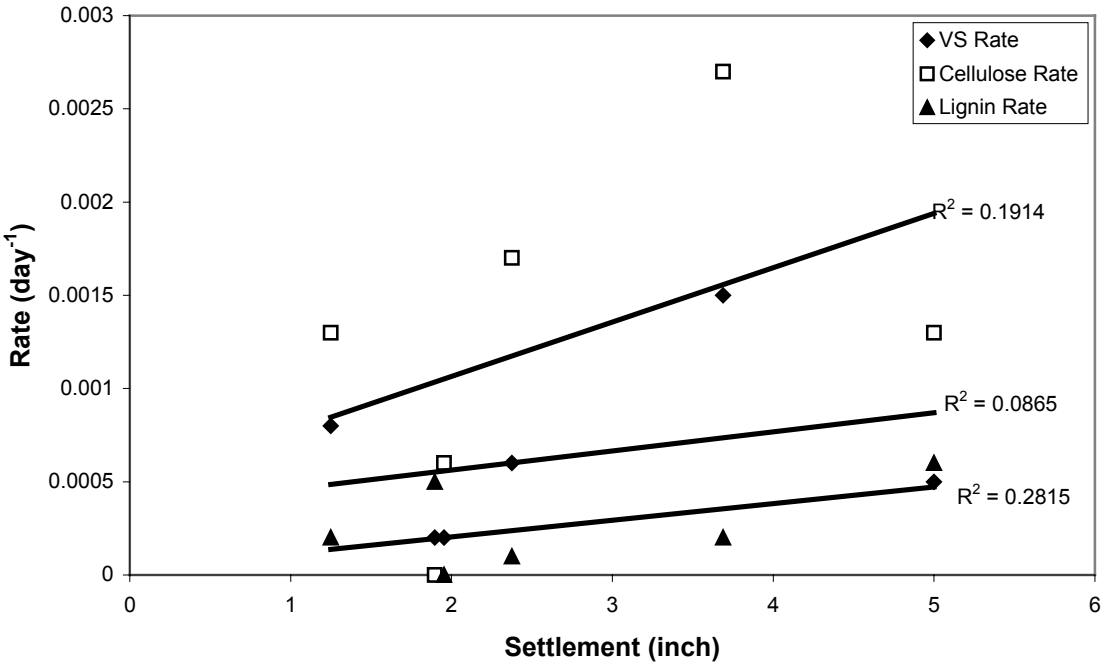

Figure 3.9. Settlement plotted with first order rates of VS, cellulose, and lignin.

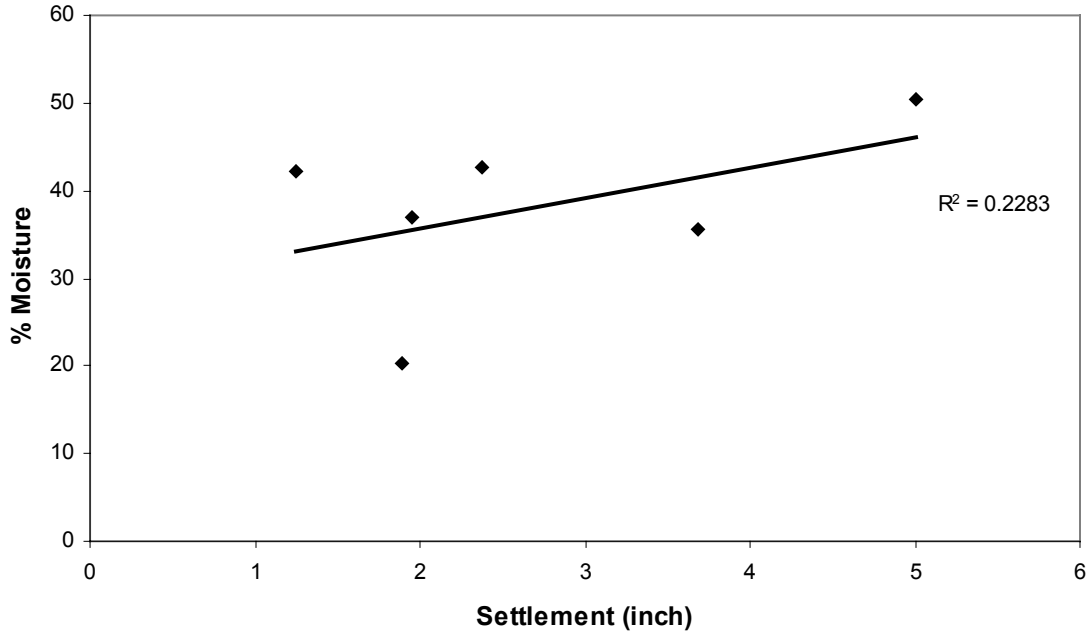

Figure 3.10. Settlement plotted with moisture for six columns.

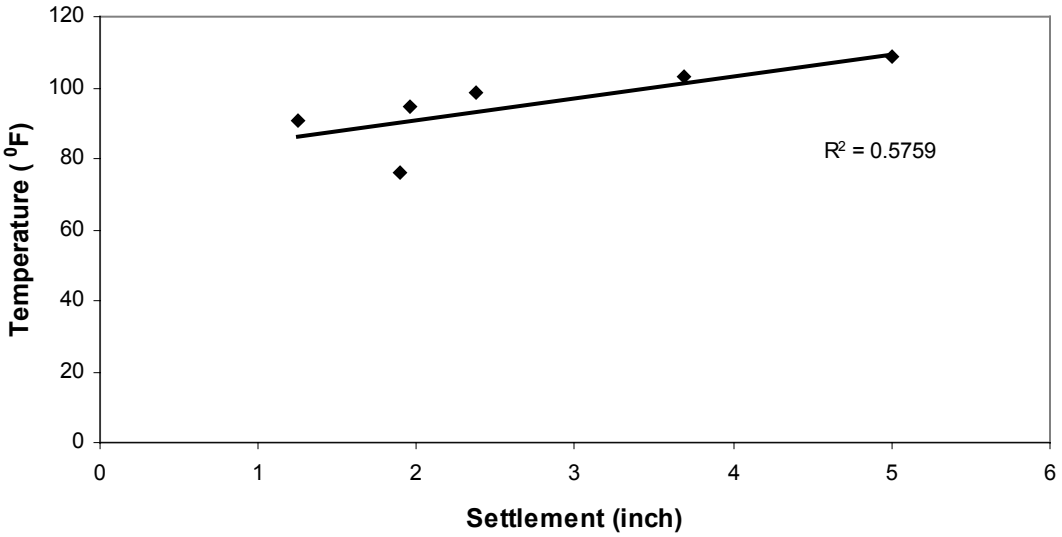

Figure 3.11. Settlement plotted with temperature for six columns.

CHAPTER 4

RELATIONSHIPS BETWEEN ANALYTICAL METHODS UTILIZED AS TOOLS IN THE EVALUATION OF LANDFILL BIOREACTOR STABILITY

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Submitted to **Journal of Environmental Engineering, ASCE**
April 2002

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RELATIONSHIPS BETWEEN ANALYTICAL METHODS UTILIZED AS TOOLS IN THE EVALUATION OF LANDFILL BIOREACTOR STABILITY

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Abstract

In this study, the refuse from 11 landfills was collected over various residence times ranging from fresh refuse to material landfilled for over 10 years and changes in the various stability parameters over time were determined. The stability parameters were compared to determine which would be easiest to run and most indicative of the stability of the refuse. Rates of stabilization for all parameters were represented by first order decay rates. Rates for volatile solids, cellulose, and biochemical methane potential (BMP) degradation were 0.0003, 0.0007, and 0.001 (day^{-1}) respectively. Lignin and volatile solids measurements were significantly affected by plastics in refuse samples and lignin was also found to degrade in landfill environments. Cellulose and volatile solids measurements correlated well with each other and with BMP measurements and were therefore be considered the best parameters to determine stability. End points for stabilized refuse were chosen as 10-20% volatile solids, 2-5% cellulose, and 10-20 (ml/g) BMP.

Introduction

Many solid waste landfills are now being designed or converted to permit more rapid stabilization of refuse. These "bioreactor landfills" have increased moisture contents and this allows for a greatly increased rate of biological activity. This concept was an outgrowth of the practice of leachate recirculation, which was originally designed as a method to limit the discharge of leachate and improve its quality. The leachate recirculation studies showed that leachate recirculation improved leachate quality, but in addition, the time needed for landfill stabilization was substantially reduced due to the increased moisture content.

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Many existing landfills are being considered for conversion to bioreactors. This is possible because the improved liner systems used under Subtitle D of the Resource Conservation and Recovery Act of 1976 provide a closed vessel-like environment that allows for leachate collection and recirculation without concern for losses to the environments. The time requirements for recirculation will depend on the time it takes to stabilize the contained solid waste mass and treat the leachate. Stabilization is generally described as the nearly complete biological conversion of degradable material to methane and carbon dioxide. Leachate quality requirements will depend on the method of disposal but would include reduced BOD and heavy metal concentrations.

Delivery of the recirculated leachate and added liquid to the waste mass is most frequently accomplished by the use of horizontal infiltration trenches, vertical injection wells, application of the leachate to the working face, spray irrigation or shallow pond infiltration. The overall process has become commonly known as a landfill bioreactor. However, the waste management industry has defined the application of liquids into two categories. These are a) leachate recirculation only and b) recirculated leachate plus addition of other available liquids such that the moisture content maximizes the stabilization rate.

The advantages of leachate recirculating systems have been well documented at both the bench and pilot-scale (Reinhart and Townsend, 1998). The practice of leachate recirculation was studied during the 1970's and early 1980's as a method of leachate treatment (Pohland, 1975; Leckie, et al., 1979; Ham and Bookter, 1982). More recently, full-scale bioreactor studies have been undertaken to determine the relevant design and operational parameters (Reinhart and Townsend, 1998). Bioreactor landfills should provide substantial economic and environmental benefits. Total degradation of the waste mass can produce settlements approaching 40 percent (Green, 2000) and can result in additional capacity that can be captured during the active phase of the landfill. Moreover, the cost of leachate management may be substantially lowered and largely eliminates the need for off-site management.

The landfill bioreactor enhances the organic biological degradation rate and, therefore, increases anaerobic gas production. Methane gas generation is enhanced and concentrated during the active life of the landfill. This makes it easier to manage the gas and should lower the total mass of climate change gases emitted to the environment. The closed landfill that has been operated as a bioreactor should become much less of a long-term environmental liability and can be integrated back into the conventional land use system much more quickly. There is a larger spectrum of positive economic end uses for a closed landfill with a stabilized waste mass and no leachate or gas concerns (Green, 2000).

While the advantages of bioreactor landfills are clearly understood, documentation of their performance has been limited. Landfill stabilization may require 50 years or longer for conventional landfills while 5 years or less may be needed to achieve stabilization using landfill bioreactor technology (Kilmer, et al. 1999; Pohland, 1975; Watson, 1993). Waste Management, Inc. began the implementation of the landfill bioreactor concept in

1998 and has plans to study these through 2003 at multiple sites. Two of the sites included in this study (Maplewood and King George, VA) are slated to be part of the EPA XL program. This "excellence and leadership" program allows private businesses, state and local governments, and federal facilities to develop innovative strategies with the EPA to achieve cost-effective or better environmental and public health protection. In this study, described in detail below, the rates of degradation and evaluation of stabilization parameters were evaluated to determine the most cost effective method for determining landfill stability and the rates of stabilization for the various landfill types.

This Study

Solid waste samples were collected and analyzed from eleven WMI landfills as part of an evaluation of stabilization parameters used to characterize landfills. The landfills range from 0.5-11 years of age. The biochemical and physical parameters evaluated to determine the rate of stabilization of the landfill waste mass have historically been cellulose, lignin, pH, volatile solids and biochemical methane potential. Certain parameters such as volatile solids are very simple, low cost, and take very little time while other analyses such as biochemical methane potential are complex and require extensive time to obtain the result. The ability to integrate the bioreactor technology with daily operations is the greatest challenge to the implementation of this approach and requires scientific, environmental and financial evaluation before it can be fully utilized.

The purpose of this study was to collect field and lab data to determine which analytical parameters are the best to describe the stability of landfill waste and if relationships exist between any of the parameters. The objective of examining the relationships between these analyses is to determine if sufficient information can be gleaned from fewer and simpler methods that will allow an accurate determination to be made as to the status of any given landfill regardless of the operational method. This will allow for the simplest and most cost effective analyses to be performed on landfill waste.

Methods and Materials

Sample Collection

Municipal solid waste (MSW) samples were collected beginning in the fall of 1999 to Spring 2002 using the sampling procedures following those traditionally used in the industry. A drill rig equipped with a 0.91m (3') bucket auger was used. Each location was sampled with the bucket auger in 3.05m (10') vertical sections with one representative composite sample prepared for each section. The initial five feet of material was generally discarded because it contained a large amount of soil cover. A ten-pound sample was extracted from each full auger and placed in a roll-off box to collect a representative composite sample. The appearance of the waste was observed

and recorded as the boring advanced. Each composite sample was thoroughly mixed while in the roll-off and a sub- sample was removed and placed in an appropriate plastic container for express shipment to the laboratory.

Some limited lab-scale studies were also performed as part of this study. Solid waste from the Metro Landfill, WI was placed in 2.44m x 0.46m (8'x18'') high-density polyethylene columns and exposed to various moisture, temperature, and leachate recirculating conditions to simulate landfill and bioreactor environments. Each column contained four sampling ports at equal intervals along the 2.44m (8') column length. Approximately 100 grams was removed from each of the four ports and a composite sample prepared for each column by thoroughly mixing the samples.

Analytical Parameters

pH

A slurry was prepared in the field by adding approximately 250 milliliters of deionized water to 100 grams of waste. The pH meter was calibrated with pH 7 standard and another standard (e.g., pH 4) expected to bracket slurry pH values. The pH was recorded if it fell within the bracketed standards. If not, the pH meter was recalibrated and the sample reanalyzed.

Moisture

The moisture content was determined by modified Standard Method 2540-B (APHA 1992). At least one kilogram of as-collected solid waste was dried in an aluminum pan at 105^0C to a constant weight after cooling under desiccation. The moisture content is determined by weight loss from the original sample and expressed as a percent.

Laboratory Sample Preparation

Oven dried (105^0 C) MSW was reduced to a particle size less than 0.3cm in a bench top glass and stainless steel blender. Further grinding in a Wiley Mill with a 10-mesh screen achieved a powder-like consistency. Non-grindables such as rocks nails, etc. were removed by hand before processing.

Volatile Solids

The volatile solids procedure followed a modified version of Standard Methods APHA Method 2440-E. Samples were dried once again at 105^0 C to a constant weight and held in a desiccator. Approximately two grams of dried MSW were placed in pre-weighed porcelain crucibles and inserted into a muffle furnace at 550°C for 2 hours. Samples were removed and allowed to cool in a desiccator to a constant weight. The percent weight loss on ignition yields the total amount of volatile matter.

Cellulose and Lignin

The cellulose and lignin analysis followed ASTM E 1758-95^{e1}. A sample size of 300 mg of dry, milled MSW was used for this measurement. The cellulose was hydrolyzed into glucose monomers in two stages using sulfuric acid. The samples were digested in three milliliters of 72% sulfuric acid in a water bath at 45^{o}C for two hours. Samples were then transferred to 250 mL septa bottles using 84 mL of nanopure water and autoclaved for one hour at 121^{o}C and 15 psi. The samples were subsequently filtered using standard TSS glass fiber filters. The volatile suspended solids (combusted at 550^{0}C) remaining after hydrolysis was considered lignin. The filtrate was then neutralized using $CaCO_3$ powder directly. The glucose was quantified using a HPLC with a refractive index detector and HPX-87C carbohydrate column.

Biochemical Methane Potential

Biological methane potential (BMP) was modified from a procedure described by Owens and Chynoweth (1993) and later by Stinson and Ham (1995). Two grams of dry, shredded MSW were added to a 250 mL Boston round septa bottle. Then, 100 mL of revised anaerobic media was added to each bottle. The media was made following these methods except for two modifications. The vitamin solution was not included, and anaerobic biosolids from the Peppers Ferry anaerobic digester, Fairlawn, VA were added as the inoculum (10% by volume). The bottles were incubated inverted for 45 days at 35^{o}C. At the end of the incubation period, one-liter Teflon gas sampling bags were connected to each bottle for twenty minutes while agitating the bottle to relieve excess pressure. A 100-microliter sample was taken from the gas-sampling bag and injected into a GC with a carbosieve packed column and a flame ionization detector. The volume of gas in the gas-sampling bag was measured using a 60 mL plastic syringe. This test was run in triplicate with one blank for every six bottles. The amount of methane measured in the blanks was deducted from that of the samples. The BMP was reported as milliliters of methane per gram of dry MSW at STP (mL/g).

Plastics

All plastic material from each laboratory column sample was identified by sight, removed by hand, and weighed. Both the plastic and non-plastic portions of the samples were dried to determine moisture and then split into two equal parts by weight. One part plastic and one part non-plastic samples were thoroughly mixed to give a representative sample of original column solid waste and the percent plastic material on a dry weight basis calculated. The remaining portion of non-plastic sample was also retained and properly labeled as containing no plastic.

Results and Discussion

The degree of stabilization of landfilled MSW has traditionally been determined by the results of cellulose, lignin and biochemical methane potential analyses (Shearer, 2001). The cellulose/lignin ratio has also been used to infer the degree of biological degradation that has occurred in the landfill MSW (Stinson and Ham, 1995). Cellulose and lignin are the principal components of wood and paper products and the disappearance of cellulose from MSW is considered a direct indicator of biological stabilization. The use of the cellulose to lignin ratio is based on the premise that cellulose is easily consumed in an anaerobic environment while lignin is not. Therefore, although the contents of a refuse sample can be highly variable, the C/L ratio of fresh refuse will be relatively constant because the ratio of cellulose to lignin in mixed paper varies little. The C/L ratio would be a larger number in fresh MSW (2-3) and lower in older, more degraded MSW (<1).

The BMP is a measure of the amount of material remaining in the MSW that may be readily converted to methane and is essentially the anaerobic equivalent to the BOD test as performed in the wastewater industry. Previous research findings also indicate that there is a strong correlation between the analytical parameters of volatile solids and cellulose (Suflita et al.,1992, Shearer, 2001), suggesting that cellulose is the primary product degraded during anaerobic treatment of MSW.

One objective of the intense analytical monitoring of multiple landfills was to determine if general relationships between parameters exist. Since analytical costs can be high, this would allow for the most inexpensive methods that provide the information necessary for operating and evaluating the status of any given landfill bioreactor or leachate recirculation system. It would also be useful to develop relationships between changes in MSW and leachate characteristics but this was not included in this study. The number of samples analyzed in this study (over 250) should allow for an accurate evaluation of the data collected from a variety of landfills at different stages of stabilization and being operated under several treatment scenarios. It should also permit a comparison of landfills to see the similarities and differences.

A comparison of volatile solids with the age of the samples, presented in Figure 4.1, shows a decrease in the amount of volatile solids with age. However, the variability is high because each landfill has unique biodegradation properties, the waste is very heterogeneous, and moisture distribution can vary spatially. Samples with volatile solids less than 20% are generally considered stabilized because they contain very little degradable material. Most of the remaining volatile solids would be expected to consist of plastics and perhaps lignin.

Figure 4.1 also shows a separate trendline for samples from Riverbend, OR. This landfill has a high moisture content in comparison to all the other landfills. Table 4.1 shows

moisture for the six landfills with the most data. No data was available from the Riverbend landfill for fresh refuse so initial (time = 0) values were assumed to be the same as other fresh refuse data and these initial values were used to determine degradation rates. The initial parameter values are listed in Table 4.2. Degradation rates for the Riverbend Landfill, presented in Table 4.3, show a 50 to 100 percent increase when compared to all other landfills. The data from Riverbend shows that a high moisture content can greatly increase the degradation of solid waste so that stabilization occurs in just one or two years. Table 4.2 also shows parameter values for waste that is considered sufficiently stabilized. These values were selected from the most degraded samples from the Riverbend landfill and the oldest samples from other landfills that were also considered highly degraded.

The percent cellulose versus age of the samples are shown in Figure 4.2. There is a substantial decrease in the percent cellulose with age and the samples from Riverbend, OR show a much higher rate of cellulose degradation than the other landfill cellulose degradation rates. Degradation rates for both the Riverbend landfill and all other landfills were described using a first order decay rate.

A comparison of cellulose and volatile solids, shown in Figure 4.3a, indicates a relatively strong correlation between these two parameters. The cellulose method is approved, accurate and the results should vary only with the sample source. The volatile solids measurement is a simple test but would be expected to vary more than cellulose due to the presence of non-biodegradable and highly variable organics such as plastics. The values of volatile solids in the samples ranged from 8-90 percent while cellulose values ranged from 2-52 percent. The slope of the linear fit to the data was approximately 2:1 and the intercept near 10 percent. The intercept of 10 percent suggests the presence of some non-cellulose substance susceptible to loss by incineration at 550^0C and could be assumed to be plastics and perhaps some lignin. The value of cellulose would appear to be reasonably predicted by volatile solids.

The relationship between cellulose and volatile solids is also confirmed by the data from the lab-scale columns shown in Figure 4.4, which shows a strong correlation between cellulose and volatile solids. The percent of plastics, determined by hand collection and weighing, is also shown on this figure and is approximately 10 percent of the weight as indicated by the intercept of the trendline. Data from the same samples are plotted on the graph but with the plastics removed. The samples without plastics show that the trendline for the cellulose and volatile solids is shifted down by 10 percent, confirming that plastic material is detected in the volatile solids measurement. If Figure 4.3a is re-plotted by subtracting 10 percent from the volatile solids measurement, the intercept of the trendline passes much closer to zero as shown in Figure 4.3b. These data indicate that the cellulose can be estimated from the amount of volatile solids minus plastic (approximately 10 percent) in a sample.

The examination of lignin versus volatile solids in Figure 4.5 shows a much weaker relationship between these parameters than for cellulose and volatile solids. The line of best fit for the data passes through the y-axis at approximately 8 percent. This is most

likely due to the inclusion of plastics in the lignin test method. The solids remaining after acid hydrolysis and filtering during the cellulose analysis determine lignin gravimetrically. The material remaining on the filter is weighed and subjected to a volatile solids analysis. The volatile portion is assumed to be lignin and the indestructible portion is inorganic debris such as glass, sand, etc. Since most plastic material is not hydrolyzed by acid and is volatile at 550 ^{o}C, it will be characterized as lignin in this test. Figure 6 shows the relationship of lignin and volatile solids from the columns and the impact of plastics on the lignin method. In this figure the trendline is shifted down by approximately 10% when the plastics are removed. This is consistent with the data in Figure 4.4 that shows these samples contain an average of 10% plastics. Figure 4.6 also shows a higher correlation between the two parameters when plastics are removed.

The values for lignin in the landfills ranged from 7-35 percent. A plot of lignin with age of the landfill (Figure 4.7) suggests that lignin is degraded but at a much slower rate than cellulose or volatile solids. Because the lignin measurement also contains plastics, the true rate of lignin degradation may be higher than indicated on the figure. A comparison of lignin with cellulose, shown in Figure 4.8, suggests that lignin degradation may occur only after cellulose levels drop below approximately 25%. These relationships indicate that lignin degradation is occurring but at a slower rate than the overall rate for cellulose. This suggests that the use of lignin as a non-degradable standard is only valid for the early stages of a landfill where the readily degradable material such as food wastes and free cellulose are being degraded.

The relationship between lignin and cellulose is also influenced by the presence of plastics. To further evaluate the influence of plastics, the lignin versus cellulose data for the laboratory columns is shown in Figure 4.9. The samples with plastics removed have an R^2 value of 0.80, which is much higher than the samples with plastics (R^2=0.30). Also, the lignin trendline is shifted down for the samples with no plastics by about 10%. Referring back to Figure 4.4, these data show that these samples contain an average of 10% plastics.

The biochemical methane potential analysis, although not an accepted standard method, offers insight with regard to the amount of material in MSW that can be readily converted to methane. The BMP is subject to variability based upon inoculum type (specific acclimated cultures versus digester solids), container volume and variations in the sample amount used. The BMP test as performed here was prepared to simulate the anaerobic landfill environment, yet be relatively simple to conduct. The relationship between BMP and volatile solids as presented in Figure 4.10a suggests that the BMP is a reliable measure of remaining biodegradable volatile solids. The intercept of the trendline at approximately 7% again shows the influence of plastics in the volatile solids test. These plastics are non-biodegradable and would exhibit no methane potential. The BMP values ranged from little or no methane production to nearly 200 mL/g dry sample. However, methane was always produced in the presence of any concentration of cellulose. As expected, the relationship between BMP and cellulose is strong, as seen in Figure 4.10b. Figure 4.11 shows a correlation of BMP with age of the sample. As the samples increase

in age, the methane potential decreases, indicating degradation and stabilization of the solid waste.

In support of the observation that lignin is degraded, although to a lesser extent than cellulose, the relationship between BMP and lignin concentration is shown in Figure 4.12. These data show a poor correlation between lignin and BMP. However, lignin does decline as BMP declines, suggesting that it, along with cellulose, contributes to the production of methane. Stinson and Ham (1995) suggested that lignin-associated cellulose may be degraded more slowly than unassociated or free cellulose. Data shown in Figure 4.8 suggests that lignin does not decline until cellulose is less than approximately 25%. When the cellulose content is less than 25%, lignin declines as cellulose declines. While these data are not conclusive because of the variability in samples, it appears that Stinson and Ham are correct and the lignin and lignin-associated cellulose comprises the bulk of the slowly degradable material in landfills. If bioreactor landfills are to reduce the time needed for landfilled solid waste to become stable, it is the lignin and lignin-associated cellulose fraction, not free cellulose, that is most critical and needs to be evaluated and characterized.

A plot of BMP versus C/L ratio in Figure 4.13a and a plot of volatile solids versus C/L ratio in Figure 4.13b both show very weak correlations. Both these plots show that the C/L ratio does not correlate well with the other parameters and this may be the result of lignin degradation and the impact of plastic material on the lignin method. Figure 4.14 does show that the C/L ratio can be correlated with the age of the solid waste sample although this correlation is weaker than the correlation between age and volatile solids, cellulose, and BMP. Therefore, there appears to be little advantage to using the C/L ratio in place of cellulose alone.

The data collected in this study suggest that lignin will degrade in landfills and the measurement of lignin is greatly impacted by plastics. Therefore, lignin may not be a good monitoring parameter in the operation of landfills or as an indicator of solid waste stability. Further, since the cellulose/lignin ratio relies of the measurement of lignin and does not correlate well with any other parameter it is of limited use as a monitoring tool.

The biochemical methane potential (BMP) was shown to correlate well with volatile solids and cellulose, and declines in an expected manner with the age of the landfill. However, the BMP measurement can be quite variable within a single sample and several replicates are needed to give a representative measurement. Also, the inoculum type and toxicity may affect the results of the test. Therefore the BMP measurement is most appropriately used for the determination of solid waste stability when used in conjunction with other measurements.

The volatile solids and cellulose measurements appear to be the best parameters to determine the stability of municipal solid waste. These two parameters correlate very well with each other, with BMP, and with the age of the solid waste sample. The cellulose measurement is accepted and shows low variability. The volatile solids measurement also shows very low variability and is very simple to perform. Since the

volatile solids measurement is affected by plastics, it may be advisable to remove all plastics before completing the test or subtract a standard value (10%) from VS measures.

Conclusions

- First order VS, cellulose and BMP stabilization rates for the landfill (Riverbend, OR) that contained the highest moisture content (48%) were twice those of the drier (31-38%) landfills.
- Cellulose and volatile solids appear to be the best parameters for characterizing landfill stability. Because the volatile solids measurement is affected by plastics, it is advisable to account for plastics when using VS data.
- Lignin appears to degrade in landfills but at a slower rate than cellulose.
- Values for lignin also include plastics unless these are specifically removed.
- Because the lignin measurement includes plastics and appears to degrade, the use of the C/L ratio as an index of degradation has no advantage over cellulose alone.
- Biochemical methane potential (BMP) correlates well with other parameters but is time extensive and results are highly variable. BMP is best used in conjunction with parameters such as cellulose or volatile solids to determine stability.
- End points that can be used to define stabilized refuse are 2-5% cellulose and 10-20 (ml/g) BMP. A volatile solids content of 10-20% may also indicate stability but plastics make this end point value less certain.

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	Moistures of Selected Landfills					
	Riverbend	Metro	King George	Maplewood	Middle Penn	Central
Highest Moisture	71	59	48	53	44	51
Average Moisture	48	31	36	38	37	33

Table 4.1. Average and Peak Moisture Contents of Selected Landfills.

	Values for start and End Points			
	VS %	Cellulose %	BMP (ml/g)	C/L
Start	85	45	175	2.5
End	10-20	2-5	10-20	0.2

Table 4.2. Starting and Ending Values of Stability Characterization Parameters.

		Degradation Rates (day^{-1})	
Landfill	VS	Cellulose	BMP
Riverbend	-0.0006	-0.0013	-0.0015
All others	-0.0003	-0.0007	-0.001

Table 4.3. Degradation Rates For Volatile Solids, Cellulose and BMP For 7 Landfills.

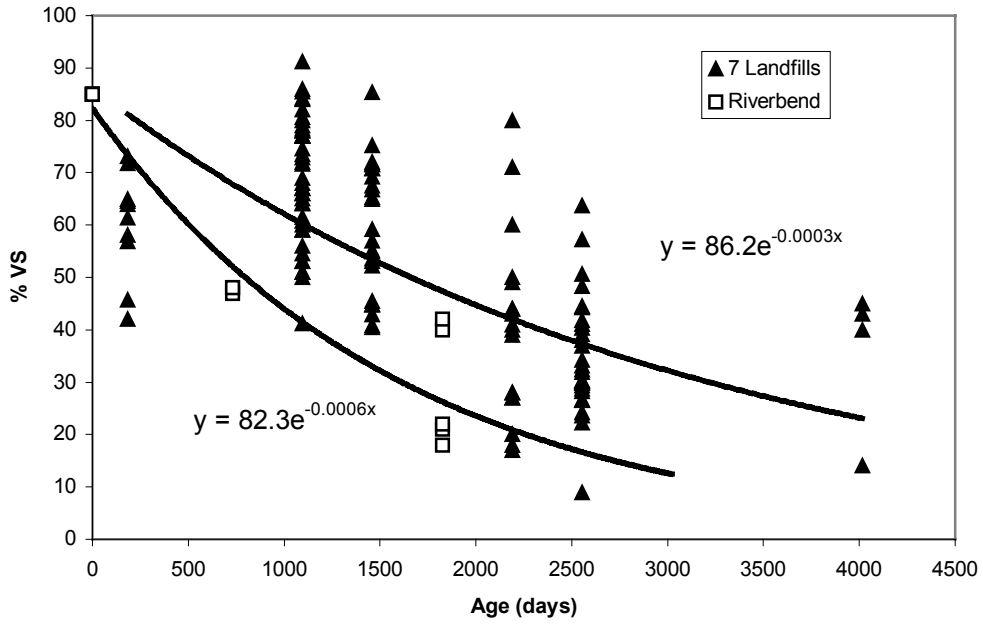

Figure 4.1. Change in Volatile Solids With Landfill Age. The Riverbend Landfill Is Plotted Separately Because It Contains a Much Higher Moisture Content.

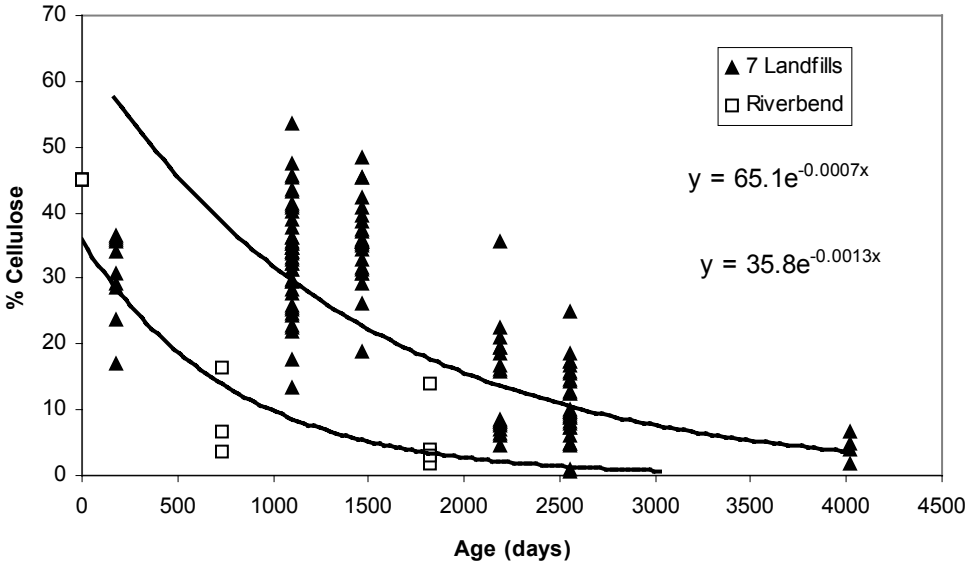

Figure 4.2. Change in Cellulose With Landfill Age For The Riverbend Landfill and Seven Other Landfills.

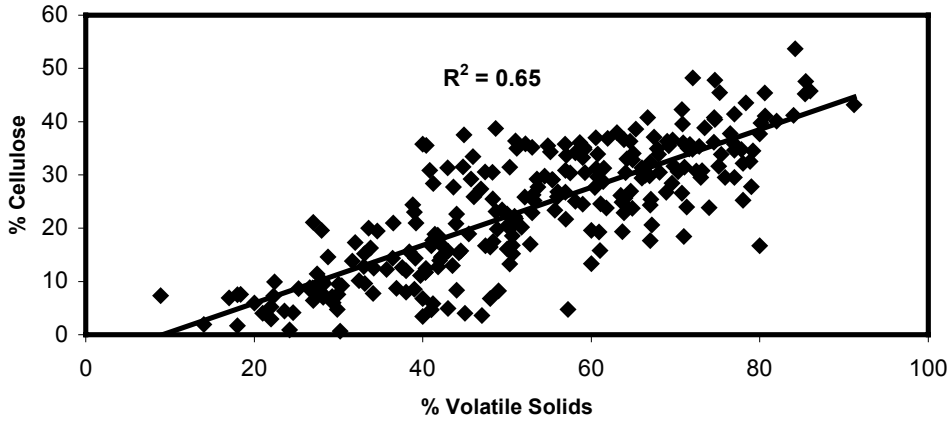

Figure 4.3a. Relationship Between Volatile Solids and Cellulose Using Data From Eleven Landfills.

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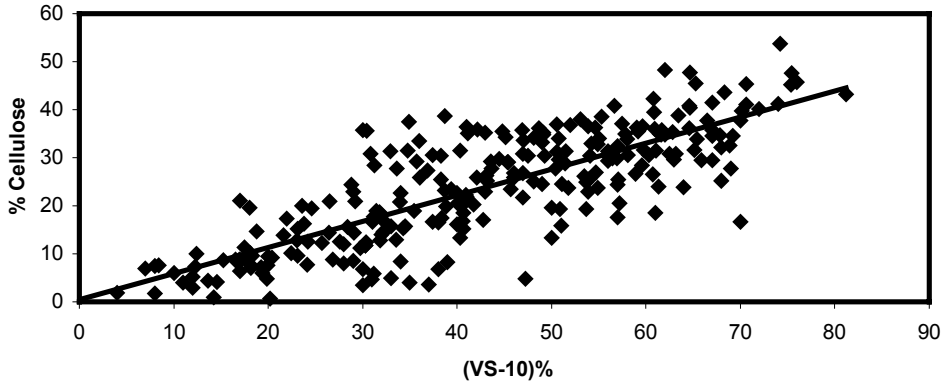

Figure 4.3b. Relationship Between Volatile Solids minus 10% and Cellulose.

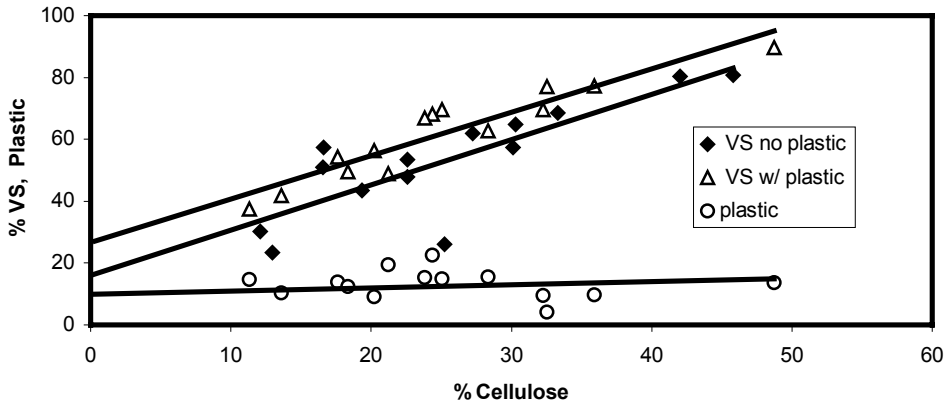

Figure 4.4. Relationship Between Volatile Solids and Cellulose for Test Column Samples With and w/o Plastics Included.

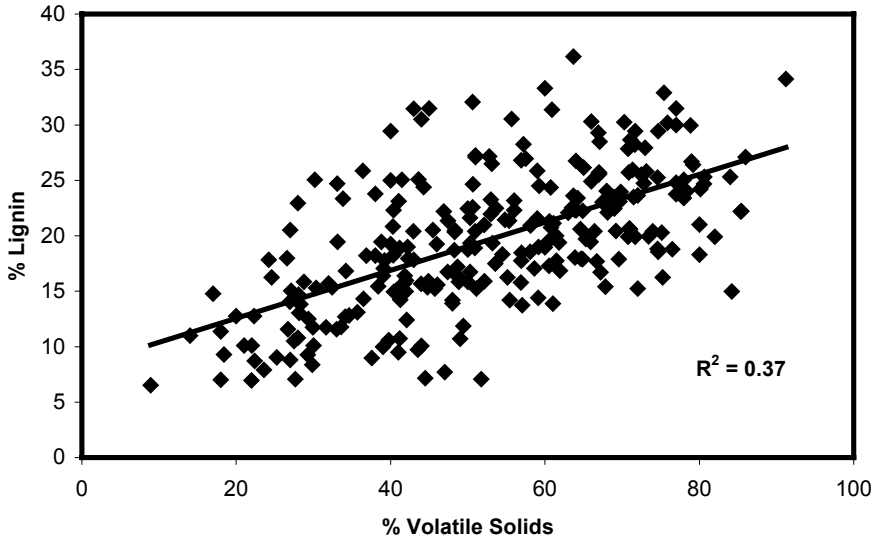

Figure 4.5. Relationship Between Volatile Solids and Lignin For Eleven Landfills.

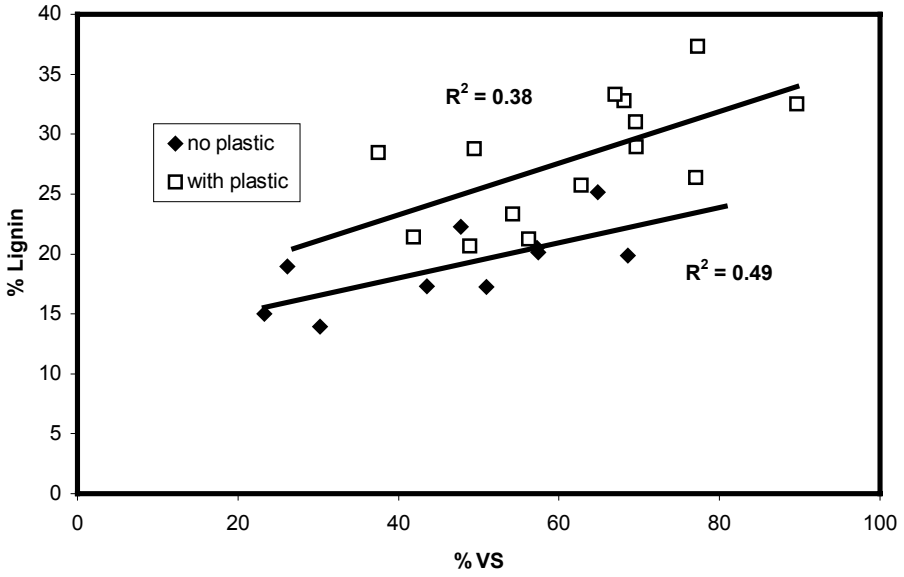

Figure 4.6. Relationship Between Volatile Solids and Lignin For Test Column Samples With and Without Plastics.

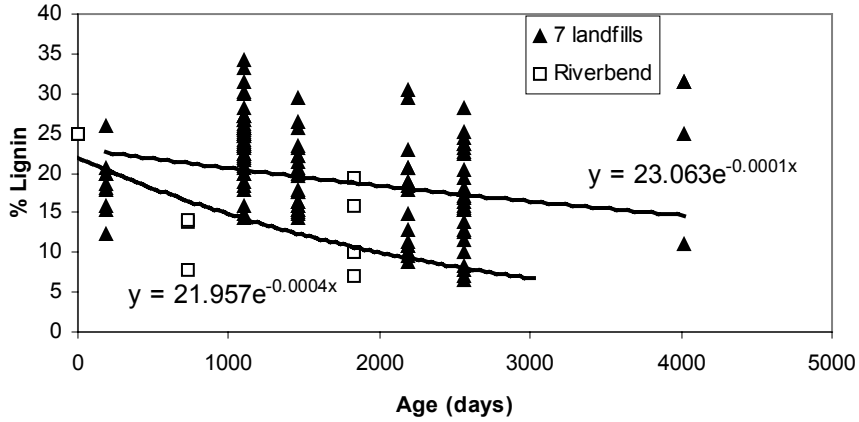

Figure 4.7. Change in Lignin With Age For Seven Landfills.

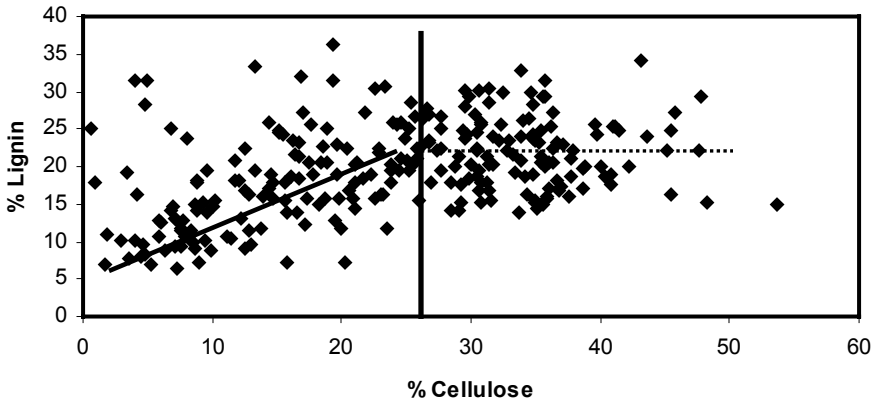

Figure 4.8. Relationship Between Cellulose and Lignin For Eleven Landfills.

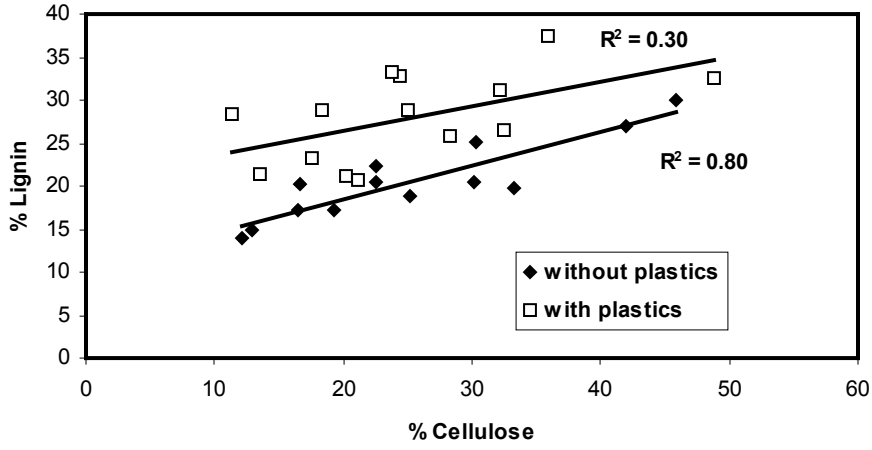

Figure 4.9. Relationship Between Cellulose and Lignin For Test Column Samples With and Without Plastics.

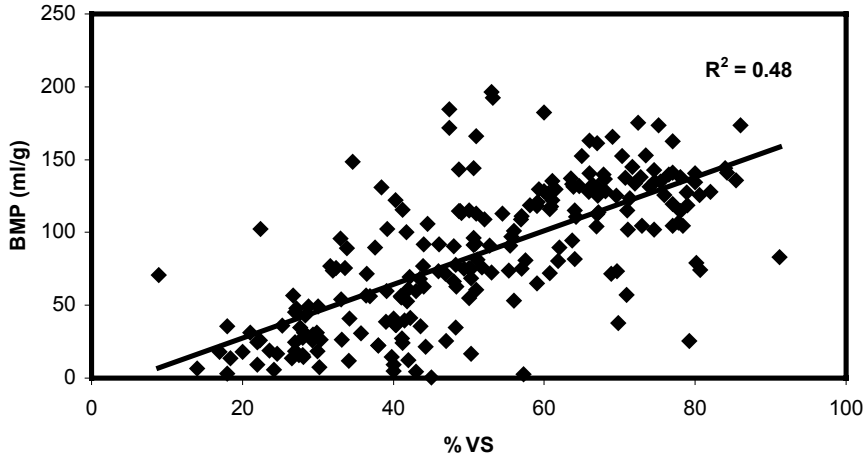

Figure 4.10a. Relationship Between Volatile Solids and BMP For Eleven Lnadfills.

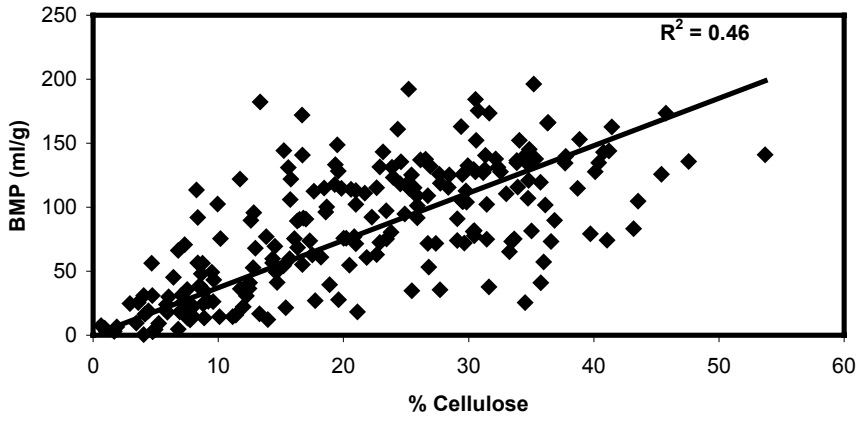

Figure 4.10b. Relationship Between Cellulose and BMP For Eleven Landfills.

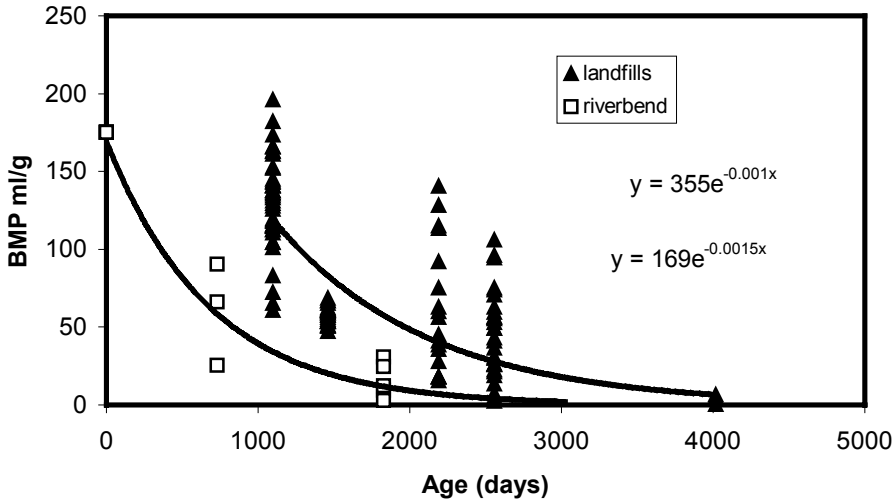

Figure 4.11. Change in BMP With Age For Riverbend and Seven Other Landfills.

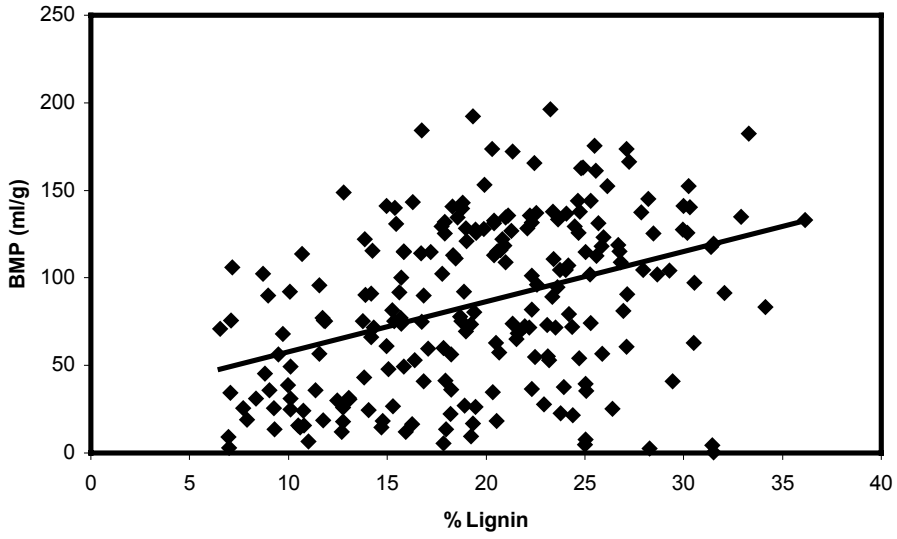

Figure 4.12. Relationship Between Lignin and BMP For Eleven Landfills.

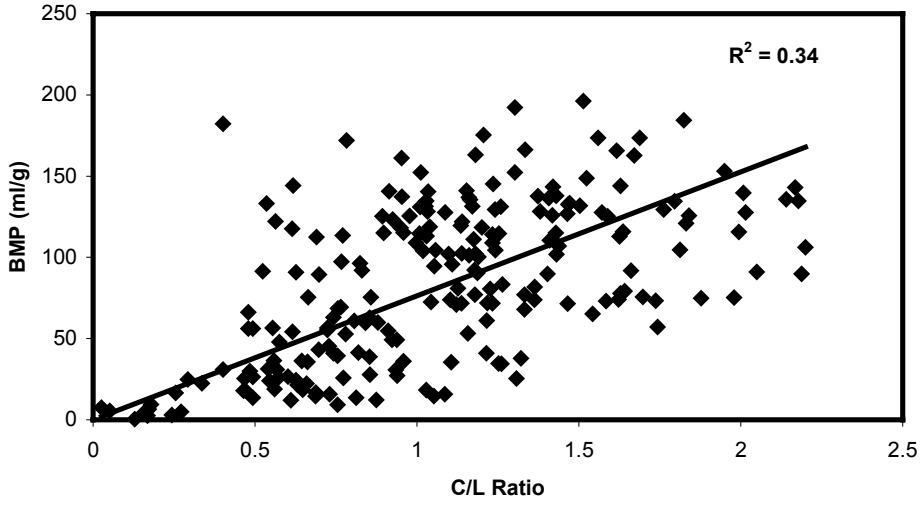

Figure 4.13a. Relationship Between Cellulose/ Lignin Ratio and BMP For Eleven Landfills.

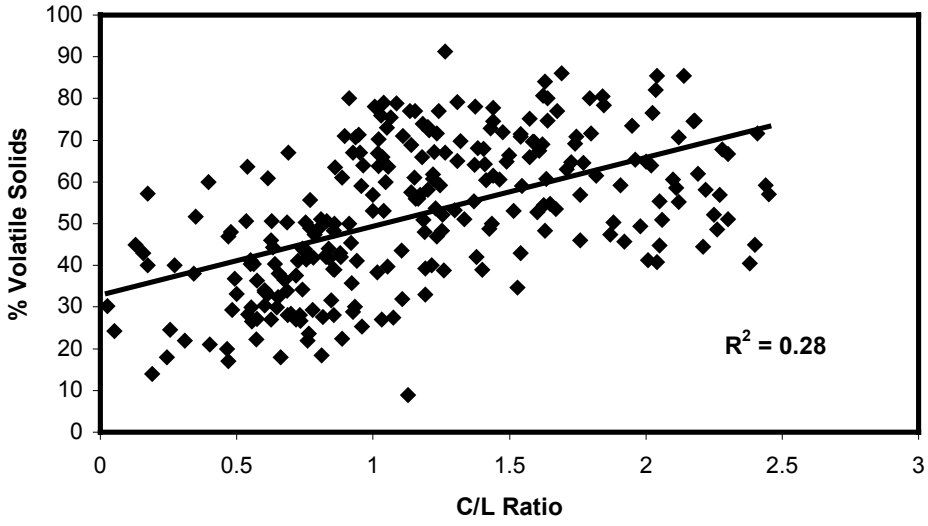

Figure 4.13b. Relationship Between Volatile Solids and Cellulose/Lignin Ratio For Eleven Landfills.

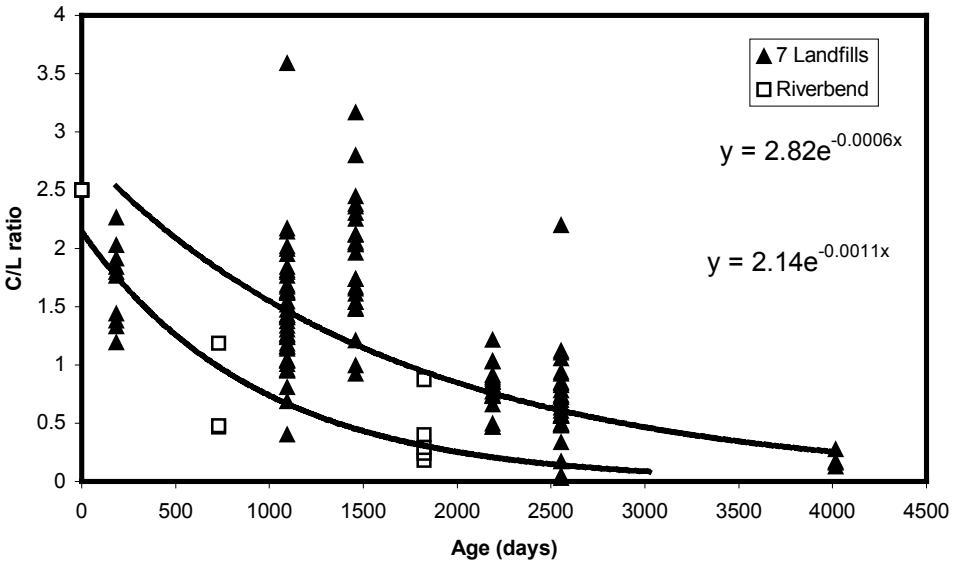

Figure 4.14. Change in Cellulose/ Lignin Ratio With Age For Riverbend and Seven Other Landfills.

APPENDIX

Landfill Name	Sample Date	Location	Depth (ft)	Age (yrs)	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig Ratio	pH	BMP (mL/g)
Riverbend	10/11/99	Bio-1	5-15	11	25.0	14.0	1.9	11.0	0.19	6.35	6.59
Riverbend	10/11/99	Bio-1	15-25	11	32.0	40.0	6.8	25.0	0.27	6.32	4.86
Riverbend	10/11/99	Bio-1	25-35	11	43.0	45.0	4.1	31.5	0.13	7.60	0.47
Riverbend	10/11/99	Bio-1	35-45	11	43.0	43.0	5.0	31.5	0.16	8.59	4.39
Riverbend	10/11/99	Bio-2	5-15	5	52.0	40.0	3.5	19.3	0.17	8.55	9.43
Riverbend	10/11/99	Bio-2	15-25	5	66.0	42.0	14.0	16.0	0.88	6.86	12.19
Riverbend	10/11/99	Bio-2	25-35	5	41.0	21.0	4.1	10.1	0.40	7.51	31.01
Riverbend	10/12/99	Bio-2	35-45	5	52.0	18.0	1.7	7.0	0.24	7.35	2.97
Riverbend	10/12/99	Bio-2	45-55	5	71.0	22.0	3.0	10.1	0.31	7.23	24.79
Riverbend	10/12/99	Bio-3	5-15	2	61.0	48.0	16.5	13.9	1.19	5.82	90.38
Riverbend	08/03/99	Bio-3	15-25	2	40.0	47.0	3.6	7.7	0.47	6.96	25.47
Riverbend	08/03/99	Bio-3	25-35	2	53.0	48.0	6.8	14.2	0.48	6.61	66.18
Spruce Ridge	11/18/99	LR 1	18-28	6	46.0	44.0	22.6	30.5	0.74	6.95	62.98
Spruce Ridge	11/18/99	1	28-38	6	32.0	44.0	8.4	10.1	0.84	6.56	91.96
Spruce Ridge	11/18/99	1	38-48	6	35.0	41.0	4.7	9.5	0.55	6.94	56.15
Spruce Ridge	11/18/99	1	48-58	6	47.0	39.0	8.5	10.0	0.86	6.60	38.80
Spruce Ridge	11/18/99	1	58-68	6	34.0	18.0	7.5	11.4	0.66	6.77	35.74
Spruce Ridge	11/17/99	LR 3	18-28	6	30.0	28.0	7.9	10.8	0.73	6.95	15.69
Spruce Ridge	11/17/99	3	28-38	6	41.0	27.0	21.1	20.5	1.03	7.10	18.24
Spruce Ridge	11/17/99	3	38-48	6	45.0	28.0	19.6	22.9	0.86	7.14	27.86
Spruce Ridge	11/17/99	3	48-51	6	24.0	20.0	5.9	12.8	0.47	7.70	17.91
Spruce Ridge	11/16/99	LR 4	18-28	6	24.0	17.0	6.9	14.8	0.47	7.03	18.19
Spruce Ridge	11/16/99	4	28-38	6	19.0	40.0	35.8	29.4	1.21	6.78	40.93
Spruce Ridge	11/16/99	Cont A	18-28	6	28.0	43.0	15.7	17.8	0.88	6.23	59.86
Spruce Ridge	11/16/99	A	28-38	6	31.0	60.0	19.6	19.0	1.05	6.60	128.34
Spruce Ridge	11/16/99	A	38-48	6	31.0	80.0	16.7	18.3	0.91	6.74	140.71
Spruce Ridge	11/16/99	A	48-54	6	14.0	27.0	6.4	8.8	0.72	7.26	45.30
Spruce Ridge	11/17/99	Cont B	18-29	6	16.0	71.0	18.5	20.6	0.90	6.71	114.96
Spruce Ridge	11/17/99	B	29-38	6	26.0	50.0	16.1	18.7	0.86	6.20	75.42
Spruce Ridge	11/17/99	B	38-48	6	25.0	49.0	8.3	10.7	0.77	6.55	113.55
Middle Penn.	12/13/99	LR 1	10-20	3	36.0	41.2	28.4	14.2	2.01	6.34	115.62
Middle Penn.	12/13/99	LR 1	20-30	3	40.0	72.8	35.4	24.7	1.43	6.75	137.85
Middle Penn.	12/13/99	LR 1	30-40	3	38.0	74.6	40.8	18.8	2.17	6.86	142.99
Middle Penn.	12/13/99	LR 1	40-50	3	44.0	80.6	45.4	24.7	1.84	7.40	125.79
Middle Penn.	12/13/99	LR 1	50-60	3	37.0	61.5	31.3	17.8	1.82	6.69	129.53
Middle Penn.	12/13/99	LR 1	60-70	3	38.0	60.8	33.9	20.7	1.63	6.58	115.78
Middle Penn.	12/15/99	LR 2	10-20	3	38.0	71.6	34.8	28.2	1.23	5.84	145.20
Middle Penn.	12/15/99	LR 2	20-30	3	38.0	73.4	38.8	19.9	1.95	6.62	153.04
Middle Penn.	12/15/99	LR 2	30-40	3	30.0	54.5	29.8	18.3	1.63	6.70	112.81
Middle Penn.	12/15/99	LR 2	40-50	3	38.0	64.2	33.0	23.4	1.41	6.81	110.62
Middle Penn.	12/15/99	LR 2	50-60	3	37.0	91.2	43.2	34.2	1.26	6.16	83.24

Table 5.1. Data from analyses of MSW from 11 landfills.

Landfill Name	Sample Date	Location	Depth (ft)	Age (yrs)	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig Ratio	pH	BMP (mL/g)
Middle Penn.	12/15/99	LR 2	60-70	3	41.0	78.3	43.5	24.0	1.85	6.41	104.65
Middle Penn.	12/15/99	GW-5	10-20	3	40.0	85.5	47.6	22.2	2.14	6.32	135.77
Middle Penn.	12/15/99	GW-6	10-20	3	29.0	84.2	53.7	15.0	3.63	6.41	140.93
Central	05/21/00	7	40-50	2	28.0	27.5	11.4	10.5	1.07	8.26	15.79
Central	05/21/00	7	50-60	2	29.6	35.7	12.3	13.1	0.92	8.15	30.80
Central	05/21/00	7	60-70	2	29.5	39.7	11.2	10.6	1.05	7.59	14.58
Central	05/22/00	8	10-20	2	20.7	22.0	5.3	7.0	0.76	8.24	9.24
Central	05/22/00	8	20-30	2	25.3	28.2	7.1	13.1	0.54	8.07	31.28
Central	05/22/00	8	30-40	2	31.9	41.2	17.8	18.9	0.94	7.83	27.11
Central	05/22/00	8	40-50	2	27.9	18.4	7.6	9.3	0.81	8.95	13.57
Central	05/22/00	8	50-60	2	33.0	50.3	13.3	19.4	0.69	7.31	16.82
Central	05/22/00	8	60-70	2	37.0	29.9	7.6	11.8	0.65	7.74	18.54
Central	05/22/00	8	70-80	2	43.0	41.4	18.9	25.1	0.75	7.56	39.48
Central	05/22/00	8	80-90	2	37.0	42.3	14.7	18.0	0.83	6.83	41.33
Central	05/22/00	8	90-100	2	26.0	33.1	15.2	24.7	0.62	7.29	54.22
Central	05/23/00	9	10-20	2	41.4	27.1	8.7	15.1	0.58	8.24	47.88
Central	05/23/00	9	20-30	2	40.5	28.1	10.1	14.7	0.69	7.56	14.51
Central	05/23/00	9	30-40	2	54.4	41.2	5.9	10.8	0.55	7.86	24.07
Central	05/23/00	9	40-50	2	35.8	34.1	7.8	12.7	0.60	7.92	12.00
Central	05/23/00	9	50-60	2	29.3	26.9	8.8	14.1	0.63	7.80	24.39
Central	05/23/00	9	60-70	2	34.2	29.3	7.2	9.3	0.78	7.82	25.74
Central	05/23/00	9	70-80	2	32.5	38.0	12.0	18.2	0.66	7.68	22.29
Central	05/23/00	9	80-90	2	35.7	24.6	4.2	16.3	0.26	7.67	16.56
Central	05/23/00	9	90-100	2	30.8	40.3	11.8	18.3	0.64	7.73	36.27
Atlantic	12/07/99	control 3-1	10-20	3	41.0	69.0	36.3	22.5	1.62	6.15	165.65
Atlantic	12/07/99	3-1	20-30	3	39.0	86.0	45.8	27.1	1.69	5.74	173.53
Atlantic	12/07/99	3-1	30-40	3	31.0	50.0	22.7	15.9	1.44	5.71	115.13
Atlantic	12/07/99	3-1	40-50	3	35.0	80.0	37.7	21.0	1.80	6.32	134.46
Atlantic	12/07/99	control 3-2	10-20	3	46.0	82.0	40.1	19.9	2.04	6.30	127.75
Atlantic	12/07/99	3-2	20-30	3	31.0	60.0	13.4	33.3	0.40	6.39	182.30
Atlantic	12/07/99	3-2	30-40	3	64.0	77.0	35.8	31.5	1.14	6.87	119.53
Atlantic	12/07/99	3-2	40-50	3	64.0	72.0	34.8	23.7	1.48	7.11	133.37
Atlantic	12/08/99	2-1	10-20	3	70.0	59.0	33.3	21.6	1.55	7.39	65.18
Atlantic	12/08/99	2-1	20-25	3	70.0	51.0	21.9	27.1	0.81	7.51	60.85
Atlantic	12/08/99	2-2	10-20	3	41.0	53.0	22.9	22.0	1.04	6.58	72.54
Atlantic	12/08/99	2-2	20-30	3	49.0	67.0	24.4	25.6	0.95	6.73	161.09
Atlantic	12/08/99	2-2	30-40	3	60.0	78.0	32.2	23.4	1.38	6.81	137.80
Atlantic	12/08/99	2-2	40-50	3	57.0	77.0	34.6	30.0	1.16	6.94	141.15
Atlantic	12/08/99	2-2	50-60	3	60.0	56.0	25.9	22.3	1.17	7.17	101.23
Atlantic	12/08/99	2-2	60-70	3	65.0	64.0	25.7	26.8	0.97	7.41	115.18
Atlantic	12/08/99	2-2	70-75	3	64.0	66.0	29.4	24.9	1.18	7.56	163.07
Atlantic	12/08/99	2-3	10-20	3	49.0	51.0	36.4	27.3	1.34	7.21	166.21
Atlantic	12/08/99	2-3	20-30	3	47.0	53.0	35.2	23.3	1.52	6.52	196.23

Table 5.1. (Cont.)

Landfill Name	Sample Date	Location	Depth (ft)	Age (yrs)	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig Ratio	pH	BMP (mL/g)
Atlantic	12/08/99	2-3	30-40	3	32.0	67.0	17.7	25.6	0.69	7.31	112.51
Atlantic	12/08/99	2-3	40-50	3	47.0	78.0	25.3	25.1	1.01	11.51	114.68
Atlantic	12/08/99	2-3	50-60	3	54.0	77.0	29.5	23.8	1.24	6.93	104.40
Atlantic	12/08/99	2-3	60-70	3	55.0	65.0	34.1	26.2	1.31	6.28	152.31
Atlantic	12/08/99	2-3	70-76	3	62.0	66.0	31.4	30.3	1.04	6.63	140.50
Atlantic	12/10/99	2-4	10-20	3	41.0	67.0	32.4	25.7	1.27	6.71	131.30
Atlantic	12/10/99	2-4	20-30	3	40.0	77.0	41.5	24.8	1.68	5.54	162.75
Atlantic	12/10/99	2-4	30-40	3	44.0	84.0	41.2	25.3	1.63	5.65	144.09
Atlantic	12/10/99	2-4	40-50	3	38.0	79.0	27.8	26.7	1.04	6.13	118.81
Atlantic	12/10/99	2-4	50-60	3	43.0	68.0	33.9	24.1	1.41	6.81	136.59
Atlantic	12/10/99	2-4	60-70	3	53.0	59.0	24.6	25.9	0.96	7.06	118.20
Evergreen	07/26/00	LR-1	8-18	7	21.6	40.4	12.5	22.3	0.56	7.51	36.50
Evergreen	07/26/00	LR-1	18-28	7	43.1	30.2	0.7	25.1	0.03	8.04	7.50
Evergreen	07/26/00	LR-1	28-38	7	35.5	44.3	15.4	24.4	0.63	7.21	21.50
Evergreen	07/26/00	LR-1	38-48	7	20.7	34.2	12.5	16.8	0.74	7.18	41.00
Evergreen	07/26/00	LR-1	48-58	7	27.5	22.3	7.3	12.8	0.57	7.53	26.00
Evergreen	07/26/00	LR-2	8-18	7	27.1	24.2	0.9	17.8	0.05	6.96	5.50
Evergreen	07/26/00	LR-2	18-28	7	34.7	57.2	4.7	28.3	0.17	6.88	2.65
Evergreen	07/26/00	LR-2	28-38	7	40.5	30.4	9.2	15.3	0.60	6.69	26.50
Evergreen	07/26/00	LR-2	38-46	7	42.9	26.6	8.9	18.0	0.56	7.26	13.58
Evergreen	07/26/00	LR-3	8-18	7	13.8	26.7	8.4	11.6	0.73	6.83	56.55
Evergreen	07/26/00	LR-3	18-28	7	22.5	33.1	9.6	19.5	0.50	7.38	26.35
Evergreen	07/26/00	LR-3	28-38	7	37.5	28.3	9.6	13.8	0.70	7.43	43.15
Evergreen	07/26/00	LR-3	38-48	7	48.5	30.0	9.5	10.1	0.93	7.43	49.16
Evergreen	07/27/00	Cntrl-4	13-23	7	28.4	63.7	24.9	23.6	1.05	6.00	94.66
Evergreen	07/27/00	Cntrl-4	23-33	7	19.8	28.8	14.6	15.8	0.93	6.73	49.21
Evergreen	07/27/00	Cntrl-4	33-43	7	32.9	41.8	12.8	16.4	0.78	6.82	52.84
Evergreen	07/27/00	Cntrl-4	43-53	7	25.0	41.0	16.7	23.1	0.72	7.05	55.32
Evergreen	07/27/00	Cntrl-4	53-63	7	29.6	39.1	14.3	17.1	0.85	7.14	59.71
Evergreen	07/27/00	Cntrl-4	63-73	7	33.0	50.6	18.6	22.6	0.83	6.79	96.27
Evergreen	07/27/00	Cntrl-4	73-83	7	31.9	23.6	4.4	7.9	0.76	7.82	18.98
Evergreen	07/27/00	Cntrl-4	83-93	7	42.5	38.0	8.0	23.8	0.34	7.81	22.55
Evergreen	07/27/00	Cntrl-5	11-21	7	24.8	32.0	17.3	15.7	1.11	6.57	73.87
Evergreen	07/27/00	Cntrl-5	21-31	7	27.9	32.4	10.2	15.4	0.65	7.03	75.41
Evergreen	07/27/00	Cntrl-5	31-41	7	18.1	29.8	4.7	8.4	0.55	8.29	31.02
Evergreen	07/27/00	Cntrl-5	41-51	7	22.4	36.9	8.7	18.2	0.49	8.05	56.14
Evergreen	07/27/00	Cntrl-5	51-61	7	23.1	29.4	6.0	12.5	0.48	7.69	29.93
Evergreen	07/27/00	Cntrl-5	61-71	7	17.7	8.9	7.3	6.5	1.13	7.55	70.86
Evergreen	07/27/00	Cntrl-5	71-81	7	30.7	44.5	15.7	7.2	2.21	6.56	106.09
Evergreen	07/27/00	Cntrl-5	81-91	7	33.8	48.3	17.5	20.5	0.86	7.17	62.82
Maplewood	08/07/01	Control-1	0-10	8	31.6	46.9	27.4	22.2	1.23	5.5	71.63
Maplewood	08/07/01	Control-1	10-20	8	40.7	55.3	29.1	21.4	1.37	5.5	73.89
Maplewood	08/07/01	Control-1	20-30	8	33.2	51.1	35.0	15.3	2.30	5.8	81.48

Table 5.1. (Cont.)

Landfill Name	Sample Date	Location	Depth (ft)	Age (yrs)	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig Ratio	pH	BMP (mL/g)
Maplewood	08/07/01	Control-1	30-40	8	38.5	57.5	30.4	27.0	1.14	7.8	81.02
Maplewood	08/07/01	Control-2	0-10	8	34.7	50.3	31.5	16.8	1.88	5.8	74.96
Maplewood	08/07/01	Control-2	10-20	8	40.1	46.0	33.4	19.3	1.76	5.5	73.29
Maplewood	08/07/01	Control-2	20-30	8	41.8	48.3	30.5	18.7	1.63	6.7	77.83
Maplewood	08/07/01	Control-2	30-40	8	52.7	74.6	36.1	25.3	1.44	8.2	101.80
Maplewood	05/11/01	Bio 1	0-10	8	42.6	75.9	29.5	30.2	1.03	5.7	125.56
Maplewood	05/11/01	Bio 1	10-20	8	39.8	61.8	23.8	19.4	1.22	7.7	80.49
Maplewood	05/11/01	Bio 1	20-30	8	33.6	51.0	21.0	20.4	2.06	5.3	113.07
Maplewood	05/11/01	Bio 1	30-40	8	37.2	73.0	29.5	28.0	1.05	5.6	104.50
Maplewood	05/10/01	Bio 2	0-10	8	28.8	77.8	34.7	24.2	1.44	5.8	106.98
Maplewood	05/10/01	Bio 2	10-20	8	51.2	63.9	22.9	22.3	1.02	8.4	131.41
Maplewood	05/10/01	Bio 2	20-30	8	40.6	68.9	26.7	23.5	1.14	8.2	71.69
Maplewood	05/10/01	Bio 2	30-40	8	27.8	69.8	31.6	24.0	1.32	7.5	37.74
Maplewood	05/10/01	Bio 3	0-10	8	39.9	79.2	34.5	26.4	1.31	5.3	25.40
Maplewood	05/10/01	Bio 3	10-20	8	38.6	62.0	36.9	16.9	2.19	8.5	89.76
Maplewood	05/10/01	Bio 3	20-30	8	38.5	80.1	39.7	24.2	1.64	5.5	79.24
Maplewood	05/10/01	Bio 3	30-40	8	32.8	74.7	40.4	18.6	2.18	6.2	134.67
Middle Penn.	02/22/01	A	3'	0.5	34.1	64.6	36.3	20.6	1.77	5.08	
Middle Penn.	02/22/01	A	6'	0.5	30.8	45.7	29.2	15.3	1.92	5.28	
Middle Penn.	02/22/01	B	3'	0.5	31.2	42.1	17.1	12.4	1.38	5.15	
Middle Penn.	02/22/01	B	6'	0.5	39.6	63.9	36.6	18.1	2.02	5.15	
Middle Penn.	02/22/01	C	3'	0.5	38.5	61.4	28.8	20.0	1.44	4.71	
Middle Penn.	02/22/01	C	6'	0.5	40.4	73.1	30.8	25.8	1.20	5.09	
Middle Penn.	02/22/01	D	3'	0.5	32.2	56.9	35.8	15.8	2.27	5.42	
Middle Penn.	02/22/01	D	6'	0.5	28.2	58.1	34.2	18.6	2.22	5.50	
Middle Penn.	02/22/01	E	3'	0.5	34.2	64.9	23.8	17.9	2.00	5.69	
Middle Penn.	02/22/01	E	6'	0.5	30.1	71.7	35.7	19.9	1.80	5.10	
King George	08/02/01	Control 1	0-15	4	46.8	55.2	34.3	16.2	2.12	6.5	61.04
King George	08/02/01	Control 1	15-30	4	38.8	44.9	37.5	15.9	2.40	7.1	61.20
King George	08/02/01	Control 1	30-45	4	24.0	44.8	31.5	15.4	2.05	6.5	51.00
King George	08/02/01	Control 1	45-55	4	31.6	43.0	31.3	20.4	1.54	5.9	53.39
King George	08/02/01	Control 1	55-70	4	26.2	52.2	35.8	15.9	2.25	5.4	57.58
King George	08/02/01	Control 2	0-15	4	26.9	53.6	29.2	17.5	1.67	6.8	66.98
King George	08/02/01	Control 2	15-30	4	37.9	71.7	35.5	29.5	2.41	6.8	58.09
King George	08/03/01	Control 2	30-45	4	34.1	66.7	40.8	17.7	2.30	5.6	50.50
King George	08/03/01	Control 2	45-60	4	25.7	40.8	30.8	15.2	2.04	5.7	47.35
King George	08/03/01	Control 2	60-70	4	31.0	65.3	38.6	19.7	1.96	5.8	60.53
King George	08/01/01	Bio 1	0-15	4	43.2	40.4	35.6	15.0	2.38	6.2	54.07
King George	08/01/01	Bio 1	15-30	4	33.2	56.9	30.8	17.8	1.76	6.3	59.40
King George	08/01/01	Bio 1	30-45	4	30.0	85.4	45.2	22.2	2.04	6.7	60.06
King George	08/01/01	Bio 1	45-60	4	29.6	70.8	42.2	19.9	2.12	6.7	68.69
King George	08/01/01	Bio 1	60-75	4	28.4	75.2	45.4	16.3	2.80	6.5	65.32
King George	07/31/01	Bio 2	0-15	4	47.5	67.4	37.1	23.0	1.61	6.3	59.18

Table 5.1. (Cont.)

Landfill Name	Sample Date	Location	Depth (ft)	Age (yrs)	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig Ratio	pH	BMP (mL/g)
King George	07/31/01	Bio 2	15-30	4	46.3	64.9	32.8	22.2	1.49	5.8	54.98
King George	07/31/01	Bio 2	30-45	4	40.0	54.8	35.5	21.4	1.65	6.6	51.47
King George	07/31/01	Bio 2	45-60	4	45.4	71.5	35.0	23.5	1.54	5.6	67.17
King George	07/31/01	Bio 2	60-75	4	40.2	70.8	39.5	25.7	1.54	5.4	60.72
King George	07/31/01	Bio 3	0-15	4	30.7	72.0	48.2	15.3	3.17	5.4	61.84
King George	07/31/01	Bio 3	15-30	4	35.7	59.1	35.2	14.4	2.44	5.8	53.76
King George	08/01/01	Bio 3	30-45	4	39.9	53.1	26.3	26.5	1.00	8.3	53.95
King George	08/01/01	Bio 3	45-60	4	43.9	69.2	35.5	20.4	1.74	7.6	62.57
King George	08/01/01	Bio 3	60-75	4	35.2	45.5	18.9	20.5	0.92	5.8	56.48
Green Valley	08/02/01	TB 1	10 - 40		33.0	74.7	47.8	29.5	1.64	6.28	
Green Valley	08/02/01	TB 1	40-70		37.4	38.8	24.4	19.5	1.26		
Green Valley	08/02/01	TB 1	70-100		31.1	39.0	23.0	16.4	1.40		
Green Valley	08/02/01	TB 1	100-145		23.1	58.6	36.1	17.1	2.11	6.09	
Green Valley	08/02/01	TB 2	9-30		46.3	60.5	37.0	17.3	2.10		
Green Valley	08/02/01	TB 2	30-60		33.9	63.0	37.9	22.1	1.71	6.45	
Green Valley	08/02/01	TB 2	60-100		32.5	53.7	27.7	22.5	1.23		
Kettleman Hills	07/07/01	3279371715				56.0	26.8	23.2	1.16	6.26	53.14
Kettleman Hills	07/07/01	3248921347				48.3	25.5	20.4	1.25	6.55	34.65
Kettleman Hills	07/07/01	3279372171				43.6	27.7	25.1	1.11	7.20	35.43
Metro	11/17/99	B	Lift 1		24.5	71.3	24.0	25.9	0.95	6.95	123.33
Metro	11/17/99	C	1		25.6	67.1	25.4	28.5	0.93	7.12	125.34
Metro	11/17/99	D	1		20.8	74.0	23.9	20.4	1.18	7.07	131.33
Metro	01/19/00	B	4		26.4	64.7	26.9	17.9	1.73	6.52	131.88
Metro	01/19/00	C	4		30.5	60.6	31.2	21.3	1.46	6.32	126.88
Metro	01/19/00	D	4		31.6	59.2	34.8	19.0	1.91	6.15	121.04
Metro	12/03/99	B	1		23.0	33.0	12.8	11.6	1.19	6.51	95.70
Metro	12/03/99	C	1		26.8	40.3	11.7	20.8	0.55	7.01	122.10
Metro	12/03/99	D	1		34.5	50.7	15.2	24.6	0.63	7.15	144.17
Metro	01/19/00	B	4		31.2	66.4	29.9	20.4	1.50	6.16	132.60
Metro	01/19/00	C	4		33.0	61.1	24.6	21.1	1.15	5.89	135.53
Metro	01/19/00	D	4		39.2	58.1	25.1	20.9	1.20	6.80	118.44
Metro	02/16/00	A-B	0-15		32.9	59.3	30.4	24.5	1.25	7.05	129.40
Metro	02/16/00	A-B	15-25		27.1	75.4	33.9	32.9	1.07	6.55	134.82
Metro	02/16/00	A-B	25-35		25.7	63.7	19.4	36.2	0.54	5.44	133.19
Metro	02/16/00	A-B	35-45		38.0	78.9	32.6	30.0	1.09	5.78	127.63
Metro	02/16/00	C-D	0-13		25.7	70.3	30.6	30.3	1.02	6.21	152.30
Metro	02/16/00	C-D	13-25		27.6	50.6	16.8	32.1	0.54	6.65	91.38
Metro	02/16/00	C-D	25-36		24.2	33.8	16.3	23.4	0.69	6.71	89.35
Metro	02/16/00	C-D	36-49		35.4	71.1	31.5	28.7	1.11	6.41	102.14
Metro	02/16/00	A-B	0-10		31.8	70.9	36.0	20.7	1.75	6.14	57.21
Metro	02/16/00	A-B	10-20		36.5	57.0	21.7	18.5	1.17	6.81	111.02
Metro	02/16/00	A-B	20-30		31.4	64.1	30.4	22.3	1.37	6.72	81.71
Metro	02/16/00	A-B	30-40		33.1	66.9	29.8	29.3	1.02	6.29	103.99

Table 5.1. (Cont.)

Landfill Name	Sample Date	Location	Depth (ft)	Age (yrs)	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig Ratio	pH	BMP (mL/g)
Metro	02/16/00	B-C	0-10		40.6	69.7	36.6	23.1	1.59	6.20	73.17
Metro	02/16/00	B-C	10-20		40.3	80.6	41.1	25.3	1.62	6.46	74.15
Metro	02/16/00	B-C	20-30		28.2	70.8	26.6	27.9	0.94	6.21	137.39
Metro	02/16/00	B-C	30-40		28.3	67.8	35.0	15.4	2.28	6.23	139.94
Metro	02/16/00	C-D	0-10		42.5	76.5	37.8	18.8	2.03	5.95	139.67
Metro	02/16/00	C-D	10-20		42.3	72.5	30.8	25.5	1.21	5.01	175.39
Metro	02/16/00	C-D	20-30		40.9	75.1	31.7	20.3	1.58	6.48	173.54
Metro	02/16/00	C-D	30-40		34.2	68.1	30.5	22.1	1.39	6.49	128.27
Metro	06/14/00	C-D	0-10		35.1	51.7	20.2	7.1	0.35	6.10	75.81
Metro	06/14/00	C-D	10-20		36.0	43.9	20.9	15.7	0.75	5.97	76.94
Metro	06/14/00	C-D	20-30		29.5	43.5	13.0	9.7	0.75	6.09	67.91
Metro	06/14/00	C-D	30-40		59.3	61.0	15.8	13.9	0.89	6.16	122.02
Metro	06/14/00	B-C	0-10		22.5	27.7	8.9	7.1	0.82	6.41	34.52
Metro	06/14/00	B-C	10-20		30.8	31.6	13.8	11.7	0.85	5.94	77.05
Metro	06/14/00	B-C	20-30		33.4	42.0	18.2	15.0	0.83	6.10	61.12
Metro	06/14/00	B-C	30-40		28.9	33.6	20.0	11.8	0.60	6.55	75.73
Metro	06/14/00	B-C	0-10		25.3	22.4	9.9	8.7	0.89	6.47	102.50
Metro	06/14/00	B-C	10-20		27.3	37.6	12.6	9.0	0.72	5.75	89.78
Metro	06/14/00	B-C	20-30		31.8	41.8	18.7	15.7	0.84	6.00	100.24
Metro	06/14/00	B-C	30-40		31.9	46.1	25.9	15.6	0.63	5.49	91.87
Metro	06/14/00	C-D	0-10		32.5	63.5	26.2	22.5	0.86	5.07	136.92
Metro	06/14/00	C-D	10-20		22.6	36.5	21.0	14.3	0.68	6.02	71.48
Metro	06/14/00	C-D	20-30		26.5	52.8	17.0	27.2	1.60	6.01	90.75
Metro	06/14/00	C-D	30-40		24.3	48.8	19.9	15.8	0.80	5.92	114.75
Metro	10/16/00	A-B	0-20		23.5	25.3	8.7	9.0	0.96	6.90	35.97
Metro	10/16/00	A-B	21-33		35.9	42.2	14.5	19.0	0.77	6.83	69.44
Metro	10/16/00	A-B	33-43		31.8	50.0	20.5	22.5	0.91	7.32	54.76
Metro	10/16/00	C-D	0-20		36.6	36.4	14.4	25.9	0.58	8.04	56.54
Metro	10/16/00	C-D	20-30		26.3	50.3	16.3	21.6	0.75	7.11	68.50
Metro	10/16/00	C-D	30-40		35.5	56.9	26.7	26.8	1.00	7.12	108.98
Metro	10/16/00	A-B	0-20		31.0	52.1	25.9	21.0	1.25	6.62	109.02
Metro	10/16/00	A-B	20-35		32.3	60.4	27.7	19.5	1.41	6.64	125.87
Metro	10/16/00	A-B	36-49		27.5	55.7	23.4	30.5	0.77	6.73	97.30
Metro	10/16/00	C-D	0-20		23.8	50.9	22.3	18.9	1.19	6.39	92.25
Metro	10/16/00	C-D	20-30		22.6	39.2	21.0	17.8	1.19	6.53	102.19
Metro	10/16/00	C-D	30-40		23.0	60.9	19.3	31.4	0.62	6.86	117.64
Metro	12/28/00	3E			28.1	55.4	29.1	14.2	2.05	6.45	91.00
Metro	12/28/00	4B			41.2	65.9	30.6	19.5	1.58	6.29	127.67
Metro	12/28/00	4C			30.0	53.2	25.2	19.4	1.30	6.31	192.33
Metro	12/28/00	4D			26.8	48.7	23.2	16.3	1.43	6.83	143.33
Metro	12/28/00	4E			31.1	60.7	29.7	24.4	1.22	6.30	72.00
Metro	12/28/00	4B			36.6	47.4	16.7	21.4	0.79	6.89	172.00
Metro	12/28/00	4E			36.8	69.6	28.5	17.9	1.59	5.80	125.33
Metro	12/28/00	5B			29.5	38.4	15.6	15.5	1.02	6.53	131.00
Metro	12/28/00	5C			38.2	67.2	20.6	16.7	1.23	5.96	114.00
Metro	12/28/00	5D			20.2	34.6	19.5	12.8	1.53	6.85	148.67
Metro	12/28/00	5E			31.3	57.0	33.7	13.8	2.45	6.19	75.33
Metro	12/28/00	5B			26.7	47.4	30.6	16.8	1.87	6.69	184.33
Metro	12/28/00	5D			33.0	49.4	23.5	11.9	1.98	6.33	75.33
Metro	12/28/00	5E			26.3	48.7	38.7	17.2	2.26	6.70	114.67

Table 5.1. (Cont.)

COLUMN #1 Sample Date	Moisture %	pH	Vol. Solids %	Ave. VS %	Cellulose %	Ave. Cell. %	Lignin %	Ave. Lignin %	Cell./Lig Ratio	Ave. C/L Ratio
05/16/01	51.6	5.17	69	69.9	37.6	37.95	29.3	27.95	1.28	1.36
			70		38.3		26.6		1.44	
			70.7							
06/29/01	51.8	5.29	72	73	38.1	35.3	30.2	30	1.26	1.175
			74		32.5		29.8		1.09	
09/19/01	54.2	5.26	61.7	65.5	27.4	26.6	28.7	31.15	0.95	0.86
			69.3		25.8		33.6		0.77	
10/29/01	50	5.33	51.8	51.25	22.6	22.95	26.9	25.7	0.84	0.895
			50.7		23.3		24.5		0.95	
10/29/01	47	5.26	53.3	52.1	31.3	27.4	25.8	23.35	1.21	1.165
			50.9		23.5		20.9		1.12	
12/10/01	51.3		57.2	62.75	32.3	28.35	25.1	25.75	1.29	1.105
			68.3		24.4		26.4		0.92	
12/10/01	47.3		70.7	69.6	24.6	25.05	30	28.95	0.82	0.865
			68.5		25.5		27.9		0.91	
02/05/02	50.9	5.54	63.8	65.05	32	30	24.8	24.05	1.29	1.245
			66.3		28		23.3		1.2	

Table 5.2. Data from analyses of MSW in Column #1.

Column #2 Sample Date	Moisture %	pH	Vol. Solids %	Ave. VS %	Cellulose %	Ave. Cell. %	Lignin %	Ave. Lignin %	Cell./Lig Ratio	Ave. C/L Ratio
05/16/01	44.6	5.51	70.2	71.83	36.3	36.85	25.3	25.9	1.43	1.42
			71.4		37.4		26.5		1.41	
			73.9							
06/29/01	47.1	6.67	70.2	67.7	25.8	30.25	24.2	23.3	1.07	1.31
			65.2		34.7		22.4		1.55	
08/01/01	43.9	5.49	67.3	67.35	28.4	26.4	25	25.35	1.13	1.04
			67.4		24.4		25.7		0.95	
09/19/01	44.7	5.55	62.6	61.35	17.2	19.35	22.9	23.5	0.75	0.82
			60.1		21.5		24.1		0.89	
10/29/01	37.5	5.75	52.9	52.8	18.9	19.3	19.6	18.5	0.96	1.045
			52.7		19.7		17.4		1.13	
10/29/01	49.4	5.6	58.1	57.8	20.8	22.45	28.7	26.35	0.72	0.86
			57.5		24.1		24		1	
12/10/01	39.1		58.7	56.25	18.3	20.2	19	21.25	0.97	0.955
			53.8		22.1		23.5		0.94	
12/10/01	38.1		52.3	54.2	20.1	17.6	23.4	23.35	0.86	0.755
			56.1		15.1		23.3		0.65	
02/05/02	41.5	5.48	51.6	54.8	20.9	22.6	19.5	23.25	1.07	0.985
			58		24.3		27		0.9	

Table 5.3. Data from analyses of MSW in Column #2.

Column #3 Sample Date	Moisture %	pH	Vol. Solids %	Ave. VS %	Cellulose %	Ave. Cell. %	Lignin %	Ave. Lignin %	Cell./Lig Ratio	Ave. C/L Ratio
05/16/01	43.4	5.29	53.4	55.83	34.8	33.95	27.9	27.9	1.25	1.25
			56.3		33.1					
			57.8							
06/29/01	41.6	5.23	48.1	51.7	33.8	30.65	27.1	28.55	1.25	1.085
			55.3		27.5		30		0.92	
09/19/01	44.3	5.46	57.2	52.95	18.3	18.45	19.6	19.65	0.93	0.935
			48.7		18.6		19.7		0.94	
12/10/01	41.2		47.6	48.85	22.3	21.2	22	20.65	1.01	1.025
			50.1		20.1		19.3		1.04	
12/10/01	46.3		51.1	49.45	18.8	18.35	29.5	28.8	0.64	0.64
			47.8		17.9		28.1		0.64	
02/05/02	39.5	5.83	39.2	45.15	24.2	24.2	18.5	20.45	1.08	1.08
			51.1				22.4			

Table 5.4. Data from analyses of MSW in Column #3.

Column #4 Sample Date	Moisture %	pH	Vol. Solids %	Ave. VS %	Cellulose %	Ave. Cell. %	Lignin %	Ave. Lignin %	Cell./Lig Ratio	Ave. C/L Ratio
05/16/01	41.4	5.62	52.1	51.83	21.4	24.2	22.4	23.35	0.96	1.035
			50.9		27		24.3		1.11	
			52.5							
06/29/01	40.8	5.53	59.4	55.85	28.1	24.65	21.9	21.2	1.28	1.155
			52.3		21.2		20.5		1.03	
09/19/01	36.6	5.43	40.4	37.85	10.9	14.6	16.9	20.95	0.64	0.685
			35.3		18.3		25		0.73	
10/29/01	38.6	5.4	36.5	36.45	10.9	10.3	14.4	14.3	0.76	0.72
			36.4		9.7		14.2		0.68	
12/10/01	29.6		41.5	37.45	9.4	11.3	38.8	28.45	0.24	0.485
			33.4		13.2		18.1		0.73	
12/10/01	30.5		43.1	41.9	16.2	13.6	23.5	21.4	0.69	0.63
			40.7		11		19.3		0.57	
02/05/02	31	5.95	41.9	37.45	14.5	15.25	17.9	19.7	0.81	0.775
			33		16		21.5		0.74	

Table 5.5. Data from analyses of MSW in Column #4.

Column #10 Sample Date	Moisture %	pH	Vol. Solids %	Ave. VS %	Cellulose %	Ave. Cell. %	Lignin %	Ave. Lignin %	Cell./Lig Ratio	Ave. C/L Ratio
05/16/01	39.7	6.59	74.1	74.23	36.9	29.7	31.9	31.95	1.16	0.93
			73.5		22.5		32		0.7	
			75.1							
06/29/01	22.6	6.23	78.6	79.3	42.5	41.65	18.9	19.7	2.25	2.12
			80		40.8		20.5		1.99	
08/01/01	36.3	5.82	69.6	72.9	26.4	26.65	23.9	23.25	1.1	1.145
			76.2		26.9		22.6		1.19	
09/19/01	38.5	5.86	76.6	77.2	24.9	26.25	28.1	28.2	0.89	0.93
			77.8		27.6		28.3		0.97	
10/29/01	34.4	6.07	64.3	62.6	31.1	29.45	27.4	26.8	1.13	1.095
			60.9		27.8		26.2		1.06	
10/29/01	46	5.82	71.2	70.15	26.9	29.1	28.2	25.6	0.95	1.155
			69.1		31.3		23		1.36	
12/10/01	38.2		77.8	77.05	33.9	32.55	24.2	26.4	1.4	1.245
			76.3		31.2		28.6		1.09	
12/10/01	37.5		67.6	68.1	22.4	24.35	38	32.8	0.59	0.77
			68.6		26.3		27.6		0.95	
02/05/02	39.8	6.49	72.7	74.7	28.7	28.5	27.8	26.85	1.03	1.06
			76.7		28.3		25.9		1.09	

Table 5.6. Data from analyses on MSW in Column #10.

Column #11 Sample Date	Moisture %	pH	Vol. Solids %	Ave. VS %	Cellulose %	Ave. Cell. %	Lignin %	Ave. Lignin %	Cell./Lig Ratio	Ave. C/L Ratio
05/16/01	44.6	5.84	79.1	77.63	31.1	30.65	31.9	32.55	0.97	0.94
			78		30.2		33.2		0.91	
			75.8							
06/29/01	41.9	5.88	79.6	79.9	36	36.6	26.3	27.15	1.37	1.39
			80.2		37.2		28		1.41	
08/01/01	42	5.73	77.9	77.25	28.6	29.3	32.4	31.95	0.88	0.915
			76.6		30		31.5		0.95	
09/19/01	43.6	5.87	71	72.4	23.7	24.15	26.9	27.4	0.88	0.88
			73.8		24.6		27.9		0.88	
10/29/01	43.4	5.82	60	60.75	30.3	26.4	23.7	24	1.28	1.105
			61.5		22.5		24.3		0.93	
10/29/01	43.9	5.81	66.6	66.95	na	23.8	22.6	24.4	na	0.91
			67.3		23.8		26.2		0.91	
12/10/01	40.2		76.6	69.5	36.8	32.25	28.8	31.05	1.28	1.055
			62.4		27.7		33.3		0.83	
12/10/01	38.5		65.7	66.95	24	23.8	31.2	33.3	0.77	0.72
			68.2		23.6		35.4		0.67	
02/05/02	41.2	6.48	69.1	67.95	25.4	22.2	29	29	0.66	0.66
			66.8		19		-			

Table 5.7. Data from analyses on MSW in Column #11.

Column #12 Sample Date	Moisture %	pH	Vol. Solids %	Ave. VS %	Cellulose %	Ave. Cell. %	Lignin %	Ave. Lignin %	Cell./Lig Ratio	Ave. C/L Ratio
05/16/01	23.7	5.63	87	87.73	26.7	24.4	37.1	35.9	0.72	0.68
			87.7		22.1		34.7		0.64	
			88.5							
06/29/01	16.5	5.9	85.9	87.8	42.8	42.25	34.8	35.4	1.23	1.195
			89.7		41.7		36		1.16	
08/01/01	20	5.95	88.6	87.45	40.9	41.1	36	36.45	1.14	1.13
			86.3		41.3		36.9		1.12	
09/19/01	21.4	5.75	84.1	83.25	43.8	43.05	31.7	33.05	1.38	1.305
			82.4		42.3		34.4		1.23	
10/29/01	22.8	5.82	82.6	79.95	33.5	33.35	40.9	40.5	0.82	0.825
			77.3		33.2		40.1		0.83	
10/29/01	21.6	5.74	86.1	85.25	38	35.95	41.2	41.45	0.92	0.865
			84.4		33.9		41.7		0.81	
12/10/01	17.7		80.7	77.3	37.2	35.9	37.5	37.35	0.99	0.96
			73.9		34.6		37.2		0.93	
12/10/01	19.6		88.8	89.65	50.9	48.75	31.4	32.5	1.62	1.505
			90.5		46.6		33.6		1.39	
02/05/02	19.9	6.05	88.1	85.95	47.7	49.05	29.4	29.8	1.62	1.645
			83.8		50.4		30.2		1.67	

Table 5.8. Data from analyses of MSW in Column #12.

	Moisture %	Vol. Solids %	Ave. VS %	Cellulose %	Ave. Cell. %	Lignin %	Ave. Lignin %	Cell./Lignin Ratio	Ave. C/L Ratio
Column #1 A	51.3	58.8	57.25	28.9	30.1	20.4	20.5	1.41	1.465
		55.7		31.3		20.6		1.52	
Column #1 B	47.3	48.4	47.75	23.2	22.6	22.5	22.25	1.03	1.015
		47.1		22		22		1	
Column #2 A	39.1	52.1	50.95	16.7	16.55	17.3	17.25	0.96	0.96
		49.8		16.4		17.2		0.96	
Column #2 B	38.1	61.4	57.45	17.1	16.6	21.3	20.15	0.8	0.825
		53.5		16.1		19		0.85	
Column #3 A	46.3	39.8	43.55	22	19.35	18.2	17.3	1.21	1.115
		47.3		16.7		16.4		1.02	
Column #3 B	41.2	25.3	26.15	26.9	25.25	19.1	18.95	1.41	1.335
		27		23.6		18.8		1.26	
Column #4 A	29.6	28.4	30.2	10.2	12.1	12.1	13.95	0.84	0.86
		32		14		15.8		0.88	
Column #4 B	30.5	22	23.3	10.1	12.95	12.6	15	0.8	0.855
		24.6		15.8		17.4		0.91	
Column #10 A	37.5	62.2	64.85	33.9	30.3	25.6	25.15	1.32	1.2
		67.5		26.7		24.7		1.08	
Column #10 B	38.2	68.9	68.6	32.1	33.3	20.2	19.85	1.59	1.68
		68.3		34.5		19.5		1.77	
Column #11 A	40.2	57.4	61.85	30	27.25	na	na	na	na
		66.3		24.5					
Column #11 B	38.5	52.6	53.4	23.6	22.6	20.7	20.55	1.14	1.1
		54.2		21.6		20.4		1.06	
Column #12 A	17.7	81.5	80.7	45.8	45.8	28.6	30	1.6	1.6
		79.9		na		31.4		na	
Column #12 B	19.6	79	80.35	44	42	26.4	27.05	1.67	1.555
		81.7		40		27.7		1.44	

Table 5.9. Data from analyses of columns samples after removal of all plastic.

	Moisture %	Vol. Solids %	Ave. VS %	Cellulose %	Ave. Cell. %	Lignin %	Ave. Lignin %	Cell./Lignin Ratio	Ave. C/L Ratio	Plastic %
Column #1 A	51.3	57.2	62.75	32.3	28.35	25.1	25.75	1.29	1.105	15.5
		68.3		24.4		26.4		0.92		
Column #1 B	47.3	70.7	69.6	24.6	25.05	30	28.95	0.82	0.865	14.9
		68.5		25.5		27.9		0.91		
Column #2 A	39.1	58.7	56.25	18.3	20.2	19	21.25	0.97	0.955	9.2
		53.8		22.1		23.5		0.94		
Column #2 B	38.1	52.3	54.2	20.1	17.6	23.4	23.35	0.86	0.755	13.9
		56.1		15.1		23.3		0.65		
Column #3 A	41.2	47.6	48.85	22.3	21.2	22	20.65	1.01	1.025	19.5
		50.1		20.1		19.3		1.04		
Column #3 B	46.3	51.1	49.45	18.8	18.35	29.5	28.8	0.64	0.64	12.4
		47.8		17.9		28.1		0.64		
Column #4 A	29.6	41.5	37.45	9.4	11.3	38.8	28.45	0.24	0.485	14.6
		33.4		13.2		18.1		0.73		
Column #4 B	30.5	43.1	41.9	16.2	13.6	23.5	21.4	0.69	0.63	10.3
		40.7		11		19.3		0.57		
Column #10 A	38.2	77.8	77.05	33.9	32.55	24.2	26.4	1.4	1.245	4.2
		76.3		31.2		28.6		1.09		
Column #10 B	37.5	67.6	68.1	22.4	24.35	38	32.8	0.59	0.77	22.6
		68.6		26.3		27.6		0.95		
Column #11 A	40.2	76.6	69.5	36.8	32.25	28.8	31.05	1.28	1.055	9.6
		62.4		27.7		33.3		0.83		
Column #11 B	38.5	65.7	66.95	24	23.8	31.2	33.3	0.77	0.72	15.4
		68.2		23.6		35.4		0.67		
Column #12 A	17.7	80.7	77.3	37.2	35.9	37.5	37.35	0.99	0.96	9.8
		73.9		34.6		37.2		0.93		
Column #12 B	19.6	88.8	89.65	50.9	48.75	31.4	32.5	1.62	1.505	13.7
		90.5		46.6		33.6		1.39		

Table 5.10. Data from analyses of column samples containing plastic.

Sample Date	Ave. % VS	Ave. % Cell.
Column #1		
04/03/00	67	33
05/17/00	64	32
07/17/00	50	25
08/31/00	44	23
12/05/00	51	21
02/15/01	59	25
Column #2		
04/03/00	60	28
05/17/00	70	26
07/17/00	56	23
08/31/00	52	22
12/05/00	59	26
02/15/01	58	22
Column #3		
04/03/00	33	12
05/17/00	44	17
07/17/00	51	24
08/31/00	53	20
12/05/00	39	12
02/15/01	46	17
Column #4		
04/03/00	38	21
05/17/00	51	18
07/17/00	42	22
08/31/00	53	23
12/05/00	50	14
02/15/01	47	16
Column #10		
04/03/00		
05/17/00	81	34
07/17/00	82	32
08/31/00	71	39
12/05/00	80	35
02/15/01	70	30
Column #11		
04/03/00		
05/17/00	83	35
07/17/00	82	26
08/31/00	74	34
12/05/00	74	34
02/15/01	68	36
Column #12		
04/03/00		
05/17/00	85	35
07/17/00	85	29
08/31/00	71	37
12/05/00	76	44
02/15/01	81	42

Table 5.11. Volatile solids and cellulose data from seven column columns before the addition of heat.

VITA

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May 2002
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