GEOENVIRONMENTAL ASPECTS OF COAL REFUSE-FLY ASH BLENDS

by

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

MASTER OF SCIENCE

in

Environmental Engineering

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October 1994

Blacksburg, Virginia

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(ABSTRACT)

The separate land disposal of coal refuse and fly ash presents difficulties throughout the Appalachian region, both in terms of disposal costs per acre and in terms of its potential environmental impacts on soil, ground water, revegetation, and slope stability. The purpose of this study was to determine how fly ash addition to coal refuse would impact on certain geotechnical properties of the refuse disposal piles, and whether the refuse-fly ash blends would be suitable as co-disposed materials. Accordingly, the compaction, permeability and shear strength characteristics of the refuse-fly ash blends were experimentally determined for varying fly ash percentages. The compaction test results indicated that, with increasing fly ash, the maximum dry density of these blends marginally decreased. The permeability test results showed that the permeability of the test specimens progressively decreased with the increase in fly ash. The shear strength results demonstrated that the addition of fly ash did not significantly influence the shear strength of the refuse. The critical factor of safety determined during slope stability analysis revealed that the tested slope geometries were stable for long term, drained conditions (using the STABGM computer program). The

volume change analysis determined that there was a minimal expansion in the volume of refuse when it was blended with fly ash. However, it may be noted that all the stated results depend on a number of factors, including the nature of the refuse and fly ash used. Therefore, these findings would be specific to bulk blends of coal refuse and fly ash only. In general, this study indicates that fly ash can be beneficially reused with respect to the geotechnical properties evaluated. Co-disposal of fly ash and coal refuse may be a reasonable alternative to present disposal methods.

ACKNOWLEDGEMENT

I would like to extend my profound thanks to Dr. Lee Daniels, Committee Chairman for his assistance, guidance and inspiration throughout the study. I would also like to thank co-advisor Dr. John Novak and committee members Dr. Tom Brandon and Dr. Jerry Luttrell for their constant help and guidance.

A very special thank you to Tom Brandon for his patience, advice, equipment and the use of the Prices Fork laboratory facilities.

Many thanks to Ronnie Alls for helping to build much of the test equipment used in my research and for giving me frequent rides to different places at odd times.

I wish to express my appreciation to all the "marginals" particularly W. T. Price, Velva Grover, Ren Sheng Li, and Barry Stewart for their help, their constant encouragement, cheerfulness, humor and for tolerating all the weird practices arising from my research!

I appreciate all those who helped to make this thesis a success including Dr. Naraine Persaud, Pam Thomas, Mike Genthner, Katie Haering, Dr. Mark Alley, Andy Rose, Alan Roach and all those whom I inadvertently overlooked.

Finally, I wish to thank the Clinchfield Coal Company for the use of the refuse samples from the Moss 3 pile and for the financial assistance provided to this project.

I wish to dedicate this thesis to my parents, whose many sacrifices made it possible for me to come to the United States to pursue graduate studies and eventually work on this thesis.

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CHAPTER 1. INTRODUCTION

Coal mining operations have come under increasing regulation including the disposal of coal refuse. Coal refuse disposal may create detrimental effects which include soil and ground water contamination and slope instability of the 'gob piles', historically resulting in landslides. Current costs of disposal are high, and the percentage of the run of mine coal feed which requires disposal is increasing. Fly ash is also a waste byproduct of coal and is produced in large quantities when coal is burned in power plants. Its disposal is also governed by strict regulations. Moreover, at certain rates of fly ash addition, coal refuse and fly ash complement each other in producing chemically neutral mixtures having a pH between 6-8. Thus, if coal refuse and fly ash could be safely co-disposed, it would greatly reduce the total disposal area needed for the two materials (and minimize total costs) with little or no adverse impacts on the environment after their co-disposal.

During the last few years, several experiments have been conducted using fly ash as an amendment to coal refuse. However, the scope of these experiments has been restricted to testing the refuse-fly ash mixtures for their chemical and vegetative impacts. So far, few studies have been conducted on the geotechnical properties or on the slope stability aspects of refuse piles blended with fly ash. Such a study is required to determine how the addition of fly ash to coal refuse would impact on certain geotechnical properties of the refuse piles. This study could lead to a greater efficiency in minimizing waste disposal by developing a better understanding about the physical properties of refuse-fly ash blends.

RESEARCH OBJECTIVES

1. To determine the density-moisture content relationships of different coal refuse-fly ash mixtures under compaction at varying levels of moisture content.

2. To evaluate the saturated permeability range for refuse-fly ash blends at varying proportions of fly ash.

3. To examine the shear strength characteristics of coal refuse-fly ash mixtures at various concentrations of fly ash.

4. To calculate the critical factor of safety in slope stability analysis of a typical refuse pile mixed with 32% fly ash for long term, drained conditions.

5. To compute the volume change of coal refuse at maximum dry density, when blended with various percentages of fly ash.

CHAPTER 2. LITERATURE REVIEW

2.10. Coal Refuse

2.11. Introduction

Coal mining and cleaning wastes (colliery waste, gob, slate, refuse, etc.) are byproducts generated in the mining of coal. They can broadly be divided into two categories (1) the overburden material and (2) the reject byproduct from a coal 'prep' plant. The overburden is the overlying material on the top of the coal seam, which is first removed during the mining of coal, and is generally called "mine spoil." The material from the seam is then processed through a 'prep' plant where the usable coal is extracted and the remaining material is disposed as refuse. The focus of this study will be on the refuse stream generated at the prep plant.

Nearly 44 million tons of coal were mined in Virginia in 1989 (Randolph et al., 1990), most of which was of the bituminous variety. The mining of this coal generated about 17- 20 million tons of coal refuse (Daniels et al., 1993). This disposal rate has been steadily increasing with the demand from the industry and an environmentally conscious public for cleaner coal.

Coal refuse is deposited in refuse disposal areas in and around mining areas. In the past (before 1977), it was disposed of in loose uncompacted piles, which would often catch fire due to exothermic pyrite oxidation or could cause landslides due to slope instability. However, with the passage of the Surface Mining Control and Reclamation Act (SMCRA) of 1977, guidelines were specified and stable piles were required to conform to rigorous geotechnical standards (Bell et al., 1989). After 1977, the coal refuse was disposed of in an altogether different way for most active operations. According to the new methods, coarser fragments (>0.5 mm) were separated from relatively finer fragments (< 0.5 mm) and both these fragments were disposed of separately at many sites. The coarse fraction is employed to serve as an impoundment to dam the finer fragments (tailings) which are disposed in the form of a slurry. This study deals mainly with the determination of various geotechnical parameters of the coarse fraction when it is blended with varying percentages of fly ash.

It is very difficult to estimate the exact area occupied by refuse piles in the United States. However, in Virginia over 4,000 ha. are reserved for the disposal of coal refuse (Daniels et al., 1992). Refuse can be detrimental to the environment because over time, it tends to produce acidic leachates which impact the soil and the surrounding vegetation.

2.12. Geological Setting

Most of Virginia's coal comes from the seven "coal-counties" of Wise, Russell, Scott, Buchanan, Lee, Tazewell and Dickenson county. The coal is bituminous to semianthracite though most of it is high to low-volatile bituminous. According to the Keystone Coal Industry Manual (1988), the coal is Pennsylvanian in age and occurs in a sequence of sandstone, siltstone and shale. In some cases, calcareous beds of fluvio/marine origin are also present. In case of coarse refuse, most of the rock types are shales and siltstones. These rocks weather very quickly because of their fissile bedding planes (Keystone Coal Industry Manual, 1988).

There are several formations with associated coal beds in the Appalachian coal fields of southwest Virginia. These include the Pocahontas, Lee, Norton, Wise and Harlan formations. The Pocahontas field is regarded as the oldest formation of Pennsylvanian age and it extends into West Virginia (Keystone Coal Industry Manual, 1988). At certain places the Lee formation overlies the Pocahontas. The Lee formation in turn rests below the Norton formation which lies below the Wise formation. At highest elevations, the Harlan formation overlies the Wise formation. Most of Virginia's coal is currently mined from the Norton and Wise formations (Keystone Industry Manual, 1988).

2.13. Properties of Coal Refuse

In conventional mining practice, material greater than 0.5 mm is regarded as coarse material and the remaining material (< 0.5 mm) is regarded as fines. By this definition, most of the material found in refuse piles is coarse in texture. Seventy-nine percent of the refuse found in the USA in a 1986 study was greater than 1mm in size and was therefore coarse refuse (Khan et al., 1986). In general, the particle size of refuse depends on the method of processing coal, the geographic location of the coal, and the weathering characteristics of the pile.

The older methods of processing coal greatly vary from modern ones. With earlier methods of coal processing, the refuse materials were hand picked and as a result few fines were incorporated into the piles. Modern methods however, involve the use of coal prep plants at most sites. In these prep plants the coarse material (> 0.5 mm) and the fine material

(< 0.5 mm) are generally separated from each other. The fine material is usually ponded as a slurry behind an impoundment of coarse refuse.

Variability in particle size has also been observed based on the geographic location of the refuse piles. Moulton et al. (1974) observed that fresh refuse in West Virginia contained 68-95% coarse fragments whereas in Pennsylvania in a study of 79 inactive bituminous piles, Davidson (1974) found the coarse fragment content to be 56-69%. However, the ASTM method of classifying coarse grained material and fines varies from the conventional mining practice discussed in previous sections. Therefore, as per section 12 of ASTM D 2487 (ASTM, 1992), coarse grained soils are those which are retained on the No 200 (0.075 mm) sieve. This ASTM classification will be used throughout this text to categorize coarse and fine grained materials. An approximate sieve analysis on a fresh refuse pile conducted by the author at the Moss 3 site in southwest Virginia revealed that the coarse particles (retained on a No 200 sieve) were in the range of 94-99%. This range is typical considering that the refuse material sampled from the pile was no more than four days old and it was derived solely from the coal prep plant.

Surface weathering of the pile also has a major impact on the particle size of the refuse. In general, the particle size of the refuse tends to decrease and the percentage of the sand and silt fractions tends to increase over a period of time. Moulton et al. (1974) observed a drop in the coarse particle size from 68-95% to 47-80% for West Virginia piles that had weathered for 30 years. Buttermore et al. (1978) and Delp (1975) observed that the coarse fragment content increased with depth on the piles that they had sampled.

2.13.2. Acidity and pH

Most fresh refuse has a near neutral pH when it first comes from the prep plant. However, over a period of time there is a decline in the pH of these piles. In a study of five refuse piles in Illinois, Hayes and Klimstra (1975) reported pH values to be in the range of 2.4 - 4.3, with a sample mean of 2.8. Similar values have also been reported by Delp (1975) and Nawrot et al. (1986). This drop in pH can be attributed to the weathering of pyrite which is an iron disulfide mineral present in the refuse. According to Watzlaf and Hammack (1989), the pyrite oxidizes to form sulfuric acid and ferrous (Fe^{+2}) and ferric (Fe^{+3}) forms of iron. Therefore, the higher the pyritic sulfur content in refuse, the greater is its potential acidity. In general, refuse with a pH of 3.5 or lower can be attributed to active pyritic oxidation of a refuse pile derived from high sulfur (>2%) coal (Stewart, 1990).

Caruccio et al. (1977), Lowson (1982), Harries and Ritchie (1987), Watzlaf and Hammack (1989), and Stewart (1990) have extensively described the mechanism of pyrite oxidation and its relation to the low pH values found at various piles.

2.14. Acid Mine Drainage

Acid Mine Drainage (AMD) is the acidic discharge leached from a refuse pile into the surrounding environment. According to Carrucio et al. (1977), the production of acid solutions caused by pyrite oxidation is detrimental only when there isn't sufficient alkaline material in the refuse pile to neutralize the acidity formed. In most cases there is little or no alkaline material present in most cases and thus, AMD remains a major challenge to the environment in most mining areas. Acid mine drainage is detrimental to vegetation and water quality because of the acidity produced in the leachate and the presence of large amounts of sulfates, ferric iron and other potentially toxic metals and compounds (Vogel, 1987).

Attempts to establish vegetation directly on extremely acidic refuse material by direct seeding without surface amendments usually fail. Various amendments such as lime and phosphate have been added to the refuse to improve its physical and chemical properties to achieve successful revegetation and pile stability. Fly ash may have great promise as a refuse amendment because it is cost effective and may achieve the twin goals of enhancing revegetation and improving drainage water quality.

2.20. Fly Ash

2.21. Introduction

Coal is the major source of energy used world wide. Burning of coal yields Coal Combustion Byproducts (CCB'S) which constitute 90% of all fossil fuel combustion wastes produced in the USA (USEPA, 1988). CCB's mainly consist of fly ash, bottom ash, scrubber sludge and fluidized bed boiler waste (Carlson and Adriano, 1993). Of these, only fly ash will be considered here as it has the maximum beneficial reuse potential and is the best documented material.

Fly ash is the particulate matter extracted from the flue gas stream after the combustion of coal in the boiler unit and before stack gas discharge. It constitutes up to 90% of the total ash produced in the boiler and it is collected by air pollution control devices such as baghouses and electrostatic precipitators (Klein et al., 1975; Natush et al.,1977). According to Muraka and McIntosh (1987), fly ash and bottom ash account for most of the 75 million tons of solid waste produced annually by the American electric utilities. In Virginia alone, around one million tons of fly ash were generated in 1989 (Haering and Daniels, 1991).

The use of fly ash as a soil amendment is controlled by a number of environmental, social, regulatory and economic factors. In the past, the fly ash was disposed of in ravines, quarries, landfills and in the ocean (Peffer, 1983; Cherkauer, 1980; Drake, 1991). This disposal may have created several environmental hazards such as sedimentation and ground water contamination due to leachate percolation. In addition, there has been increasing public concern over the disposal of ash and its possible health implications. So to minimize the possible adverse environmental impacts, a series of regulations restricting the disposal of fly ash were passed in the 1970's and 1980's (Peffer, 1983). In 1990, ocean dumping of fly ash was also banned. Thus, disposal of fly ash has become increasingly difficult and expensive. Therefore, if fly ash can be effectively reused, then its disposal and overall management costs could be greatly reduced. At present, about 20% of the fly ash is utilized, mainly in the construction industry. The remaining 80% is disposed of in landfills (Cherkauer, 1980). If the beneficial reuse potential of fly ash is pursued, then great economic savings could be accomplished. With these objectives in mind, the beneficial reuse potential of fly ash as an amendment to coal refuse was studied.

2.22. Ash Generation

The amount of fly ash generated at a given plant depends on many factors such as the composition of parent coal used, the efficiency and type of emission control devices and the methods of ash disposal used (Adriano et al., 1980). For instance, typical ash percentages of 5.7% and 9.7% by weight are produced in the Appalachians for cleaned coal and raw coal respectively (Haering and Daniels, 1991).

Several devices can be used to separate the particulate fly ash from the stack gases. These devices include mechanical collectors (such as baghouses and filters) and electrostatic precipitators. Mechanical collectors such as baghouses are convenient to operate and are relatively inexpensive. They have a high efficiency of 99% with particle removal greater than 1 μ. However, these collectors have certain drawbacks. For example, their removal rates may not conform to EPA standards and their operating range is restricted to strictly dry and low temperature conditions. For this reason, many utilities prefer to use electrostatic precipitators. Electrostatic precipitators consist of two parallel plates containing opposing charges. The negatively charged fly ash is collected at the cathode (Golden, 1983). Electrostatic precipitators have a maximum efficiency of up to 99%, with particle removal of greater than 2μ observed at pressure losses of 5 cm of water or less (Golden, 1983). Metallic electrostatic precipitators can be used at high temperatures to remove fly ash from corrosive gases, such as SO_2, which contain high percentages of particulate matter greater than 1 μ in size.

2.23. Ash Classification

As per standards set by ASTM, fly ash is classified as either class C or class F depending on the source of the parent coal (Ferguson, 1993). Class C ash is a high calcium, pozzolanic fly ash, generated in the combustion of western sub-bituminous or lignite coal (Usmen and Bowders, 1988). Class F fly ash is formed in the burning of bituminous or anthracite coals which are found in the eastern, midwestern and southern parts of the United States. Class F fly ash may display weak self-cementing properties due to its comparatively lower calcium content (Nicholson and Kashyap, 1993). Many class F fly ashes are non alkaline, low in pH, and entirely non-pozzolanic.

2.24. Regulatory Aspects

Fly ash is regulated as a fossil-fuel combustion (FFC) waste by the EPA under the Resource Conservation and Recovery Act (RCRA) of 1976. Ever since 1978, there was a question as to whether the EPA should classify fly ash as a hazardous waste under Subtitle C of RCRA. However, because of limited information on the nature of the risks posed by fly ash, there was little or no headway. Finally in 1993, after considerable debate and a court case (leading to a consent decree), the EPA issued its final regulatory document 40 CFR Part 261. As per this document, fly ash is exempted by the EPA from regulation as a hazardous waste under RCRA Subtitle C. Instead, as part of its ongoing assessment, the EPA is planning to regulate fly ash as a nonhazardous solid waste according to RCRA Subtitle D (USEPA, 1993).

2.25. Mineralogical Characteristics

Fly ash consists mainly of cenospheres which are glassy silt sized particles containing numerous impurities embedded in and adsorbed on their inert silica matrices (Haering and Daniels, 1991). Structurally, these cenospheres are solid, hollow or irregularly shaped or are filled with other cenospheres (Page et al., 1979). These cenospheres range from 20μ to 200 μ in diameter and have particle densities of 0.4 g/cm^3 to 0.8 g/cm^3 (Ray and Parker, 1978). The percentage of the total cenospheres in the ash is dependent on a number of factors such as the type of coal burned and the method of extraction of the ash from the stack gases. The cenospheres constitute about 5% of the total fly ash by weight and about 20-80% of the total ash by volume (Hecht and Duvale, 1975; Adriano et al., 1980). Studies by Adriano et al. (1980) indicate that fly ash consists of mainly (70-80%) glassy and spherical particles with the remaining portion being made up of mineral clasts such as quartz (SiO_2) and hematite (Fe_2O_3). However, in a study of Tennessee fly ashes, Ray and Parker (1978) found the total percentage of cenospheres to be as low as 20% of the fly ash with the remaining fraction being made up of accessory minerals.

2.26. Physical properties

The physical properties of fly ash vary with the nature of the coal burned and the total amount of ash (3%-30%) present in the coal (Ray and Parker, 1978). The physical properties of the ash also vary with the type of furnace used and the collector setup (Haering and Daniels, 1991). Depending on the type of ash generated, the fly ash fraction ranges from

0.005 mm to 0.1 mm in diameter (Hecht and Duvale, 1975; Plumley, 1971). However, for most fly ashes, the average particle size is less than 0.010 mm (Chang et al., 1977).

In a study using various fly ashes, Chu et al. (1976) observed that the color of fly ash ranged from a light tan to grayish black. This color variation in the ash was attributed to the increased levels of iron or carbon in the ash. An increase in iron was found to impart a light tan hue to the ash, while an increase in carbon was found to yield a grayish black tone (Ray and Parker, 1978).

2.27 Chemical Properties

The chemical properties of fly ash depend on the geological and geographical factors related to the deposits of coal and on the physical properties of the ash (Ray and Parker, 1978). These properties also depend on the combustion conditions and on the removal efficiency of the air pollution devices such as electrostatic precipitators and mechanical collectors.

Fly ash contains most of the naturally occurring elements (Klein et al., 1975) though 95-99% of most ashes are composed of oxides of mainly Si, Al, Fe and Ca (Theis and Wirth, 1977; Ray and Parker, 1978). According to the Ray and Parker (1978), there are 20-50 trace elements present in fly ash. Some of these trace elements which can negatively affect flora and fauna include Boron, Molybdenum, Selenium and Vanadium. In general, the concentration of the trace elements decreases with particle size (Davison et al., 1974). This is because the smaller particles with high surface area can adsorb greater concentrations of elements per unit weight to their surfaces.

The pH of most moist fly ashes varies from 3-12, though most of the coal fly ashes mixed with water were found to have a pH of 8 to 12 (Chu et al., 1976). In general, the total Ca content coupled with the ratio of Fe to Ca is the primary determinant of alkalinity in fly ash. Typically, low-Ca eastern fly ashes are less alkaline than the western fly ashes which have a high concentration of Ca (Ray and Parker, 1978). Thus, eastern fly ashes generally have low pH values (3-6) while western fly ashes have high pH values (8-12) (Ray and Parker, 1978). These observations are in agreement with a study conducted by Dorans and Martens (1972), in which the pH of various fly ashes studied by them was found to vary from 4.5 to 12.

2.28. Engineering Properties of Fly Ash

The engineering properties of fly ash vary with different types of ashes and their removal mechanisms. Thus, bituminous coal produces relatively finer fly ash than the ash produced from burning lignite (Tolle et al., 1982). The ash removed from mechanical collectors (like baghouses) is relatively coarse (>0.001µ) with sand size particles predominating. However, in the case of electrostatic precipitators, the ash is relatively finer (<1µ) with the predominance of the silt size particles (Haering and Daniels, 1991). Most fly ash samples have a silt loam texture, with 65-90% of the particles being less than 0.010 mm in diameter (Chang et al., 1977; Roy et al., 1981). Particle size analyses conducted by several researchers indicate that the silt size fraction constitutes a major portion of the fly ash. For instance, a particle size analysis on Illinois fly ash by the Chicago fly ash company revealed that the ash contained 71% silt sized particles and the remaining portions being sand and clay sized particles. In their studies involving PEPCO fly ash, Lamb et al. (1976) concluded that though fly ash contains clay size particles, it is still non-plastic from an engineering standpoint. Roy et al. (1981), Tolle et al. (1982), and Mattigod et al. (1990) conducted a series of experiments on a variety of fly ashes. They observed that fly ash has low bulk density (1.01-1.43 g/cm^3) and specific gravity (1.6-3.1). Moderately low values (7x10^{-5} cm/s to 1x10^{-4} cm/s) of saturated permeability for fly ash were also reported by Peffer (1983) and Drake (1991). Certain fly ash materials also possess self hardening or pozzolanic properties. Thus, these materials can serve as good cementing agents particularly when they are blended with other materials such as coal refuse and asphalt. This 'age hardening' or latent strength development occurs due to the pozzolanic nature of fly ash (Bacon, 1976). In general, self hardening properties can be determined from CBR tests. According to Joshi et al. (1976), in the case of high Ca, high pH, low C fly ash, self hardening properties can be indicated empirically when the samples attain CBR values above 15, after wetting for 96 hours.

The compressive strength of an ash sample can be determined for a given compactive effort. For instance, Grand Avenue fly ash from Kansas City developed unconfined compressive strengths of 965 to 2206 kPa (140 to 320 lb/ sq. in.) within a 28 day period for a 95% degree of compaction at a modified Proctor effort (Joshi et al., 1976). Studies by Lamb (1973) on fly ash show that the maximum shear strength as determined from unconsolidated-undrained triaxial tests is attained at optimum moisture values.

2.30. Coal Refuse-Fly Ash Blends

Extensive studies have been undertaken on the vegetative and geochemical aspects of refuse-fly ash blends by Haering and Daniels (1991), Stewart et al. (1992), Jackson (1993) and Stewart et al. (1994) on a variety of sites in Virginia. Additional site specific studies have been carried out by Fail and Wochok (1977), Keefer et al. (1980), Taylor and Schumann (1988) and other researchers. However, limited or no studies have been done so far on the geotechnical characteristics of these blends or on the slope stability aspects of the co-disposed piles of refuse and fly ash. Isolated experiments have been performed in some mining areas on select engineering properties of refuse-fly ash blends. For instance, in a West Virginia mine, 150-200 tons/acre of fly ash were blended with a refuse pile to investigate the hydraulic properties of this mix. It was observed that the water holding capacity, infiltration rate, porosity and seepage rate were significantly impacted by the addition of this ash to the refuse pile (Adams et al., 1972; Plass and Capp, 1974). Thus, the addition of certain proportions of fly ash to refuse may have the potential to improve the engineering properties of refuse, thus improving certain geotechnical characteristics of the gob piles.

2.40 Background Studies

2.41. Initial Column Study

A series of parallel experiments on the geochemistry of refuse-fly ash mixtures is being conducted in the Department of Crop and Soil Environmental Sciences at Virginia Tech at this time. The initial column study was begun in the spring of 1991. In this study, eight columns were packed with refuse or bulk blended mixtures of refuse and fly ash. These columns were set up in the greenhouse and subjected to 2.54 cm. of acid rain once every four days. This leaching frequency was decreased to once a week after seven months of leaching. Leachates from these columns were collected and analyzed for pH, electrical conductivity (EC), and for the presence of certain elements such as Fe, Mn, B and Ca using instrumentation techniques such as Atomic Absorbance Spectrophotometry (AAS) and Inductively Coupled Plasma Electron Spectrophotometry (ICPES).

Results from the first column study indicate that three years of successive leaching of fly ash amended columns has yielded a steady pH of 8 (Jackson, 1993). Also, a decline in Fe and Mn levels was observed in these leachates with time. However, leachates from unamended refuse columns exhibited a sharp decrease in pH from 7 to 2, in less than four months of leaching. In general, it was noticed that leachate quality improved with time for fly ash amended columns. From the basic leachate data generated by these columns, it was inferred that refuse columns amended with ash were effective in controlling pyrite oxidation and acid generation. On the downside, however, leachate from fly ash amended columns had higher levels of Na and K than the leachate obtained from unamended refuse columns. The electrical conductivity (EC) of the leachate was also monitored in this study. The EC values indicate the concentrations of soluble elements in the leachate. Thus, a decrease in EC values was observed with leaching over a period of time corresponding to declining soluble salt levels in the leachate. The following conclusions can be drawn about the first column study:

1. Addition of fly ash to refuse as an amendment improves leachate quality and

reduces the concentration of metals present in the leachate over time.

2. Fly ash amended columns are useful in controlling pyrite oxidation and acid generation. The amount of Fe leached from these columns sharply decreases after initial leachings.

2.42. Column Experiment 2

The second column study, which is an ongoing investigation, was undertaken in the spring of 1992 to expand upon the results from the first column study. The objectives of this study are to determine the optimal refuse fly ash ratio and to compare more conventional lime/topsoil and rock-P-treatments in addition to using fly ash. Fifteen treatments, each having three replications are employed in this study. Therefore, there are a total of forty-five columns in which this study is carried out. Each of these columns has a constant mass of 36 kg refuse and a twenty-cm diameter. Some of these treatments are

1. Unamended refuse (control)
2. Refuse + 5% Westvaco fly ash
3. Refuse + 10% Westvaco fly ash
4. Refuse + 20% Westvaco fly ash
5. Refuse + 33% Westvaco fly ash
6. Refuse + 20% Clinch River fly ash
7. Refuse + 33% Clinch River fly ash

These columns are subjected to 2.5 cm of simulated acid rain each week. The leachates of these columns are collected once a week and are analyzed for pH, EC, Fe, Mn, S and B. The objective of this study is to also generate leachate quality data in a lab environment in order to model field conditions.

The results from the second column study obtained so far show that the quality of leachate generated was influenced by the percentage of fly ash blended with refuse in these columns (Jackson, 1993). Thus, leachate from the 5% Westvaco ash mix had a basic pH for only a few weeks and thereafter it turned acidic. The leachate from the 10% Westvaco fly ash blend maintained a pH of 8 for nearly 40 weeks and subsequently it also acidified. Conversely, the leachate from 33% Westvaco fly ash amended columns has, until now, sustained a basic pH of over 8, with low levels of soluble salts in the leachate. The most alkaline ash used was the Clinch River (CR) fly ash and leachates from columns containing 20% CR ash have maintained a pH level of 9 for over two years, with decreasing elemental concentrations in the leachate. In general, when an ash amended column acidifies, the elements from the ash are available to be leached in a low pH environment. This results in the acid stripping of metals from fly ash, which in turn, may lead to an increased level of metals in the leachate. Such was the case for the columns which turned acidic. Therefore, a large increase in EC was observed for these acidifying columns (since EC depends on the amount of soluble salts in the leachate). However, for non-acidifying ash-amended columns, the EC values were found to decrease with time corresponding to a decrease in the metal concentration in the leachate. Thus, the following conclusions can be drawn from the second column study:

1. Alkaline fly ash can control pyritic oxidation in coal refuse if sufficient alkalinity is present in the mix and can thus prevent the blend from acidifying. However, if there isn't enough alkalinity in the blend, the acidification of the mix will eventually take place.

2. Acidification of ash amended mixtures may result in acid stripping which could lead to leachates having higher metal concentrations than those found in the unamended refuse leachate.

3. Acid mine drainage can also be controlled by using non-alkaline fly ash blended with ground limestone.

2.43. Field Studies

In the spring of 1992, field plots were installed in Wise county in order to study the leachate properties of refuse-fly ash mixtures and verify the results of column studies and geochemical models. The fly ash samples used for these experiments were the Mead paper fly ash (FA1), Clinch river fly ash (FA2) and Chesterfield fly ash (FA3). FA2 was surface applied and bulk blended in proportions of 20% and 33% by volume while the FA1 and FA3 were blended only at the rate of 33% by volume (Stewart et al., 1992).

The leachate quality of the treatments is being measured with the help of buried lysimeters which were placed selectively into three replications for each of the six treatment types. Therefore, there are eighteen lysimeters in all and the percolated leachate from each lysimeter is sampled with the help of a pump. However, the frequency of the leachate sampling was dependent on the rainfall pattern (Stewart et al., 1992).

These leachate samples were collected on an approximately 4-week interval. These samples analyzed for pH, EC and for elements such as Al, B and Cu. The field results indicated that there was an overall decline in the pH of the leachates over time compared to the leachates that were initially collected. However, the decline in the pH varied with the percentage of fly ash that was bulk blended with refuse and with the type of fly ash used. A decline in the EC of the leachates was also observed compared to the EC values first recorded from the leachates from the ash treated lysimeters. The decline in EC values was probably due to the leaching of entrained salts from the lysimeters. Data from this experiment shows that the mobility of most metals (Al, Cu, Mn etc.) is largely a function of pH. Thus, when the pH drops below 4, the metal becomes soluble and increasing amounts of metals are found in the leachate. However, for a pH of 4.5 or more, the level of elements in the leachates remains fairly low. It was found that B can be a problematic material as it is initially leaches amounts which can cause plant toxicity, but with prolonged leaching its presence is greatly decreased.

The studies conducted so far have given us invaluable data on the leachate chemistry and the revegetation potential of the refuse-fly ash mixtures. However, no study has as yet been conducted on the geotechnical characteristics of the refuse-ash mixture concept. Such a study could greatly benefit the citizens of Virginia through reduced waste disposal costs and through potential improvements in water quality in the coalfields.

CHAPTER 3. MATERIALS AND METHODS

This chapter deals with the selection of coal refuse and fly ash utilized, and with the methodologies used for testing these materials as refuse-fly ash blends. Accordingly, this chapter is partitioned into two sections as follows: 3.10) Materials and 3.20) Methods. The materials section discusses the scope of this investigation, and the description and sampling procedures used for the Moss 3 refuse pile and Clinch River fly ash. The methods section summarizes the experimental procedures used for this study. A detailed description of these methodologies along with the results obtained is discussed in Chapter 4.

3.10. MATERIALS

3.11. Scope of this Study

Coal refuse and fly ash were used in this study. The coal refuse used was obtained from the Moss 3 pile, in Russell county, which is owned by the Clinchfield Coal Company. The fly ash was obtained from a fly ash landfill, also in Russell county, which is owned by the Appalachian Power Company (Apco). Only bituminous coarse coal refuse (> 0.075 mm) was used for this investigation. All tailing fines (< 0.075mm) were rejected and as such these are excluded from the scope of this study. Fly ash was blended with coal refuse in proportions ranging from 8% to 32%, in increments of 8%. It was found that refuse-fly ash blends containing greater than 32% fly ash were not workable and the properties of these blends were dominated by the properties of fly ash. Therefore, blends containing more than

32% fly ash were not included in this investigation. Pure coal refuse was also used in the testing and analysis of these materials as a control in order to serve as a means of comparison for the test blends. Pure fly ash was also used as a control material for the compaction and permeability tests.

3.12. Moss 3 Coal Refuse Pile

A number of coarse coal refuse piles from southwest Virginia were considered for this study, but only the Moss 3 pile was selected. This is because Moss 3 is the largest pile in the region and has typical coarse refuse fragments. Moreover, its analysis represents the worst possible case scenario in terms of slope stability and design. Only coarse coal refuse was considered since the main objective of this study was to determine the geotechnical impacts of adding fly ash to a coarse refuse pile. Fine refuse (or slurry) has been excluded from the scope of this study.

The Moss 3 coal refuse pile is located in Russell county and is managed and owned by the Clinchfield Coal Company, a subsidiary of the Pittston Coal Management Company. It is the largest and oldest pile in the area having existed for at least 30 years. The refuse found at this pile is mostly coarse in nature and is a byproduct from the coal 'prep' plant, which processes and cleans the mined coal. A flow chart of the various processes occurring in a typical prep plant (such as Moss 3) is displayed in figure 1.

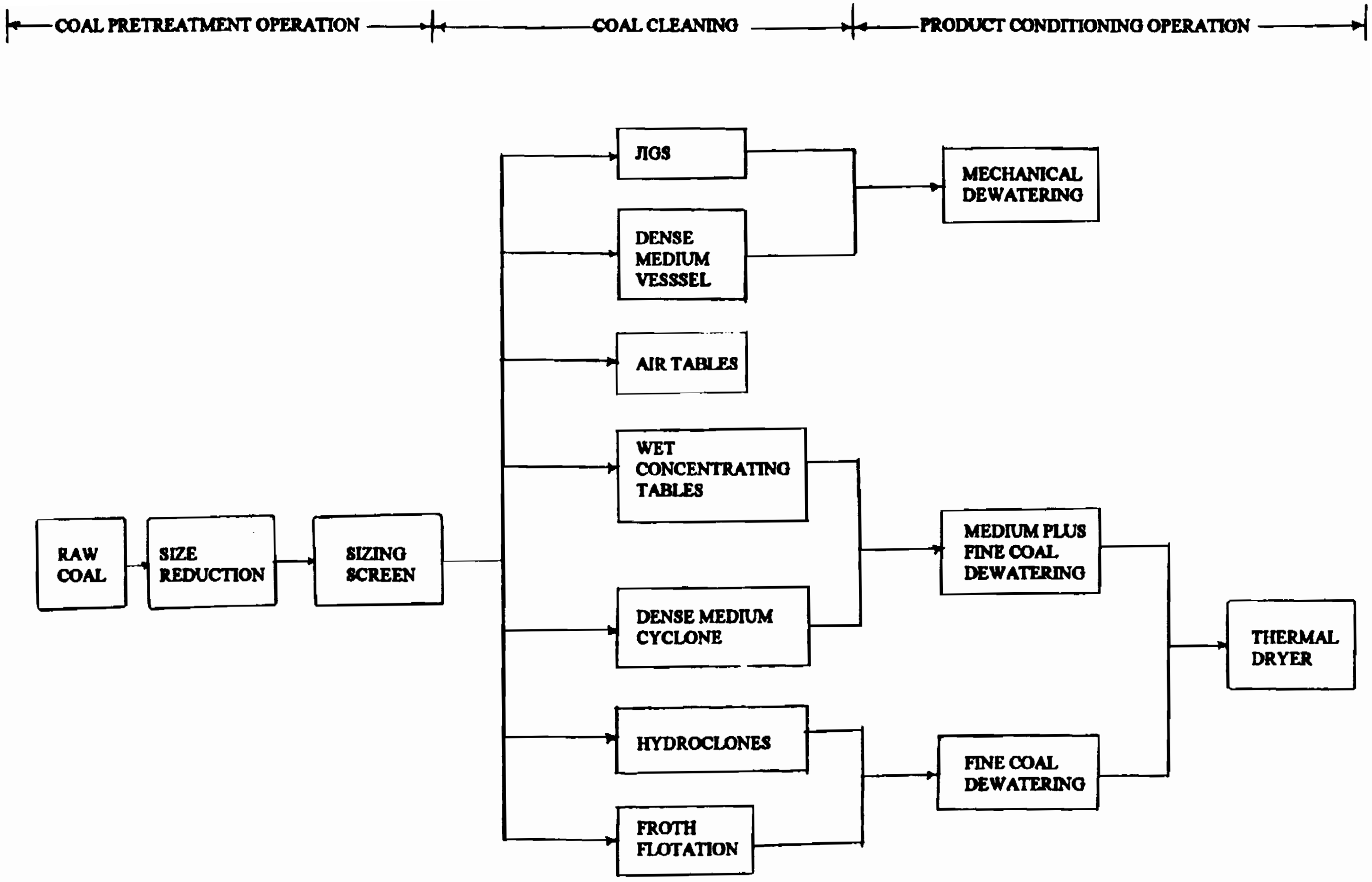

Figure 1. Coal Cleaning Processes in a Typical Prep Plant

A description of the fundamental operations taking place in a typical prep plant (such as Moss 3) is presented in Appendix E. The disposal of the refuse material from the prep plant is aided by a conveyor belt which continuously transports the wet coal refuse to the top of the pile. This refuse is then uniformly spread over a large surface of the pile using pneumatic rollers. The Moss 3 pile has an estimated areal extent of 260 hectares (one mile^2). Since the refuse is unevenly deposited over the valley, the height of this pile varies from section to section and it could range from 15 to 46 m (50 to 150 feet), with an estimated average height of 30 m (100 feet). The Moss 3 pile is located at the periphery of the mining site and therefore it acts as an embankment for the liquid slurry and fines generated during coal extraction. Over a period of time, weathering takes place in most piles, resulting in smaller fragments and fines. However, in case of the Moss 3 pile, these fines are quite negligible (< 5%) compared to the overall coarse fragment content in the pile.

Coarse coal refuse was sampled only from the Moss 3 pile since this pile contains coal refuse typical to that found in southwestern Virginia. Only fresh coarse refuse (< 4 days old) was sampled, in order to prevent the occurrence of pyritic reactions and weathering mechanisms that take place in older piles. The coal refuse was collected in five 0.21 m^3 (55 gallon) barrels. The refuse in three of these barrels was collected below the conveyor belt as it came out from the prep plant. The other two barrels were filled with relatively recent refuse (< 4 day old) from four random points on the surface of the pile. The depth sampled at these random locations extended to a maximum depth of 0.60 m (2 feet) from the surface of the pile. In order to get a sample which would be as representative as possible, the refuse from the five barrels was thoroughly mixed and air dried over a period of ten days. The air dried material was then stored in air tight 0.21 m^3 (55 gallon) barrels, with polyethylene seals, to limit chemical reactions taking place within the refuse.

3.15. Clinch River Fly Ash:

Different fly ashes were considered for this study from various locations in southwestern Virginia and eastern West Virginia. Most of these were found to be low pH (<6) acidic fly ashes with a few exceptions such as the Clinch River fly ash. The Clinch River fly ash was eventually chosen for this study because of its properties such as its alkaline nature, silt loam texture and mildly pozzolanic characteristics. A fly ash having such properties can greatly enhance the physical and chemical properties of refuse-fly ash blends and can act as a good binding material in refuse-fly ash blends.

The Clinch River fly ash is produced at the Clinch River power plant operated by the Appalachian Power Company (Apco) in Russell county. This ash is currently disposed of in a fly ash landfill and is watered down and compacted to prevent its dispersion. Five 0.21 m^3 (55 gallon) barrels were used to sample the fly ash from this ash landfill. The fly ash collected was wet, uncompacted and about a day old. It was then air dried for 10 days. All the clods formed after drying were crushed into powder. The total volume of the dried ash was then thoroughly mixed to get a representative sample. This ash was then stored in 0.21 m^3 (55 gallon) barrels, with polyethylene seals, in order to prevent the material from getting contaminated. These air dried refuse and fly ash specimens were later tested for compaction, permeability and shear strength.

3.20. METHODS

This section gives briefly outlines the history and the methodologies of the various tests that were conducted. The methodologies and results of these tests are extensively described in Chapter 4. Before conducting these test, a preliminary grain size analysis was carried out for individual samples of coal refuse and fly ash to determine their gradation characteristics. The procedure and results of these analyses are also described in Chapter 4. Three laboratory test series were conducted on refuse-fly ash mixes beginning in the spring of 1993. These tests were conducted to determine the compaction, permeability and shear strength characteristics of refuse-fly ash blends at various rates of fly ash. The percentages of fly ash used ranged from 8% to 32% by weight, in increments of 8%. Coal refuse and fly ash served as control specimens. 100% coal refuse was used as a control for all the tests while 100% fly ash was used as a control for the compaction and permeability experiments.

The compaction test was carried using a modified Proctor compactive effort, using a 0.002 m^3 (0.075 ft^3) mold, a 4.54 kg (10 lb) rammer and a compactive effort of 2,700 kN-m/m^3 (56,000 lbf-ft/ft^3), as per the procedure outlined in ASTM D 1557-91 (ASTM, 1992). The procedure, computations and results of this test are described in chapter 4. The compaction test data is useful in the design of engineered refuse fills and in the execution of permeability and shear tests. This test data is also helpful in computing the volume change characteristics of a refuse fill, blended with various rates of fly ash.

The permeability test was carried out for coal refuse, fly ash and refuse-fly ash blends to determine whether the addition of fly ash to refuse would have any impact on the refuse permeability. The falling head method of permeability determination was used to conduct this test. In this test, a falling head apparatus was designed using a burette as a standpipe and a 23 cm (9-in.) high, 20cm (8-in.) diameter PVC column as a permeameter. Since no ASTM standard was available, this test was carried out using the traditional methods of permeability determination, as explained in the experimental procedures section in chapter 4. The permeability test data is useful in determining the percentage of fly ash required to reduce the flow of leachate through a refuse pile, thereby reducing the potential acid mine drainage of the pile. However, the lower the permeability, the greater the chance for an undrained failure of a slope.

A consolidated-undrained (CU) triaxial shear strength test was conducted to determine the effective cohesion (c') and the frictional angle (ϕ') of refuse-fly ash blends and 100% refuse. According to the ASTM test procedure 4767-88 (ASTM, 1992), a cylindrical specimen was sheared using a load frame after it was initially compacted, saturated and consolidated. The deviator load, deflection of specimen and the pore pressure were monitored during the shearing process. From these variables, c' and ϕ' values were obtained. The experimental procedure, computations and results of this test are extensively described in chapter 4. The shear strength parameters were used in the slope stability program STABGM to determine the critical factor of safety of the Moss 3 pile blended with fly ash.

In general, the data from the compaction, permeability and shear strength tests were used to determine the best proportion of fly ash needed to enhance the geotechnical properties of the refuse-fly ash pile. These test data were also used in computing the volume change of the mix (at maximum Proctor dry density conditions) at varying rates of fly ash. The experimental approach used for these methods and the results obtained are thoroughly dealt with in Chapter 4.

CHAPTER 4. EXPERIMENTAL PROCEDURE AND RESULTS

4.10. Particle Size Analysis (PSA) for Coal Refuse and Fly Ash

4.11. PSA of Coal Refuse

A particle size analysis was carried out for 60 kg of coal refuse by passing it through a set of seven sieves (see table 1). Based on the cumulative material retained in each of these sieves, the percentage of various refuse fractions (such as sand) was determined. The refuse sample was then classified, on the basis of the predominant size fractions, using ASTM D 2487-90[1] (ASTM, 1992). This specimen was finally classified as a well graded gravel with sand, using the following criteria:

1. The % of coal refuse retained on the No. 200 sieve was 98.5%. Since more than 50 % of the refuse was retained on the No. 200 sieve, it was classified as a coarse grained material.

2. The % of the material passing through the 3-in. sieve and retained on the No. 4 sieve was 63 %. More than 50% of the material was retained on the No. 4 sieve. Therefore, this material was characterized as a gravel.

3. The coefficient of uniformity (C_u) was much greater than 4 and the coefficient of curvature (C_c) lay between 1 and 3. Therefore, the refuse material identified as a well-graded gravel (GW) according to ASTM D 2487-90 (ASTM, 1992).

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[1] Standard Test method for the Classification of Soils for Engineering Purposes

4. The refuse specimen was ultimately classified as a well-graded gravel with sand since it was predominantly gravel (63%) but contained 15% or more sand.

The uniformity and curvature coefficients were used in this investigation to determine the relative proportions of coarser and finer refuse particles in the test specimen. These coefficients are defined by ASTM D 2487-90 (ASTM, 1992) as follows:

The coefficient of uniformity, $C_u = D_{60}/D_{10}$

The coefficient of curvature, $C_c = D_{30}^2/(D_{10} \times D_{60})$

where D_{60}, D_{30} and D_{10} are the particle diameters corresponding to 60%, 30% and 10% finer on the cumulative particle size distribution curve respectively. The C_c and C_u values for the given refuse specimen were calculated and they were found to be 1.70 and 23 respectively. The significance of these coefficients is discussed in Chapter 5.

The results obtained from the sieve analysis of this specimen are displayed in table 1. The grain size distribution curve for the refuse specimen was plotted from this sieve analysis and it is illustrated in figure 2. The relevance of the particle size distribution of coal refuse is addressed in Chapter 5.

4.12. PSA of Fly Ash

The pipet method was used in the grain size analysis of Clinch River fly ash (Day, 1965; ASA, 1990). In general, the pipet method is a popular laboratory procedure which is used to determine fine soil fractions such as silts and clays. This method involves the following three stages:

Table 1. Particle Size Analysis for Moss 3 Coal Refuse

Sieve #	Sieve Size, mm	Cumulative Retained, kg	Cumulative Retained, %	Cumulative Passing, kg	Cumulative Passing, %
3-in.	75	0.00	0.00	60.00	100.00
3/4-in.	19	17.00	28.00	43.00	72.00
No. 4	4.76	37.60	63.00	22.40	37.00
No. 10	2.00	46.60	78.00	13.40	22.00
No. 40	0.425	55.00	92.00	5.00	8.00
No. 200	0.075	59.10	98.50	0.90	1.50

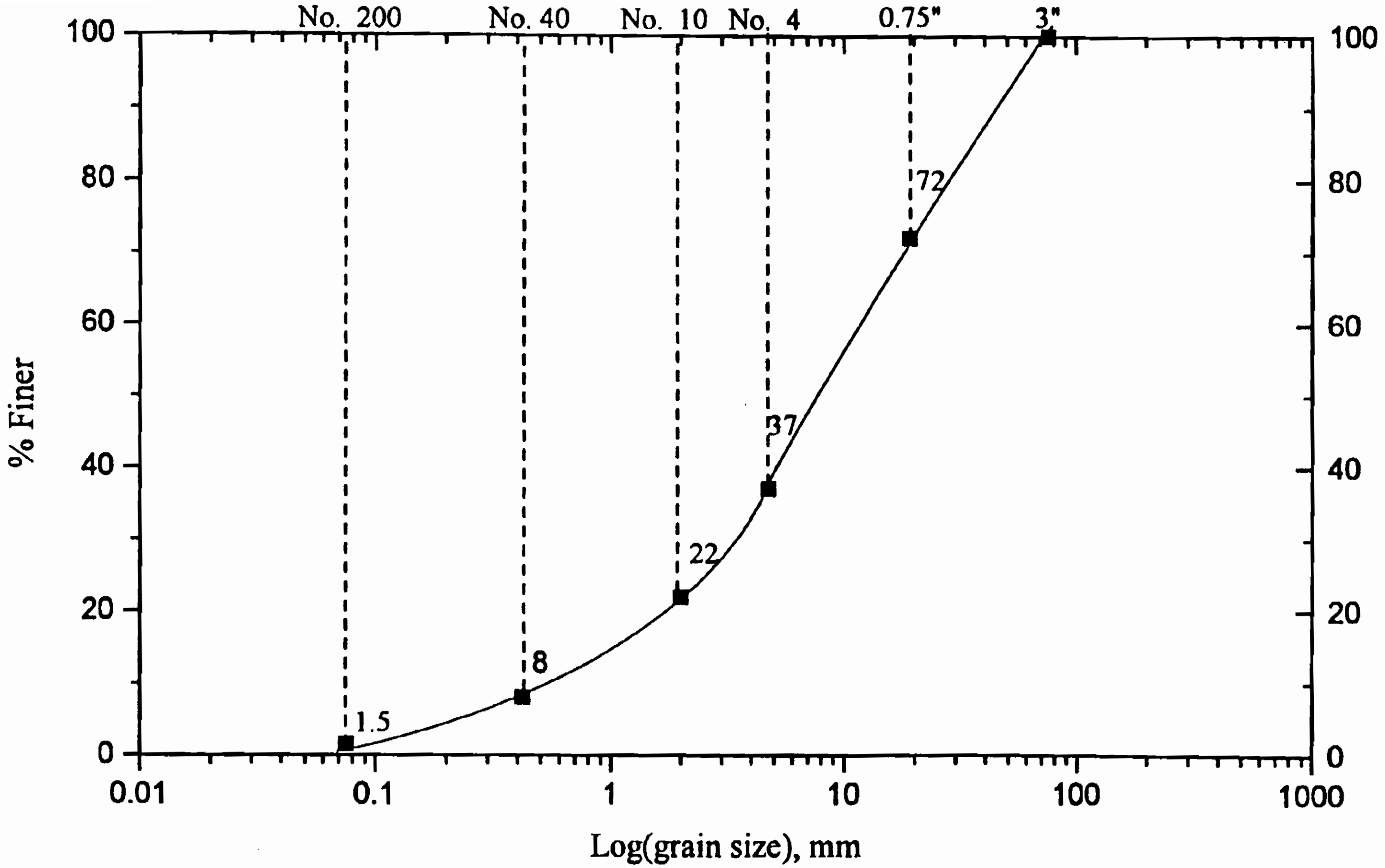

Figure 2. Grain Size Analysis of Moss 3 Coal Refuse

1. Dispersion and Wet Sieving
2. Dry Sieve Analysis
3. Sedimentation Analysis with Pipet Sampling

In the dispersion and wet sieving method stage, ten grams of fly ash were mixed with water and calgon and the fly ash in solution was allowed to disperse into sand, silt and clay fractions. All the sand size particles were then removed from solution by wet sieving the mixture through a No 300 (47 μ) sieve. The sand size particles were further separated into other sand size fractions by using the dry sieve method. Meanwhile, the supernatant passing through the No. 300 (47 μ) sieve contained silt and clay size particles. These particles were separated from the supernatant by using the sedimentation and pipet sampling procedure. This procedure was based on the different settling rates of silt and clay solids. In this procedure, three samples were pipetted from the same solution at different times and these were oven dried. The silt and clay fractions were then computed from the sample data.

The particle size analysis of fly ash suggests that the fly ash mainly consists of 14.4% sand, 82.2% silt and 3.4% clay sized fractions according to the ASTM system. However, as per the USDA system, fly ash consists of 26.3% sand, 70.3% silt and 3.4% clay sized fractions. Thus, on the basis of the USDA soil textural classification chart, the fly ash was classified as a silty loam. The sieve sizes and the percentage material passing (or retained) in the sieves are indicated in table 2. The particle size distribution curve for fly ash is illustrated in figure 3. The practical relevance and other aspects of the grain size distribution of fly ash are extensively discussed in Chapter 5.

Table 2. Particle Size Analysis for Clinch River Fly Ash

Sieve #	Sieve Size, mm	Cumulative Retained, gm	Cumulative Retained, %	Cumulative Passing, gm	Cumulative Passing, %
18	1.00	0.00	0.00	10.00	100.00
35	0.50	0.04	0.40	9.96	99.60
60	0.25	0.11	1.10	9.89	98.90
140	0.105	0.66	6.60	9.34	93.40
200	0.075	1.44	14.40	8.56	85.60
300	0.047	2.85	28.50	7.15	71.50
-	-	4.78	47.80	5.22	52.20
-	-	8.59	85.90	1.41	14.10
-	-	9.66	96.60	0.34	3.40

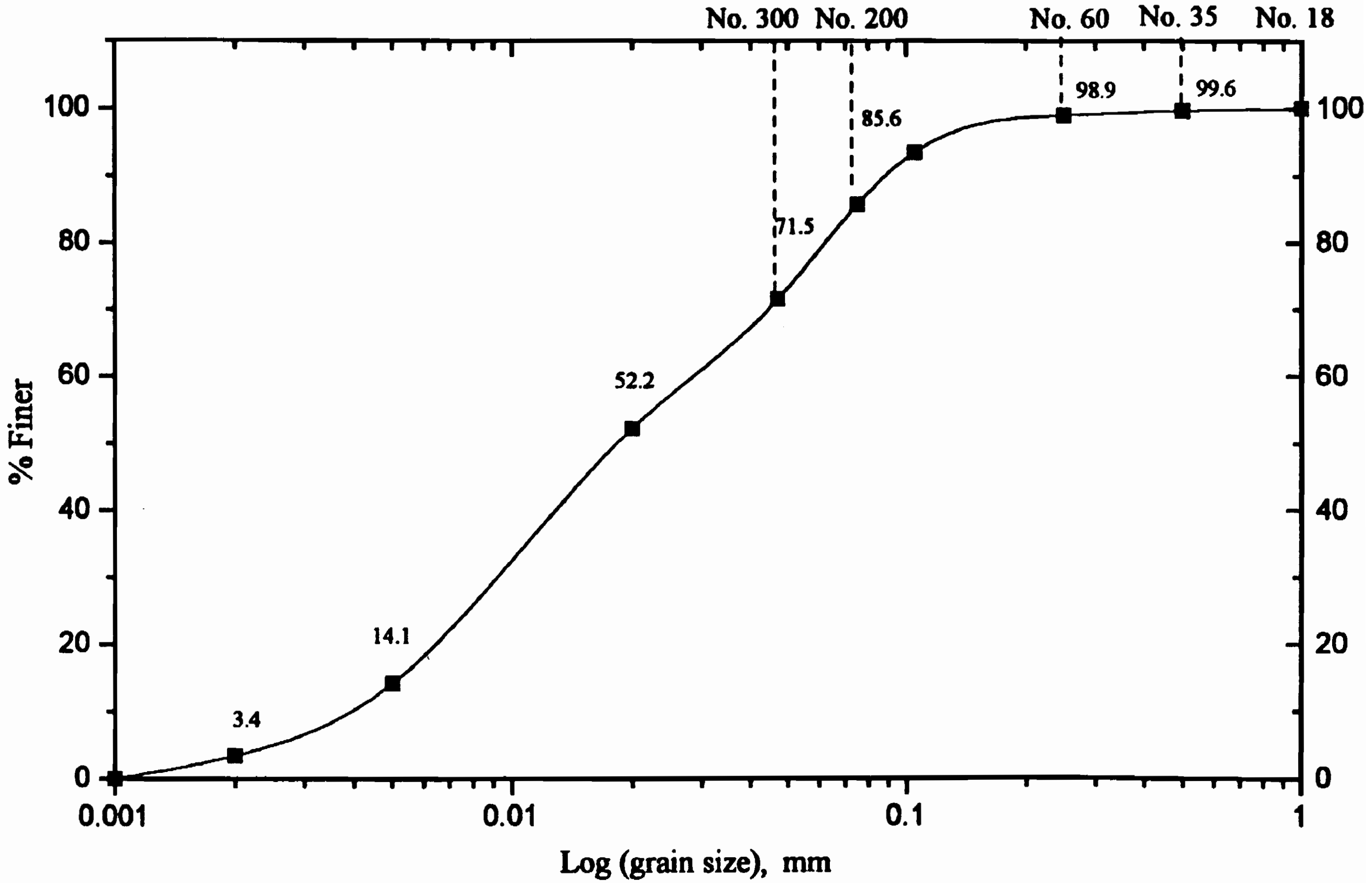

Figure 3. Grain Size Analysis for Clinch River Fly Ash

4.20. Modified Proctor Compaction Test:

The compaction test was conducted to obtain the maximum dry density (γ_{Dmax}) and optimum moisture content (w_o) characteristics for coal refuse-fly ash blends. This test was carried out for a total of six specimens which included four refuse-fly ash blends and two control specimens (i.e. 100% coal refuse and 100% fly ash). In case of the refuse-fly ash blends, the fly ash was blended with coal refuse at rates of 8% to a maximum of 32%, in increments of 8%. The compaction procedure was carried out as per the guidelines laid down in Method C of ASTM D 1557-91[2] (ASTM, 1992). Method C was chosen over other procedures because of the size of the mold used (15.2 cm (6-in.) diameter), and because most of the material retained on the 3/4" (19mm) sieve was between 10 to 30% of the total specimen weight.

As per the compaction test procedure, each sample was compacted in five layers with a rammer at a fixed moisture content. The moisture content after compaction (w) was then determined and the dry density of a given specimen was calculated based on the data obtained during the test. On the basis of these data, dry density-moisture content curves were plotted for all the test specimens. The compaction curves for refuse, fly ash and refuse fly ash blends are illustrated in figure 4. The experimental procedure for the compaction test are described in the subsequent sections as follows:

1. Six specimens consisting of four refuse-fly ash blends and two controls were used

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[2] Standard Test Method for Moisture Density Relations of Soil and Soil Aggregate Mixtures Using 10-lb (4.54-kg) Rammer and 18-in (457-mm) Drop.

for this test. Each of these specimens had five samples (replicates) with each replicate being compacted at a different moisture content. The moisture content required for each specimen varied from 4-25%, depending on the nature of the sample tested.

2. Each replicate, at a given moisture content, was placed in five layers in a Proctor mold. Each layer was compacted with 56 blows of a 44.5 N (10 lb) rammer. The rammer was dropped at a height of 0.45 m (1.5 feet) as per the prescribed ASTM procedure.

3. Compactive effort imparted, by the rammer, per unit volume of the specimen:

= (0.0445 KN) x (0.45 m) x (56 blows/layer) x (5 layers) / (0.002 m^3)

= 2700 kN-m/m^3 (56, 000 lbf-ft/ft^3)

4. The 100% saturation curve (or 0 air voids curve) was also plotted for various specific gravities as illustrated in figure 4. These curves are plots of the dry density vs the saturated moisture content of samples, at various specific gravities. The saturation curves were drawn along with the compaction plots since they act as an useful aid in plotting and interpreting the compaction curves.

The compaction procedure was repeated for other replicates to establish a relationship between dry density and moisture content. Compaction curves were plotted for a total of six specimens. The results obtained from this test indicate that the coal refuse sample had the highest maximum dry density of 19.5 KN/m^3 (125 lbf/ft^3) with a corresponding optimum moisture content of 6.6%. The maximum dry densities and the corresponding optimum moisture contents for the refuse-fly ash blends and the controls are tabulated in table 3. The compaction curves for all the specimens are displayed in figure 4.

Table 3. Compaction Test Results

Sample #	Blend Type	Optimum MC %	Max. DD γ_{Dmax} kN/m^3	Max. DD γ_{Dmax} lbf/ft^3
1	100% CR	6.6	19.50	125
2	CR + 8% FA	6.3	19.38	123
3	CR + 16% FA	7.0	18.70	120
4	CR + 24% FA	8.3	18.50	119
5	CR + 32% FA	8.3	18.20	117
6	100% FA	20.0	13.31	85

Legend

MC	Moisture Content
DD	Dry Density
CR	Coal Refuse
FA	Fly Ash

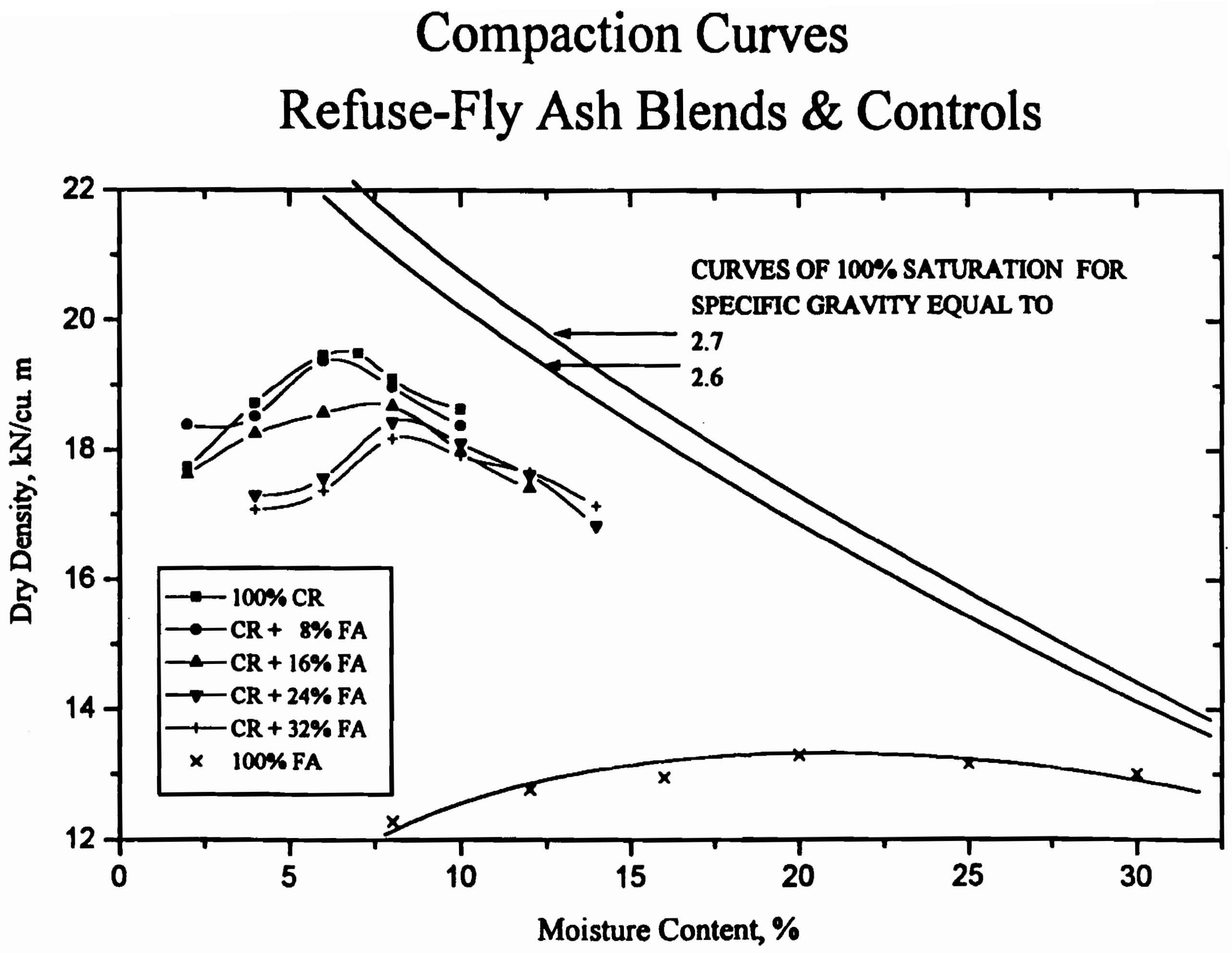

Figure 4. Compaction Test Results

The compaction curves for each specimen are illustrated from figures A1 to A6 in appendix A. The relevance and implications of the compaction test results are extensively discussed in Chapter 5.

4.30. Permeability Experiment:

The permeability test was carried out to determine the coefficient of permeability (k) of the coal refuse blended with different rates of fly ash. This test was carried out for a total of six specimens which included four refuse-fly ash blends and two control specimens (i.e., 100% coal refuse and 100% fly ash). The fly ash used for the refuse-fly ash blends ranged from 8% to a maximum of 32%, in equal increments of 8%.

The falling head method was chosen over the constant head method in permeability determination. This is because of the flexible nature of the falling head experimental set up and because the refuse-fly ash blends were expected to have a permeability of 10^{-4} meters/sec or less (Head, 1982).

In general, the falling head apparatus consisted of a large permeameter, a burette with an adjustable valve, a collection device and a timer as shown in figure 5. The permeameter was a solid 20 cm (8-in.) diameter PVC pipe which had an overall length of 25 cm (10 in.). Its main function was to house compacted test specimens. The burette was filled with water and attached to a pipe at the top of the permeameter. Its function was to provide a water head for the test sample in the permeameter. The collection device was attached to the bottom of the permeameter (see figure 5). Its main role was to collect the water leaving the permeameter. The permeameter bottom was permanently sealed with a plexiglass plate having a 3/4" (19-mm) pipe at its center. Before conducting the permeability test, a typical test sample was compacted to 95% of its maximum dry density as defined by ASTM D 1557-91[3] (ASTM, 1992). This compacted test sample was then placed in a permeameter and the permeameter was sealed at both ends. Initially, the permeability test was conducted by allowing water to flow from the burette into the permeameter until the specimen was saturated. The water was then allowed to exit the specimen after it was completely saturated. The coefficient of permeability (k) was calculated based on the head loss of water in the burette and the time required for this head loss. This experiment was carried out as follows:

1. For a typical test run, around 10 kg (22 lb) of test material were thoroughly mixed and compacted. The material was compacted in a mold at 95% of the maximum dry density, which was determined from ASTM D 1557-91[3] (ASTM, 1992). After the specimen was compacted, the base plate of the compaction mold was removed and the specimen was transferred from the mold to the permeameter.

2. Glass beads were placed at the top and bottom of the specimen in the permeameter, in quarter inch layers, to ensure accuracy in permeability determination. The top of the permeameter was then sealed with an easily detachable plexiglass covering using silicone sealant.

3. Water from the burette was then allowed to saturate the test specimen by

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[3] Standard Test Method for Moisture Density Relations of Soil and Soil Aggregate Mixtures Using 10-lb (4.54-kg) Rammer and 18-in (457-mm) Drop.

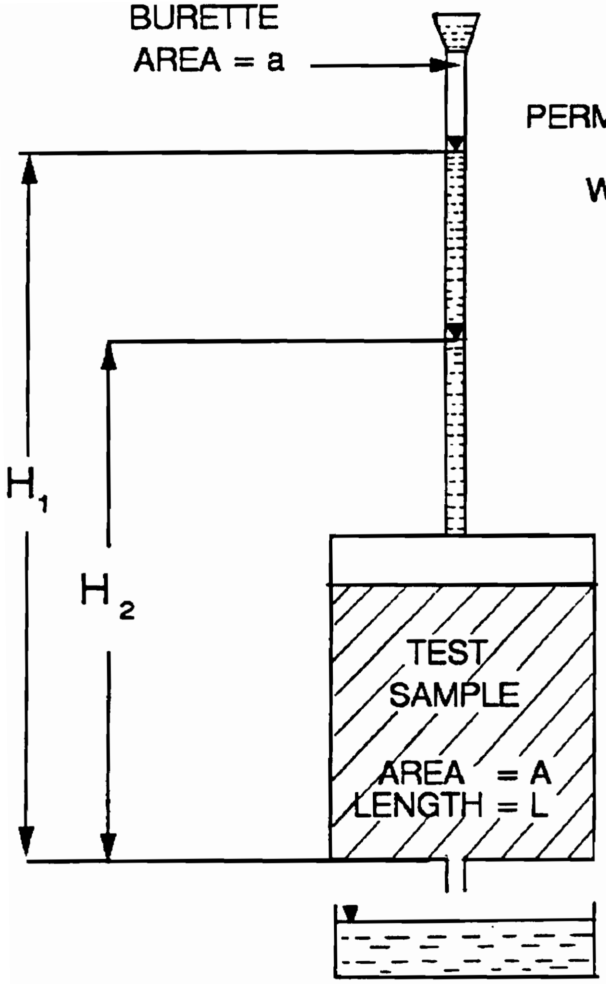
repeatedly draining the water-filled burette into the permeameter. The test specimen was assumed to be saturated when steady state conditions prevailed. Steady state conditions for the falling head test were characterized by the flow into the permeameter equaling the flow out of the permeameter. Steady state conditions were also indicated by small variations (5-10%) in the calculated permeability coefficients (k).

4. For a typical test run, the valve on the burette was closed and the burette was filled with distilled water up to a desired mark. The initial head, H_1 was measured from the base of the permeameter to the level of water in the burette (see fig 5).

5. The valve in the burette was then opened and the timer was started. When the water in the burette reached a desired level, the burette valve was closed and the timer was simultaneously stopped. The new head of water, H_2 was measured for the new water level in the burette. This procedure was repeated for a number of test runs until sufficient permeability test data was obtained.

6. After several test runs for a given specimen, the upper plexiglass covering of the permeameter was removed and the sample was replaced by a different specimen. The entire procedure (steps 1-5) was repeated for this new test specimen.

7. The diameters of the burette and the permeameter were measured by using a pair of vernier calipers and a standard scale respectively. Based on these measured diameters, the cross-sectional areas of the burette (a) and the permeameter (A) were calculated. The coefficient of permeability was then calculated using (Head, 1982):



PERMEABILITY = $(aL/AT)\ln(H1/H2)$

WHERE:

a = BURETTE AREA, cm
L = SAMPLE LENGTH
A = SAMPLE AREA, A cm
T = TIME OF TEST, sec
H_1 = WATER HEAD AT $t=0$
H_2 = WATER HEAD AT $t=T$

Figure 5. Experimental Setup for Permeability

$$k = \frac{aL(\text{Ln}\,(H_1/H_2)}{AT}$$

where k = coefficient of permeability, cm/sec

a = cross-sectional area of the burette, cm^2 ($in.^2$)

A = cross sectional area of the permeameter, cm^2 ($in.^2$)

L = length of the specimen in the permeameter, cm (in.)

T = time taken for the water to move from the initial to final level in the burette, s

H_1, H_2 = the heads of water between which permeability is determined, cm

The average permeability of the specimens decreased from 2.9×10^{-3} cm/s (for 100% refuse samples) to 7.9×10^{-5} cm/s (for refuse containing 32% fly ash). A summary of the permeability results for these specimens is shown on table 4. The permeability results are also illustrated in figure 6. The individual permeability test data are displayed from tables B1- B8 in the appendix. These permeability results are extensively discussed in Chapter 5.

4.40. Shear Strength Investigation (CU Test)

4.41 Introduction.

This section deals with the shear strength tests carried out for coal refuse and refuse-fly ash blends. This complex experiment was carried out to primarily determine c' and ϕ' values of these materials and thereafter, based on these results, analyze a refuse pile for slope stability.

Table 4. Permeability Test Results

Sample #	Blend Type	Permeability, k (cm/s)
1	100% CR	2.86E-03
2	CR + 8%FA	1.01E-03
3	CR + 16%FA	2.56E-04
4	CR + 24%FA	1.71E-04
5	CR + 32%FA	7.88E-05
6	100%FA	5.78E-05

Legend

CR	Coal Refuse
FA	Fly Ash

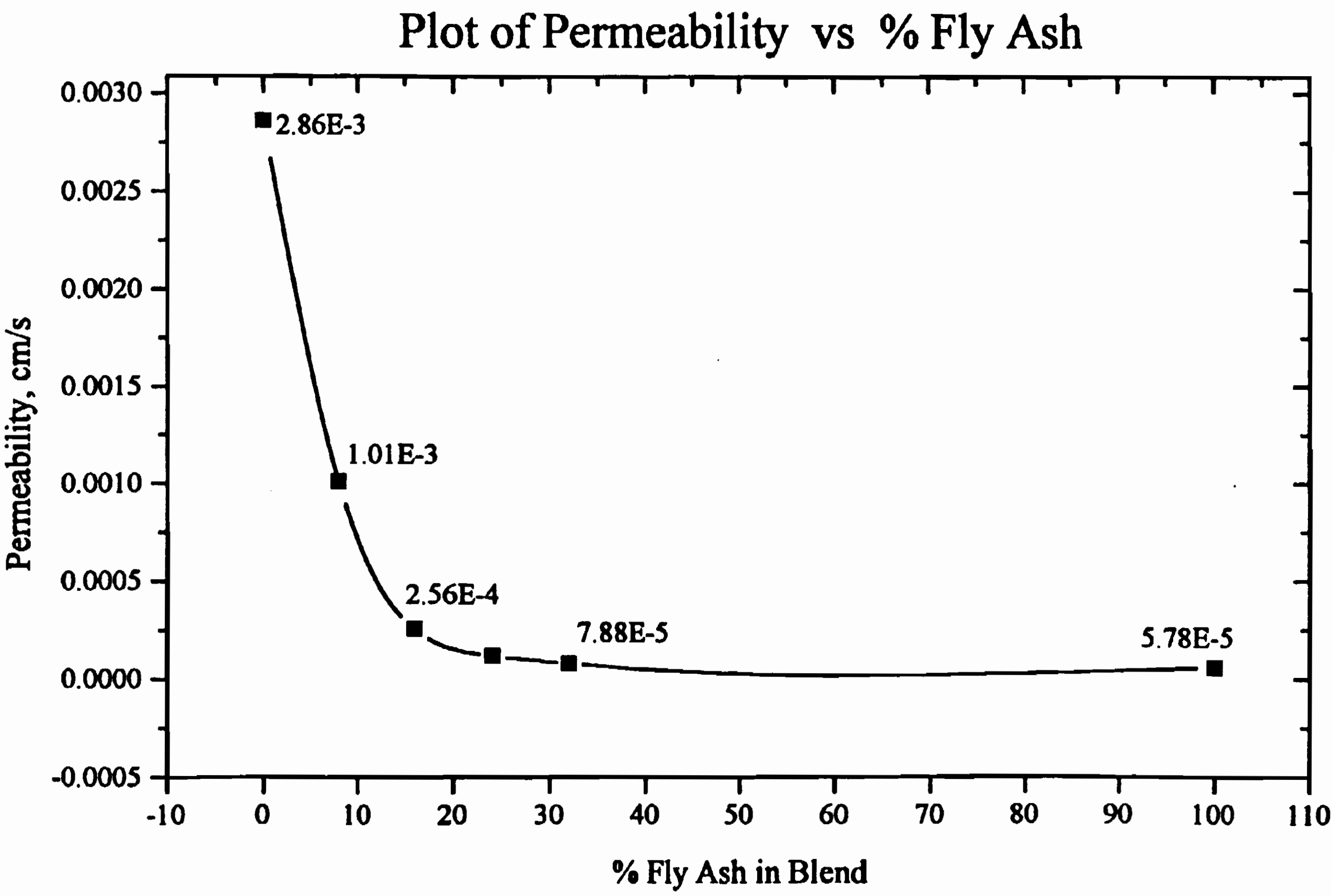


Figure 6. Permeability Test Results

The triaxial compression test is the most versatile test used in the measurement of shear strength properties. There are three types of basic triaxial compression shear tests, i.e. the unconsolidated-undrained (UU), consolidated-undrained (CU) and the consolidated-drained (CD). The test for consolidated-undrained triaxial shear strength was determined for a set of four specimens, using ASTM D 4767-88[4] (ASTM, 1992). The samples used for the CU test consisted of a refuse specimen and three refuse-fly ash blends. The refuse material used for these specimens consisted only of the fraction passing through the 3/4" (19-mm) sieve. The oversized material (> 3/4") was rejected. Fly ash was bulk blended with refuse at rates of 8% to 24%, in increments of 8%, to produce three refuse-fly ash blends.

Each of these specimens was tested at initial confining stresses (σ_3') of 10, 20 and 30 psi (69, 138 and 207 kPa). The deviator stresses, strain, axial and confining stresses, principal stress ratio, p, q and A were determined for each sample using the CU test. These parameters were used to plot the Mohr circles and the effective stress paths for these specimens and thus determine their c' and ϕ' values. During testing, these samples displayed dilatant properties, i.e. the tendency to expand. As a result, negative pore pressure values were generated. The deviator stress, effective stress and other shear strength parameters for the test specimens will be discussed in later sections.

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[4] Standard Test Method for Consolidated-Undrained Triaxial Compression Test on Cohesive Soils

4.42. Apparatus:

The apparatus used for the CU test was complex and it was constructed by keying together various components of shear devices, an existing pore pressure board, some old machinery, and a network of gauges, tubes, hoses, nuts and bolts. As a result, it took more than two months to construct and much of the operation of the machine was manual and unconventional. The results obtained by using this equipment, compared favorably with the literature. The apparatus used for the consolidated-undrained triaxial shear test consisted of the following components:

4.42.1 Axial Loading Device:

The axial loading device that was used was a load frame. The load frame consisted of a flat plate screwjack driven by an electric motor and operated through a geared transmission as shown in figure 7. This device had a mechanism of 24 gears by which the rate of axial strain could be controlled by adjusting the gears.

4.42.2 Load Ring:

The load ring consisted of a proving ring (PR) to which a dial gauge was attached (see figure 7). This dial gauge measured the PR deflection which was caused by axially loading the test specimen. However, the extent of PR deflection was indicated by a PR constant which was calculated as the slope of a factory calibrated load-deflection curve. This calibrated load-deflection curve was linear in the load range of 0 to 6000 lb (0 to 26.5kN) for which the specimen was tested. The PR constant for this linear portion was computed as 2.5 lb/div. (0.011 kN/div) This means that in an actual test run, a dial gauge reading of one division represented an axial load of 2.5 lb (0.011 kN) acting on the test specimen.

4.42.3. Triaxial Compression Chamber (TCC):

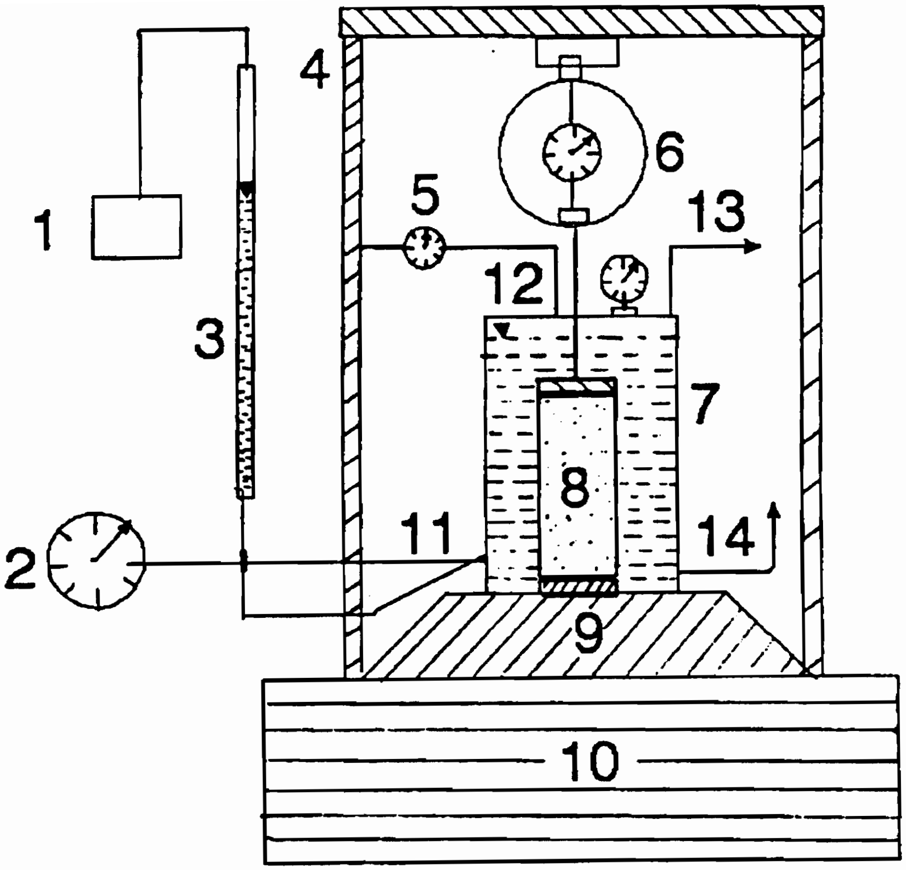
The triaxial compression chamber (TCC) was a vital component of the shear strength apparatus since it housed the specimen during the testing process. It consisted of a top plate and a base plate, separated by a cylinder of solid, transparent, and pressure resistant plexiglass (see fig. 7). The TCC had a rating of 14.4 kPa (300 lb/ft^2). The top plate of this chamber had an nozzle for the application of air pressure. The base plate of the TCC was fixed to the specimen base cap (see fig. 7). This plate was also connected to a hose through which pressurized water was supplied to fill or to empty the chamber.

4.42.4 Strain Gauge:

The strain dial gauge was attached to an arm of the load frame, and it measured the axial displacement of the sample, during the final shearing stage of the specimen. Each division on the dial gauge represented an axial displacement of 0.001 in. (0.025 mm) within the specimen from which the total strain ε was calculated.

4.42.5 Volume Change Measuring Device:

A calibrated burette was used to measure the volume change of a test specimen during



Legend

1 Back Pressure Gauge
2 Pore Pressure Gauge
3 Burette
4 Load Frame
5 Strain Gauge
6 Proving Ring/Dial Gauge
7 Triaxial Compression Chamber

8 Test Specimen
9 Load Plate
10 Machine Block
11 Pore Pressure Lines
12 Cell Gauge
13 Air Pressure
14 Water Pressure

Figure 7. Triaxial Compression Device

the consolidation stage of the CU test. During consolidation, the drainage valves were opened and water from the test sample was allowed to drain into the burette. The volume of water in the burette increased in proportion to the decrease in sample volume due to its consolidation. Therefore, the volume change in a test sample could be calculated.

4.42.7 Pore Water Measuring Device:

The pore water measuring device consisted of a back pressure source, a burette, two drainage tubes and a pore water gauge, which were coupled in series (see figure 7). The back pressure gauge was attached to a burette, which in turn was linked to two drainage tubes and a pore pressure gauge. The pore water measuring device was used mainly during the saturation and the shearing stages of the CU test and it had two functions. First, to inject water in the specimen pore space during the saturation stage and second, to monitor the sample pore pressures during the shearing stage. During the initial saturation stage of the specimen, the back pressure source extruded water from the burette to the specimen through the drainage tubes as shown in figure 7. During the axial loading (shearing) stage of the specimen, this apparatus was used solely for monitoring the pore pressures within the test sample, with all other valves of this device being closed.

4.42.8 Rubber Membrane:

A 0.025-in. thick latex membrane was used to encase the specimen within the triaxial compression chamber to prevent leakage. The rubber membrane was encased around the specimen and end caps using a membrane expander. The top and bottom of the specimen were attached to the end caps with O rings and vacuum grease.

4.42.9 Miscellaneous Devices:

A digital timer, weighing device, split compaction mold, specimen trimming device, O ring expander, series of wrenches to assemble and remove the specimen and water content cans were provided as required.

4.43. Procedure:

The procedure used for the CU test was carried out according to ASTM D 4767-88[5] (ASTM, 1992) consisted of four stages, which are as follows:

1. Specimen Preparation and Mounting Phase
2. Saturation stage
3. Consolidation stage
4. Axial loading (shearing) stage.

During the first stage, the material used was carefully screened for oversize particles and it was then compacted to form cylindrical specimens, which were then mounted inside a triaxial compression chamber for testing. In the second stage (i.e., saturation stage) of this experiment, the specimen was subjected to an external confining pressure (σ_3'). The

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[5] Standard Test Method for Consolidated-Undrained Triaxial Compression Test on Cohesive Soils

saturation phase was necessary to expel the air from the hoses and specimen voids and to drive the air into solution. After a specimen was completely saturated, the consolidation phase was carried out to reach equilibrium under drained conditions. Consolidation was carried out at a particular effective consolidation stress (σ_3') at which the strength of the specimen was required to be determined. The final stage was the shearing stage in which the specimen was axially loaded to failure under undrained conditions, using a geared load frame.

In the shearing stage, the axial load, pore pressure and strain were monitored at a constant confining stress (σ_3). Several parameters were then calculated based on these measured test variables. These parameters were used to obtain c' and ϕ'. The estimated time of failure (t_f) required for shearing a typical test specimen was computed from the t_{100} value obtained during consolidation. Based on this t_f value, a critical strain rate for the load frame was calculated. A proper strain rate is essential for the experiment because it allows the equalization of pore pressures within the specimen during shearing. The shearing test procedure is specified in ASTM D 4767-88 (ASTM, 1992).

4.44. Calculations:

Based on the data obtained in the CU test, various variables were calculated. These parameters were essential in determining the c' and ϕ' values and in studying the behavior of the test material. The following parameters were closely monitored during the CU test and they were later used for the calculations:

a. Time taken for consolidation

b. Load dial gauge reading

c. Strain dial gauge reading

d. Chamber confining pressure, σ_3

e. Pore pressure, u

From the CU test data, a series of formulae (from different sources) were used to compute a number of variables including the strain rate and the deviator stress. These calculations are presented in the following sections.

4.44.1 Strain Rate Calculations:

When the specimen was axially loaded, a failure strain of 20% was assumed. This failure strain was assumed to be the worst case scenario. However, in most cases, the specimen failure during shearing occurred even before the estimated time of failure was approached. In general, the maximum strain rate which occurred in any test during shearing was 0.1% per minute, with an average strain rate of 0.06% per minute. Thus, the 20% failure strain wasn't a governing criterion in the failure analysis. The following formulae were used to compute the strain rate $\dot{\varepsilon}$:

Therefore, $\dot{\varepsilon} = 0.20\ H / t_f$

where $t_f = 1.6\ H^2 / Cv$ ....(Head, 1982)

where $C_v = \prod D^2 / \lambda\ t_{100}$ ....(Head, 1982)

where: $\dot{\varepsilon}$ = strain rate

H = height of the specimen

D = diameter of the specimen

t_f = time of failure for a specimen during shearing

C_v = coefficient of consolidation

t_{100} = time required for primary consolidation

λ = coefficient for drainage condition; this has a value of 2.25 when drainage of the specimen at both ends are considered for this test, and when H/D<2.

4.44.2 Deviator Stress Calculations:

The deviator stress is the ratio of the deviator load P to the cross-sectional area A_{cc} (corrected for consolidation and strain). The following formulae were used to calculate the deviator stress:

a) Change in specimen length ΔH = (Strain gauge reading in div.) x 0.001 in./div.

b) Specimen height (H_c) and cross-sectional area of the specimen (A_c) due to consolidation:

$H_c = H_0 (1 - \Delta V / 3V_0)$ .... (Head, 1982)

$A_c = A_0 (1 - 2\Delta V / 3V_0)$ ....(Head, 1982)

where:

H_0 = original height of the specimen

A_0 = initial cross-sectional area of the specimen = $\prod D^2 / 4$

ΔV = change in volume during consolidation

V_0 = initial volume of sample before consolidation

c) The axial strain ε: $\varepsilon = \Delta H / H_c$

where: ΔH = change in specimen length

H_c = specimen height after consolidation

d) Corrected cross-sectional area A_{cc} due to strain ε

$$A_{cc} = A_c / 1 - \varepsilon$$

e) Applied load P: P = (Load gauge reading in div.) x (PR constant)

where: PR constant = 2.5 lb/ div. (0.011 kN/div.)

f) Deviator stress $\Delta \sigma_d$:

$$\Delta \sigma_d = P / A_{cc}$$

4.45 Determination of c' and ϕ'

A total of four specimens were tested using the triaxial compression test under consolidated and undrained conditions. These specimens included one 100% refuse sample and three refuse-fly ash blends. The fly ash used for the blends varied from 8% to 24% in equal increments of 8%. The c' and ϕ' values for these specimens were determined using the Mohr circle method which is discussed in detail in the subsequent sections.

4.45.1 Mohr Circle Method:

The main stresses which act on a particle are the principal major stress (σ_1), the principal intermediate stress (σ_2) and the principal minor stress (σ_3). In triaxial tests, $\sigma_2=\sigma_3$, so only a two dimensional state of stresses, consisting of σ_1 and σ_3, were considered. A typical Mohr circle was plotted by using the effective major principal stress (σ_1'), the effective minor principal stress (σ_3'). Therefore, in this study, three different Mohr circles were plotted for each test series. For practical considerations, however, only the top semi circles of the Mohr circles were considered. The tangent passing through these circles is known as the Mohr's envelope or failure envelope. The intercept made by this failure envelope is the cohesion c' and the slope of the envelope determines the angle of friction ϕ'. The Mohr circle plots for the four test series are presented in the appendix C. The c' and ϕ' values obtained by using this method are summarized in table 5. The Mohr circle data are discussed in depth in Chapter 5.

4.46 Conclusion:

The triaxial test was conducted on a set of four specimens which included a 100% coal refuse sample and three refuse-fly ash blends. The fly ash was blended with refuse at rates ranging from 8% to 24% in equal increments of 8%. Various shear strength parameters were measured and calculated for these specimens based on the CU test.

Table 5. Shear Strength Results

Sample	Type of Blend	Mohr Circle	
#		c'	ϕ'
1	100% CR	0	39.00
2	CR + 8%FA	0	37.70
3	CR + 16%FA	0	37.00
4	CR + 24%FA	0	37.00
5	CR + 32% FA	0	37.00
6	100%FA	0	37.00

Legend

CR	Coal Refuse
FA	Fly Ash

The results from the refuse-fly ash blends were contrasted with the results of the control refuse sample and thus, the behavior of these blends could be studied. Some of these results were plotted and these curves are illustrated in figures 8 to 11. The relevance and implications of these plots are discussed in detail in Chapter 5. The following test results were plotted:

4.46.1 Deviator stress (σ_D) vs. Strain (ε)

4.46.2 Effective stress (σ_3') vs. Strain (ε)

4.46.3 Principal Stress Ratio (σ_1'/σ_3') vs. Strain (ε)

4.46.4 p' vs. q

4.46.1 Deviator stress (σ_D) vs. Strain (ε)

The deviator stress-strain plots were plotted for four specimens. A peak deviator stress is often used as the failure criterion for triaxial tests. These stresses were used in the Mohr circle diagrams to determine c' and ϕ' for the test specimens. The stress-strain plots for these test specimens are shown in figures 8 to 11. These plots are extensively discussed in Chapter 5.

4.46.2 Effective stress (σ_3') vs. Strain (ε)

The effective stress (σ_3')-strain (ε) curves were plotted for a set of four specimens. Since ($u = \sigma_3 - \sigma_3'$), at a constant σ_3 value u had an inverse relationship with the σ_3'.

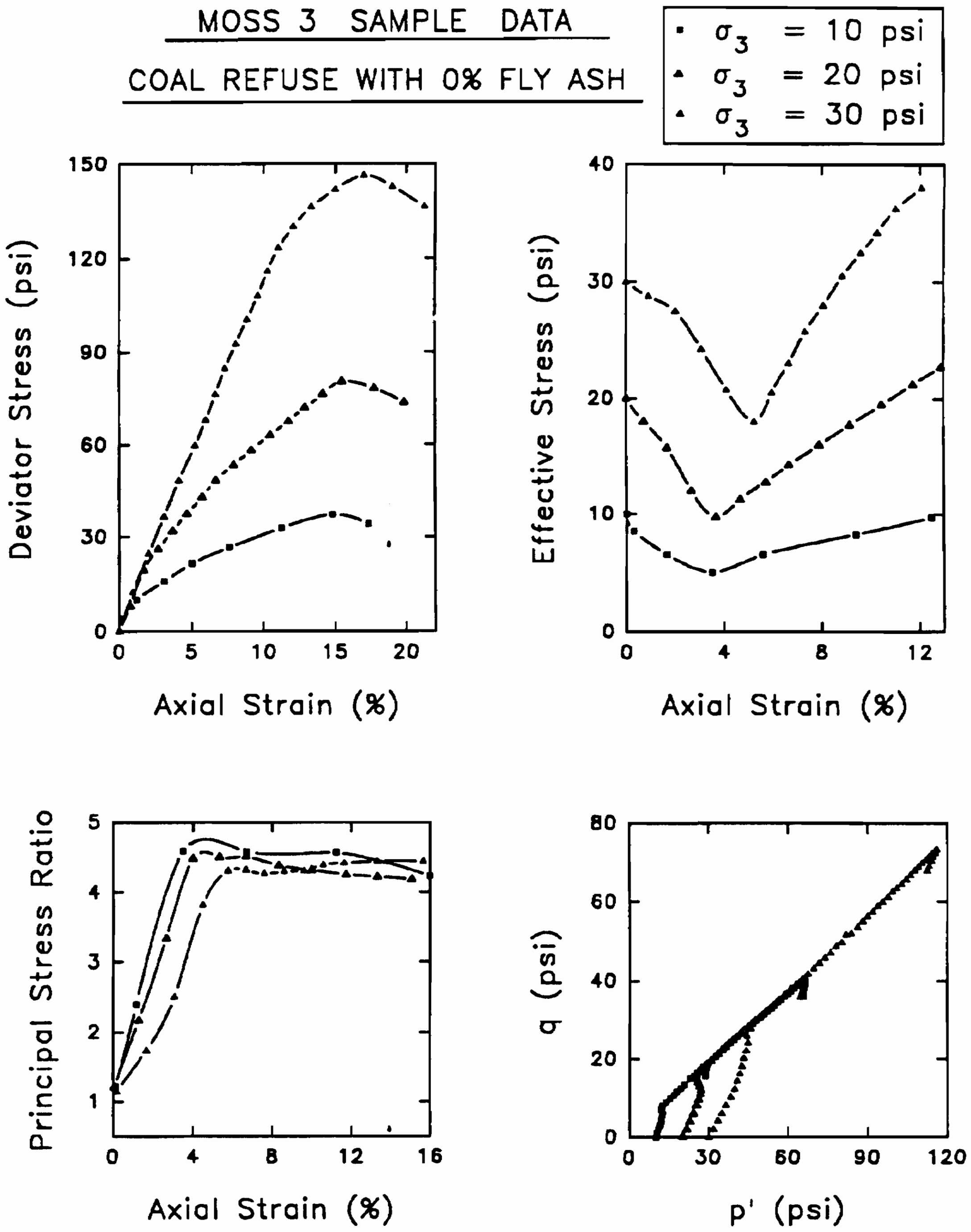


Figure 8. Moss 3 Sample Data

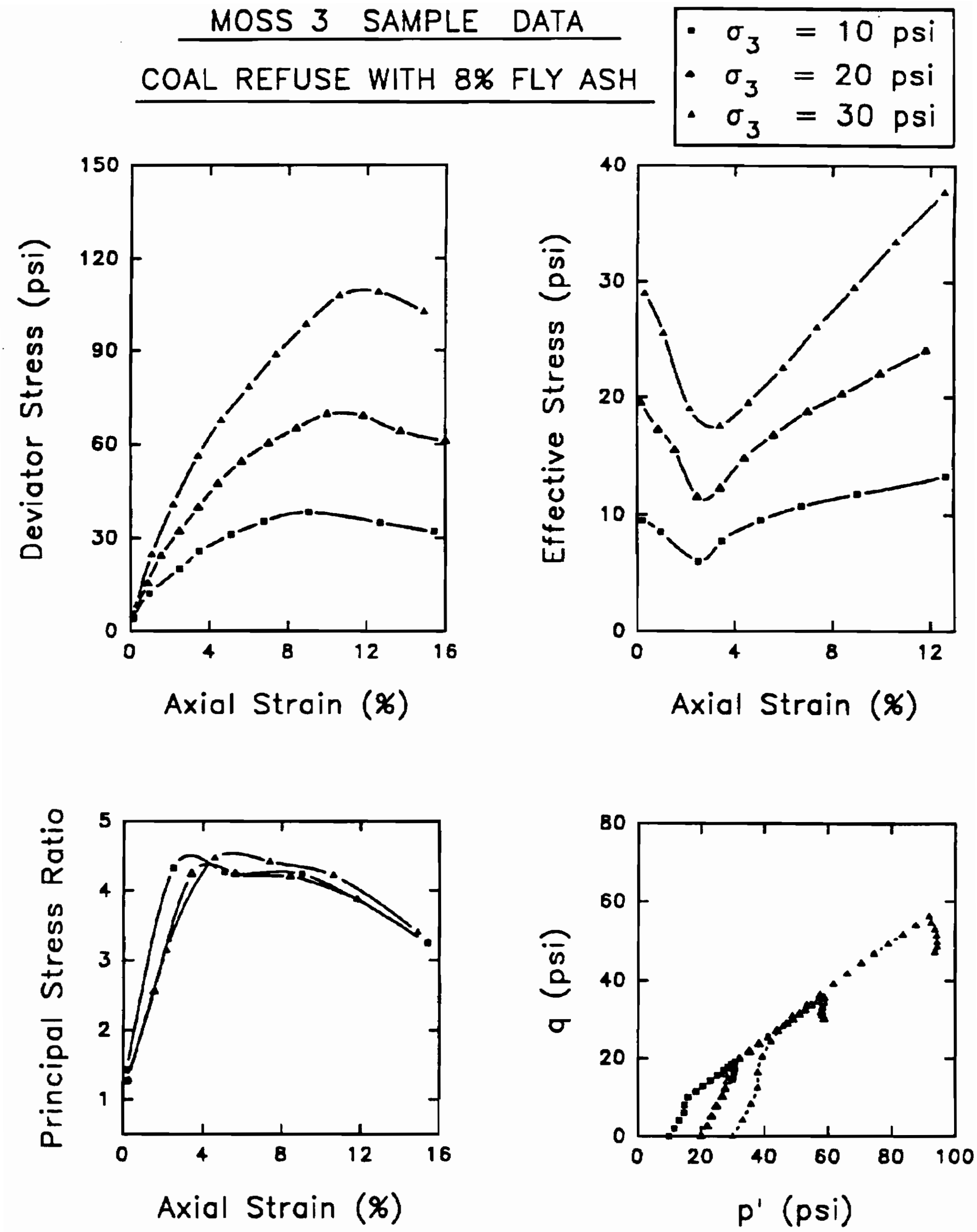


Figure 9. Moss 3 Sample Data

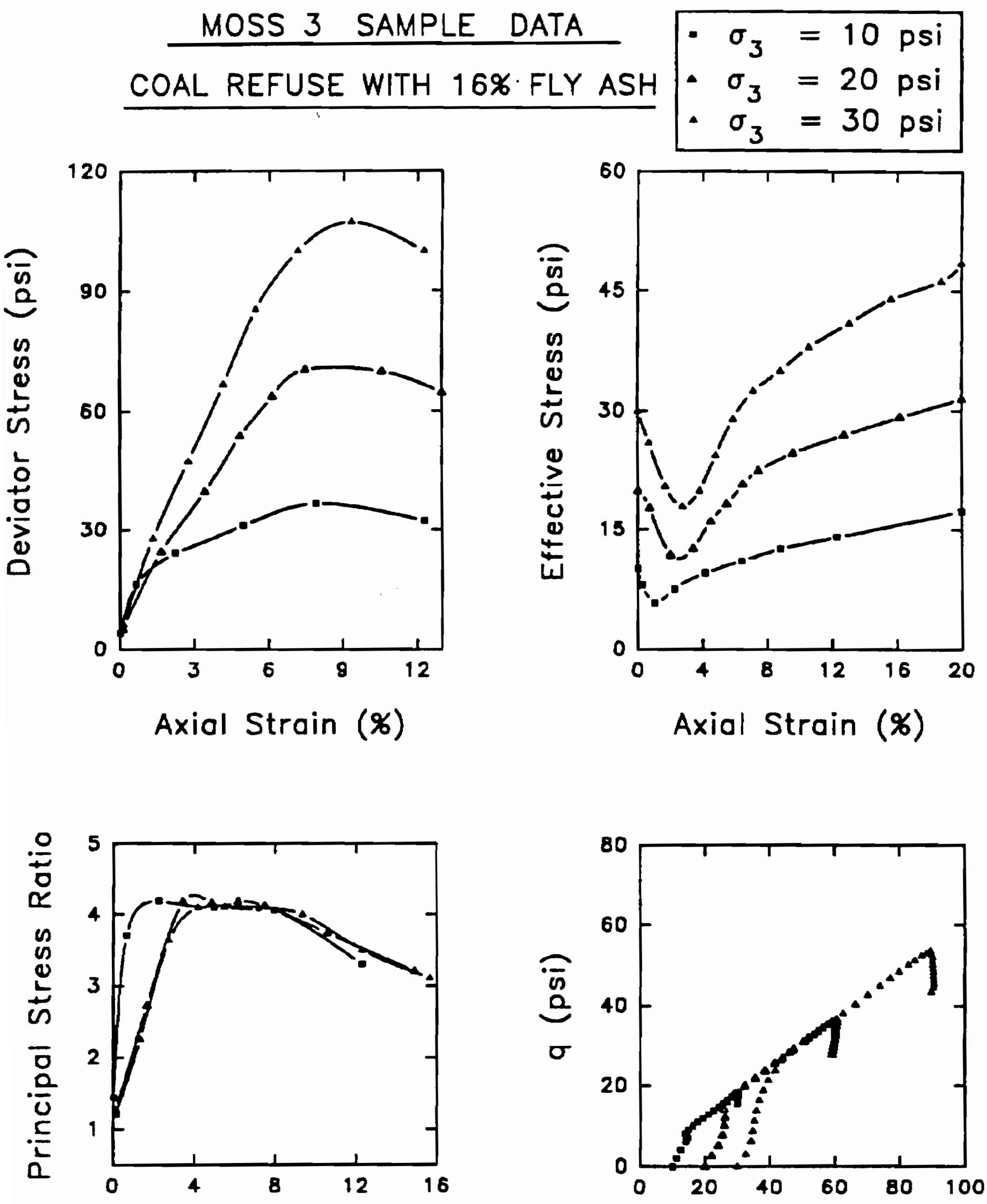


Figure 10. Moss 3 Sample Data

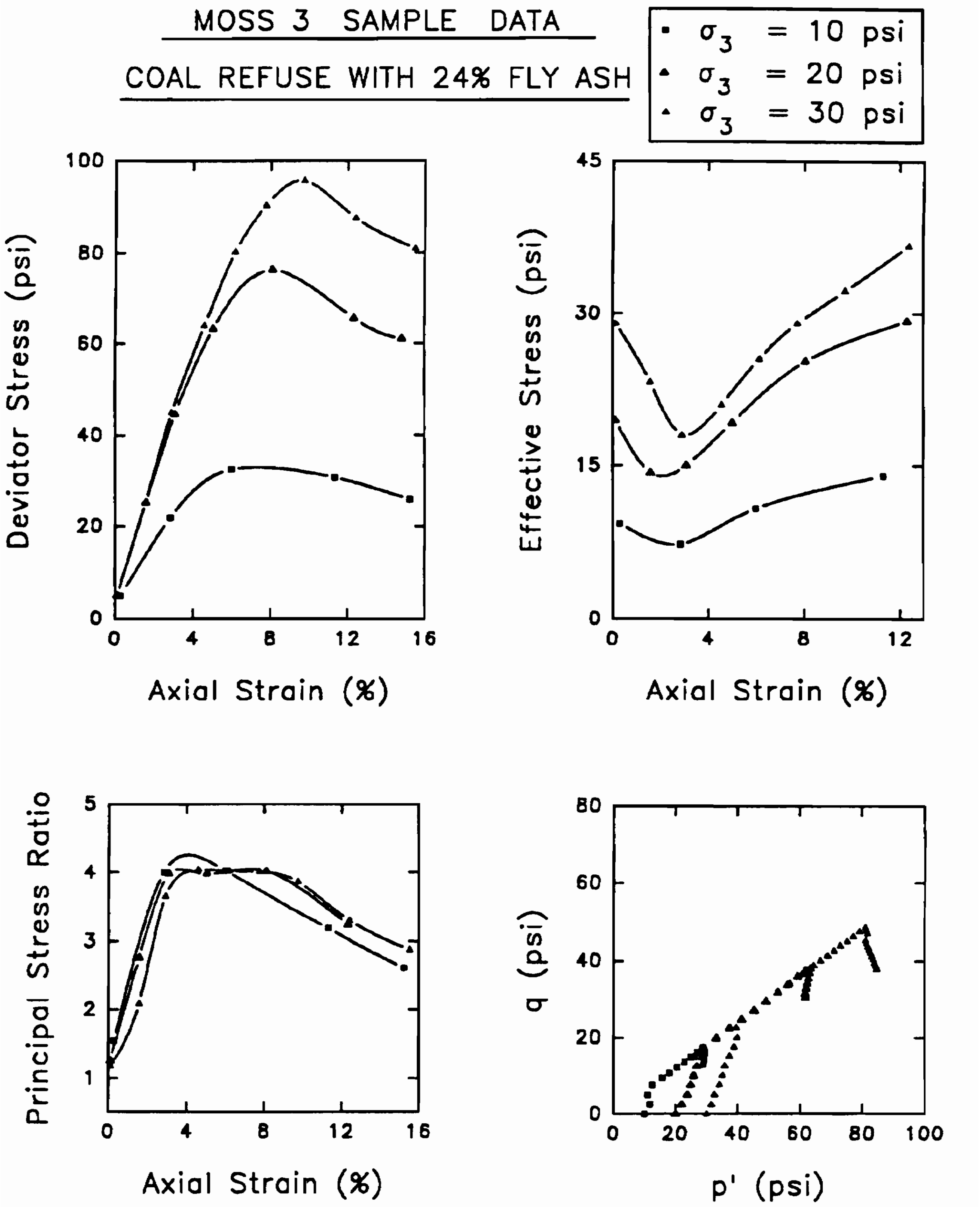


Figure 11. Moss 3 Sample Data

Therefore, when the effective stress values were at their minimum, the pore pressure values were at their maximum and vice versa. The effective stress-strain curves for these test specimens are displayed in figures 8 to 11. These plots are discussed in detail in Chapter 5.

4.46.3 Principal Stress Ratio (PSR) vs. Strain

The Principal Stress Ratio (σ_1'/σ_3') - Strain curves were plotted for four samples to determine the approximate value of ϕ'. The PSR-strain curves for the four test specimens are displayed in figures 8 to 11. These plots are discussed in depth in Chapter 5.

4.46.4 p' vs. q

Stress paths can be used to graphically represent the changes in stress that occur in a triaxial test for each of the four test samples. These paths are represented by p'-q plots. These plots are illustrated in figures 8 to 11.

Thus, three geotechnical tests (i.e., compaction, permeability and shear strength) were carried out on refuse-fly ash blends and on the control(s). The experimental procedures and results for these tests have been described in previous sections. The results for all these tests are summarized in table 6.

Table 6. Summary of Test Results

SAMPLE #	BLEND	COMPACTION γ_{Dmax}		PERMEABILITY Falling Head	SHEAR STRENGTH Mohr	
		kN/m^3	lb/ft^3	cm/s	c'	ϕ'
1	100% CR	19.50	125	2.86E-03	0	39.00
2	CR + 8% FA	19.38	123	1.01E-03	0	37.70
3	CR + 16%FA	18.70	120	2.56E-04	0	37.00
4	CR + 24%FA	18.50	119	1.71E-04	0	37.00
5	CR + 32%FA	18.20	117	7.88E-05	0	37.00
6	100%FA	13.31	85	5.78E-05	0	37.00

4.50. Slope Stability Analysis

An effective stress or long term slope stability analysis was carried out for the Moss 3 coal refuse pile using a computer program STABGM. This program uses the Ordinary Method of Slices (OMS) and Bishop's Modified Method (BMM) to calculate the factor of safety of embankments and slopes (Duncan et al., 1985). The factor of safety (F) in slope stability procedures is the ratio of the existing shear strength to the minimum shear stress, which is required to keep the slope of the pile in a state of barely stable equilibrium (Duncan et al., 1985).

Therefore, F = (Shear strength of the pile)/ (Shear stress required for equilibrium)

For both methods (BMM and OMS), the slope geometry of the pile is divided into many slices (See figure 12) and the moments (of each slice) are taken from the center of the circular arc. Using moment equilibrium equations, the shear stress and strength are then calculated in terms of the overall slope geometry and soil properties. In case of the OMS method, it is assumed that the resultant of the side forces on any slice acts parallel to the base of the slice. Therefore, as part of this assumption, the resultant does not influence the normal stress at the base of the slice. This is a conservative assumption which leads to lower factors of safety. Therefore, there may be an error of no more than 10% in most cases (Whitman and Bailey, 1967; Duncan and Wright, 1980). The major assumption made in the Bishop's Modified Method (BMM) is that the resultant of all the side forces in a slice act horizontally (as opposed to acting parallel to the base of the slice as in OMM method). Therefore, based on this assumption, this method provides a more consistent summation of vertical forces of all slices and thus satisfies vertical equilibrium conditions (which the OMS does not satisfy). Therefore, the Bishop method is usually preferred in slope stability investigations. However, for better understanding of slope stability, both these methods were used in this investigation. The slope geometry of an average pile is illustrated in figure 12.

For OMS, $$F = \frac{\Sigma(W\cos\alpha - ul)\tan\phi' + \Sigma\ c'l}{\Sigma W \text{ Sin } \alpha}$$ (Chirapuntu, 1975)

For BMM, $$F = \frac{\Sigma(c'b + (W-ub)\tan\phi' / m_\alpha}{\Sigma W \text{ Sin } \alpha}$$ (Bishop, 1955)

where m_α = $\cos\alpha\ (1+ \tan\phi' \tan\alpha / F)$

W = weight of the slice

c', ϕ' = Mohr-Coulomb strength parameters

α = angle of inclination at the base of the slice

u = pore pressure water at the base of the slice

l = length of arc at the base of slice

b = slice width $= l\cos\alpha$

STABGM program was used to determine the critical factor of safety needed for the slope stability of the Moss 3 refuse pile, by using both the Bishop and OMS methods. Before executing the STABGM program, a data file was created using a text editor. A number of parameters pertaining to the Moss 3 pile were specified in this data file. These parameters included the dimensions of the pile, number of layers, limiting tangents, soil boundaries and

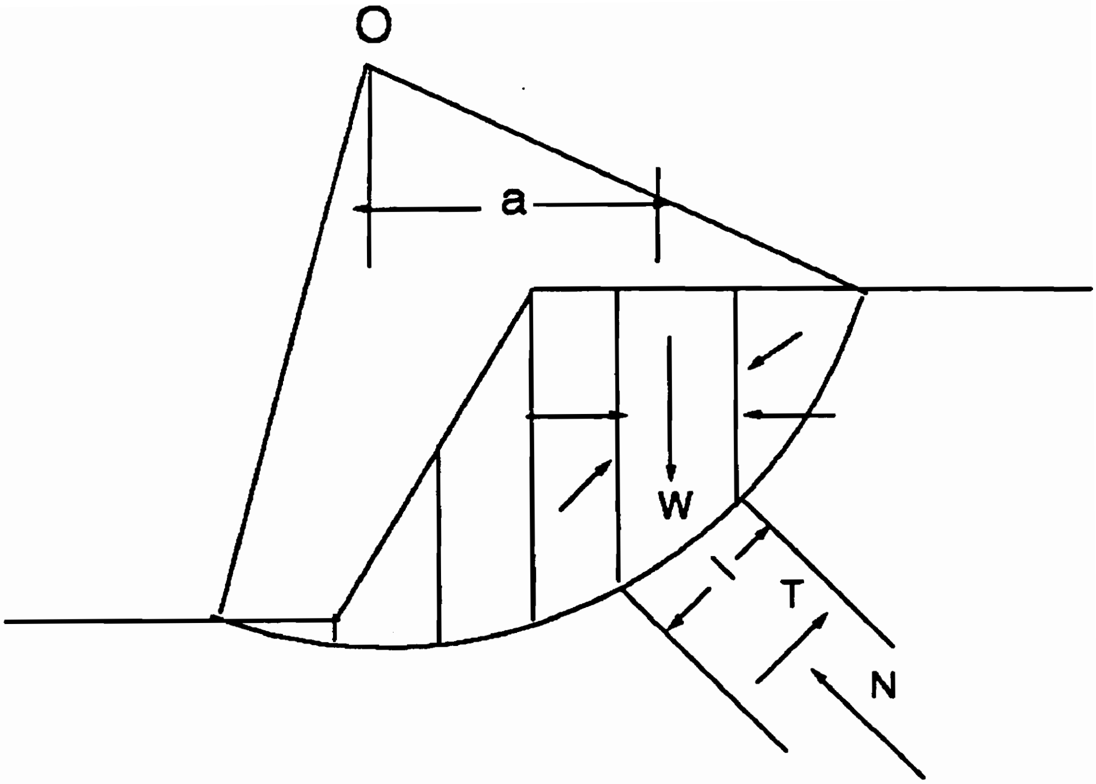
Mohr circle data. In order to simplify the slope stability model, the seismic coefficients and pore pressure parameters were assumed to be zero. The critical F value obtained for the Moss 3 pile was 1.43. The Moss 3 slope data and the iterations for slope stability (using the STABGM program) are displayed in the appendix D. The slope stability results are discussed at length in Chapter 5.

4.60 Volume Change Calculations:

The refuse from Moss 3 pile was analyzed for volume changes when it was blended with varying rates of fly ash. The fly ash was blended with refuse, in rates of 8% to 32%, in increments of 8%. Thus, the analysis was carried out for a total of five specimens, including a control 100% refuse sample and four refuse-fly ash blends. This analysis was carried out to see whether the volume of the refuse pile would be affected with the addition of fly ash and if yes, to what extent the volume of this pile would be affected. Accordingly, the volume-moisture content curves were plotted for these five specimens, in order to contrast the differential increase or decrease of refuse volume with moisture content. Modified Proctor compaction tests were carried out for the test specimens as per the ASTM procedure outlined in section 4.20 (page 37). The dry density-moisture content curves obtained from this test are shown from figures A1 to A6 in appendix A. Based on these compaction test results, the volume change curves were plotted in the following manner:

1. The dry density of a material was calculated as the ratio of its mass to its volume.

Therefore, $\gamma_D = M / V$



where:
W = Weight of slice
N = Normal force at the base of slice
T = Shear strength at the base of slice
l = Length of arc at the base of slice
a = Distance between the center of slice to center of slip circle

Figure 12. Slope Geometry of an Average Pile

where γ_D = Dry density of material, kN/m^3

M = Mass of the material, kg

V = Volume of the material, m^3

2. For a constant refuse mass of 1 kg (i.e., $M = 1$ kg), the volume is inversely related to the dry density of the test sample (from step 1).

Therefore, $\gamma_D = 1/V$

Rearranging the terms in the dry density equation:

$$V = 1/\gamma_D \quad \ldots \text{(volume equation)}$$

3. Now, each dry density value had a corresponding moisture content as shown in the compaction curves in figure 4 (page 40). Thus, when these dry density values were substituted in the volume equation (from step 2), the volume-moisture content curves were obtained.

The minimum volume attained by each test specimen was compared to the control (100% refuse specimen) to determine the extent of volume change in refuse due to fly ash addition. The plots of the sample volume vs. the moisture content are displayed in figure 13. The impacts of these volume changes are discussed at length in Chapter 5.

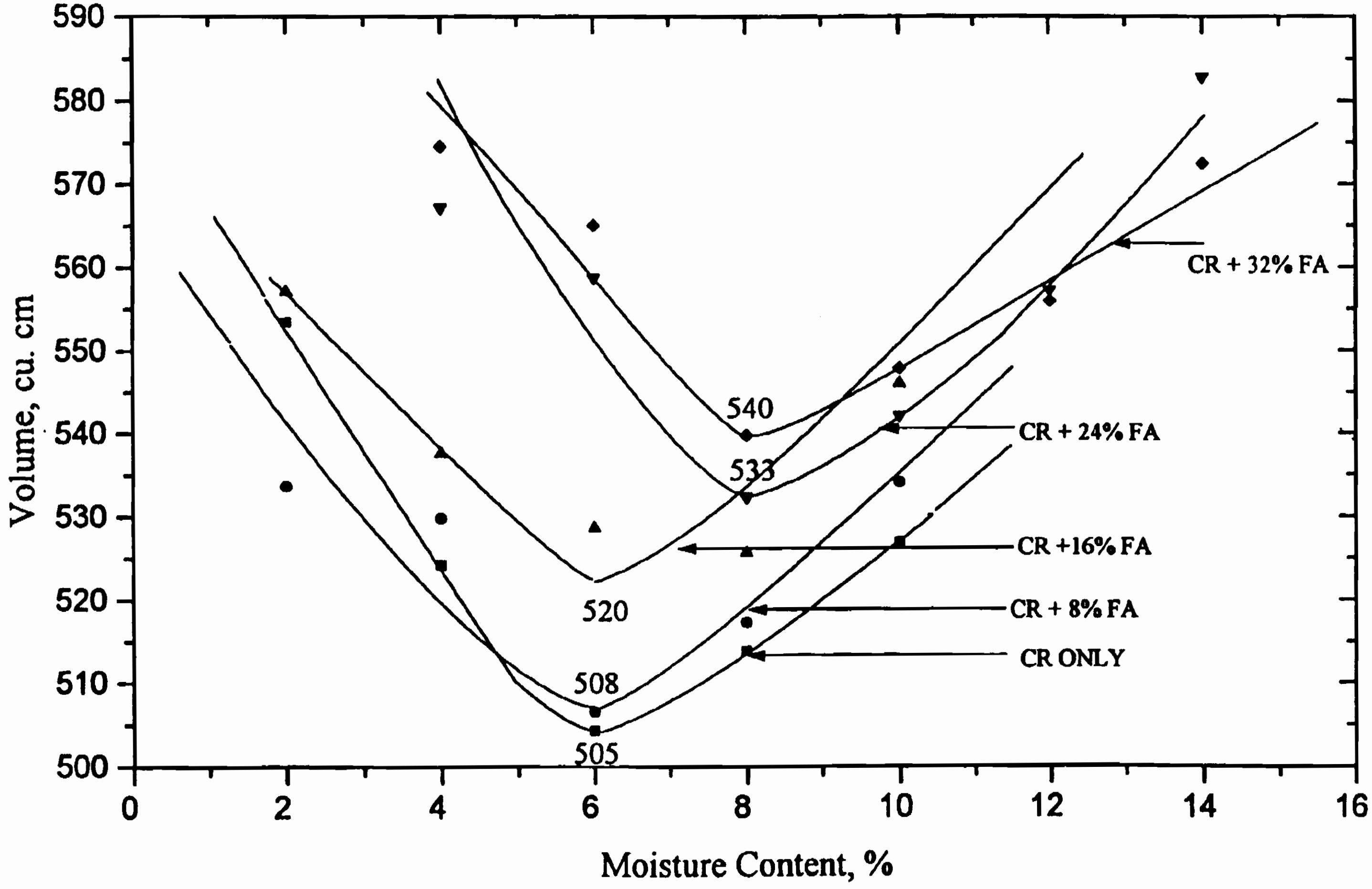

Volume Change in Refuse-Fly Ash Mixes per Kg of Refuse

Figure 13. Volume Change Curves

CHAPTER 5. DISCUSSION OF RESULTS

Coal Refuse and fly ash were analyzed for grain size, compaction, permeability and shear strength in order to determine their suitability as refuse-fly ash blends. Based on these tests, the slope stability potential and the volume change characteristics of these blends were determined. The test data and analyses of these investigations are reported in Chapter 4. This chapter discusses the relevance and application of the test data from an engineering and utilization viewpoint.

5.10. Particle Size Analysis (PSA):

5.11. PSA of Refuse:

According to the sieve analysis of the coal refuse, the sample is a well graded gravel with sand. As per the gradation curve of this material, it was observed that the refuse is predominantly coarse in nature, having only 1.5% fines (passing through No 200 sieve) with a uniformity coefficient of 23. In general, the test sample consisted of mainly coarse refuse and it had a similar grain size to refuse investigated by other researchers. For instance, a grain-size analysis of coal refuse from eight sites in West Virginia by Busch et al. (1974) revealed that the refuse specimens contained a large amount of coarse refuse. The uniformity coefficients of those samples varied from 14 to 250. Moulton et al. (1974), Davidson (1974), Delp (1975) and Buttermore et al. (1978) have reported similar results. Thus, the grain size distribution of the Moss 3 refuse specimen appears to be representative of the coarse refuse found in the Appalachian coal fields. It was also observed that the particle size of the Moss 3 refuse increased with the depth of the pile. Such a trend was also noticed by Moulton et al. (1974), Delp (1975), Buttermore et al. (1978) and other researchers in a study of several refuse piles in Virginia and West Virginia. This phenomenon is probably due to physical weathering processes which take place on a refuse pile surface over a period of time.

The uniformity and the curvature coefficients define the relationship between the coarser (D_{60}) and finer (D_{10}) refuse sizes on a gradation curve. Thus, the uniformity coefficient (C_u) indicates the relative proportions between the D_{60} and D_{10} sizes. However, the shape of the distribution curve between these two sizes is defined by the curvature coefficient (C_c). Coal refuse had a C_u value of 23 and a C_c value of 1.7, both of which were determined from figure 2 (page 33). Since the C_c value of refuse was between 1 to 3, the sample was determined to be well graded. The compacted coarse refuse particles displayed a higher degree of permeability than finer refuse particles. This is due to the void spaces which exist between the coarser refuse grains, which permit the easy flow of water.

5.11. PSA of Fly Ash:

The purpose of this study was to determine if fly ash could be blended with coal refuse and whether the refuse-fly ash blends would be suitable as co-disposed materials. Thus, the particle size distribution of fly ash is relevant in determining to what extent the physical properties of a pure refuse pile would be affected if fly ash was blended with it. The grain size analysis of Clinch River fly ash revealed that the range in grain size varied from

0.001mm to 1mm (see figure 3 on page 36). As stated in Chapter 4, this fly ash was classified as a silty loam as per the USDA soil textural classification chart (based on the sand, silt and clay sized fractions). Thus, a comparison between the gradation curves of refuse and fly ash (see figures 2 and 3) indicates that fly ash and refuse can be suitably bulk blended together because of their complimentary particle size ranges.

5.20. Discussion of Test Results:

This section discusses the results obtained from the compaction, permeability and shear strength tests.

5.21. Proctor Compaction Test:

The Proctor compaction test had great significance in this study since it acted as a foundation upon which the other tests could be conducted. This test was carried out on refuse, fly ash and four refuse-fly ash blends, and was conducted to determine maximum dry density (γ_{Dmax}) and the optimum moisture content (w_o) parameters for various test specimens. It was observed that 100% refuse had a maximum dry density of 19.5 kN/m^3 (125 lb/ft^3) with an optimum moisture content of 6.6%. Moulton et al. (1974) obtained similar results on some northern West Virginia refuse piles. They observed that the maximum dry density of those piles varied from 14.3 to 19.4 kN/m^3 (91 lb/ft^3 to 124 lb/ft^3) with optimum moisture contents of 5.6% to 15.4%. However, in this study, the decrease in the maximum dry density of coal refuse was marginal even when 32% fly ash was blended to it. Thus, the maximum dry density of 100% coal refuse only slightly decreased (by 1.3 kN/m^3) with the addition of 32% fly ash. However, mainly because of its lower particle density (due to its cenospheres), the maximum dry density of 100% fly ash was considerably lower than that of refuse (by 6.3 kN/m^3). In general, the optimum moisture content for the four refuse-fly ash test blends varied from 6.3% to 8.3%. However, the optimum moisture content for 100% fly ash was found to be 20%. Such a high moisture content level, can partly be explained by the presence of partially hydrated lime (CaO) in fly ash (Smith, 1993).

The maximum dry density and the corresponding optimum moisture content values obtained from this test had several applications. These parameters were used to calculate the moisture content and compactive energy required to achieve 95% compaction for specimens which were tested for permeability and shear strength. In addition, the maximum dry density of refuse and fly ash were also used in the STABGM program, to determine the critical factor of safety required for the stability of a refuse pile blended with fly ash. The Proctor compaction curves, in general, were used to compute the volume change of coal refuse blended with various rates of fly ash at maximum dry density conditions.

The Moss 3 pile is compacted by mechanical rollers immediately after the refuse is disposed of from a conveyor belt to the pile. The main benefit of compacting this pile is to achieve a reduction of subsidence in the pile mass due to a smaller void ratio. Moreover, pile compaction in general, increases its strength, thereby improving its stability. The compaction of a refuse pile could also decrease its permeability which may result in less seepage within the pile and reduced oxygen migration. This reduced seepage potential may result in a lower leachate volume being generated from the pile.

5.22. Permeability Experiment

The falling head permeability test was conducted on coal refuse, fly ash and four refuse-fly ash blends. D'Appolonia (1975) reported that the typical k values for laboratory compacted coal refuse range from 10^{-2} to 10^{-6} cm/s. The reported values of permeability of fly ash under similar conditions varied from 7×10^{-5} cm/s to 1×10^{-4} cm/s (Peffer, 1983; Drake, 1991). For this investigation, the permeability (k) of 100% coal refuse was 2.86×10^{-3} cm/s and that of 100% fly ash was 5.78×10^{-5} cm/s. Thus, it was observed that the permeabilities of refuse and fly ash, by the falling head method, were in agreement with the literature. It was observed that, of all the samples tested, the permeability of 100% refuse was the maximum while the permeability of 100% fly ash was the minimum. In general, it was observed that compaction of refuse-fly ash blends results in fly ash being embedded into refuse void spaces. It was also observed that the presence of fly ash in the refuse voids decreases the permeability of refuse-fly ash blends as a whole. Thus, as the percentage of fly ash in these specimens increased, the permeability of the test blends decreased. It is possible that if the Moss 3 pile were blended with fly ash, even at nominal percentages, the permeability of this pile could decrease with a possible reduction in leachate volume. However, with reduced permeability, the same amount of leached salts may be concentrated into a smaller volume of water, thus enhancing the possibility that the leachate could be potentially toxic to plants and animals. This reduced permeability also has slope stability implications. Reduced pile permeability may lead to undrained conditions which could be critical. Therefore, further studies may be required to analyze the Moss 3 pile for undrained conditions of slope stability.

5.23. Shear Strength Investigation:

5.23.1 Shear Strength Results:

Results from the consolidated-undrained triaxial compression test (CU test) show that the test samples were cohesionless ($c' = 0$) with ϕ' values of 39° and 37° for refuse and fly ash respectively. However, due to the slightly pozzolanic nature of damp fly ash present in some test samples, a small c' intercept (< 5 psi) was sometimes observed on the Mohr circles of these specimens. For practical purposes, however, c' was assumed to be zero. Thus, the behavior of these test specimens resembled sands since sands also are cohesionless with high ϕ' values. It was observed that in general, the c' and ϕ' values for refuse and fly ash were in complete agreement with the literature. Thus, in most cases, compacted coal refuse was found to have a peak ϕ' ranging from 25° to 41° (Bishop and Simon, 1976). Most fly ashes are found in the ϕ' range of 35° to 45° (Joshi et al., 1976; Lamb, 1973).

5.23.2 Significance of Test Curves

The relevance of the deviator stress vs. strain, effective stress vs. strain, and principal stress ratio (PSR) vs. strain are discussed in the following sections. The Mohr circle method is also discussed later in this section.

It was observed that among all test specimens, the 100% refuse sample had the maximum peak deviator stress value. It was also observed that the peak deviator stress of the test samples decreased with the proportional increase in fly ash. Thus, among all test samples, the refuse-fly ash blend with 24% fly ash had the lowest shear strength because of its lowest peak deviator stress value. Therefore, this test sample also possessed a minimum ϕ' of 37°. It may be noted that the failure strain was computed from these curves as the value corresponding to the peak deviator stress. It was noticed that the highest failure strain was for 100% coal refuse (15% to 18%) and the lowest failure strain was for refuse blended with 24% fly ash (7%-9%). Thus, the failure strain was found to decline considerably with the increase in fly ash in refuse-fly ash blends. However, even the lowest possible failure strains (7%-9%) obtained from these plots were quite high compared to the failure strains that are typically encountered in an actual refuse pile.

The effective confining stress-strain plots were another tool used in analyzing the results of the CU test. These stress-strain curves were useful in determining the failure strain and pore pressures of test samples.

The principal stress ratio (PSR) is the ratio of the effective axial stress (σ_1') to the effective confining stress (σ_3). Plots of PSR vs strain gave an indication of the ϕ' value of the test specimens. The ϕ' value is computed from the maximum PSR. The results obtained from these plots for a given set of three replicates, showed a marginal decline ($< 1^0$) in ϕ', with increasing σ_3' values. However, this variation safely falls in the confines of experimental error. It was also observed that the PSR value declined with the addition of fly ash with refuse. Therefore, the lower the PSR of a specimen, the lower is its ϕ' value. For instance, the average maximum PSR ranged from 4.5 (for 100% refuse) to 4.1 (for refuse blended with 24% fly ash) yielding ϕ' values of 39° and 37° respectively.

5.30. Application to Industry:

5.31. Introduction:

Coal refuse, fly ash and some refuse-fly ash blends were tested for compaction, permeability and shear strength. The primary purpose of this testing was to determine how the geotechnical properties of a refuse pile would be affected if the refuse (from this pile) was bulk blended with varying rates of fly ash. The Moss 3 refuse pile was considered in this study as a typical pile. Therefore, all industrial applications were modeled on the basis of this pile. These applications include the determination of the optimum percentage of fly ash needed. The slope stability analysis and volume change investigations were also carried out. All these applications are described in subsequent sections.

5.32. Optimum % of Fly Ash

This section examines the optimum fly ash percentage assuming fly ash would be uniformly bulk blended with refuse. The layering of fly ash in a pile or the placement of "cells" within a gob pile are not considered in this section because of inadequate test data. The best percentage of fly ash blend needed to ensure optimum results may depend on the type of test conducted. The 8% fly ash blend is the most suitable blend to achieve optimum results for the compaction and shear strength experiments. However, for the permeability experiment the best blend would be the one containing 32% fly ash. Therefore, a compromise needs to be reached based on the priority of the objectives desired. It was observed that the maximum possible decline in the compaction (1.3 kN/m^3) and shear strength values (2°) was comparatively marginal. Whereas the decrease in the permeability was considerable (two orders of magnitude) for blends containing 32% fly ash. Therefore, the 32% fly ash blend could be suitable in the long run assuming this much ash was available for a given pile. This blend would also use the maximum amount of fly ash, which could contribute to substantial ash utilization in the long term. This beneficial reuse of fly ash would be particularly valuable in Virginia, where it could be used in coal refuse piles to possibly minimize acid mine drainage and potentially revegetate waste refuse piles. Such utilization would prevent the ash from being classified as a solid waste under state guidelines and could pave the way for future waste minimization efforts.

5.33. Slope Stability Analysis

The slope stability analysis of the Moss 3 pile was computed based on the results obtained from the three tests. The stability analysis of the pile is required to maximize the fill potential of the pile without endangering its safety aspects. The computer program STABGM was used for the analysis of the slope stability of the pile. As a common rule, the minimum factor of safety increases with an increase in the dry density of material input into the model. The worst possible conditions (such as height and slope of pile) were assumed in order to overcome any drawbacks this model may have in simulating field conditions. The critical factor of safety (F) obtained for the Moss 3 refuse pile, from the STABGM slope stability program was found to be 1.43. This F value was the minimum value obtained, from a number of slip circles which were generated by the STABGM program. As stated in Chapter 4, the F value was obtained on the basis of layering 32% fly ash in a 3 m (10 ft) lift. No data were available to compare this F value with F values from other refuse piles. However, this value appears reasonable from a geotechnical embankment design standpoint. It should be noted that this analysis was for long-term drained conditions. This may not be the most critical condition in the service life of the disposal pile.

5.34. Volume Change Investigation

The volume changes in refuse (when blended with fly ash) were computed based on the Proctor compaction test. It was found that, at a fixed mass and at maximum unit weight conditions, the volume of refuse increased with the addition of fly ash. However, even the maximum observed expansion of refuse was quite low. For instance, at maximum Proctor conditions, there was a maximum expansion of 0.035 m^3 per Mg of refuse for blends containing 32% fly ash. If this blend had been compacted with a lower compactive energy or if less fly ash was added to it, then the volume change of refuse would have been even lower. Such a low volume change takes places because the fly ash occupies the void spaces in refuse. The presence of fly ash in void spaces ensures tight packing with minimum expansion, particularly at maximum dry density conditions. Thus, if fly ash is blended into the

Moss 3 coal refuse pile, the volume expansion effects would be minimal and it would not affect the overall properties of the pile .

5.35 Other Scenarios

So far, in all the tests that were conducted, the fly ash was thoroughly mixed with refuse to obtain bulk blends of refuse and fly ash. All previous sections in this chapter deal mainly with this scenario. However, two other scenarios of blending fly ash with refuse need to be examined from the permeability and stability point of view. These scenarios are as follows:

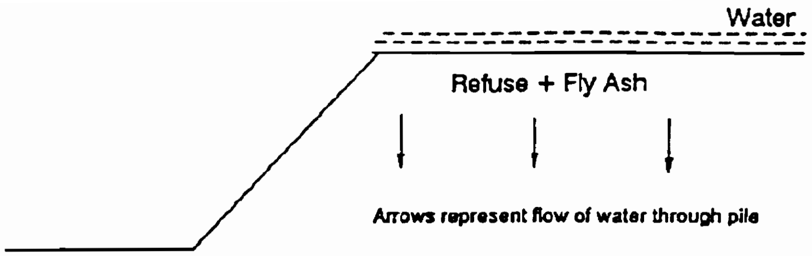
1. Fly ash is layered into a coal waste pile in alternating layers of refuse and fly ash.
2. Fly ash bulk compacted in "cells" within a refuse pile.

In the first scenario, fly ash is alternately layered with refuse in 20 cm lifts (see figure 14). When water flows through this layered pile, there could be comparatively rapid drainage through the refuse layers, and the ponding of water on the fly ash layers. This perching of water on fly ash could result in most of the water flowing laterally with some of it percolating vertically through the ash layer. The water flowing horizontally could flow out along the pile outslope and later seep again into the pile, even if the pile is terraced on the outslope (as most piles are). In some cases, the resulting permeability of water in the pile may be limited by the permeability of the fly ash (10^{-5} cm/s) present in the pile. In cases of high volume, high flows (such as 10 year storm water flows) the flow (and permeability) could be unpredictable and it may even result in erosion and scouring of the pile face and internally, depending on the intensity and volume of such a flow. Also, for such a situation, even if the pile is terraced, water may still accumulate at the toe of the pile creating slope stability problems. Therefore, to avoid an unstable pile and to reduce erosion and scouring, a suitable leachate collection system could be installed above the pile toe. Alternately, a 10 m blanket of compacted refuse could also be surface applied to the pile to prevent instability. However, further studies are required for long term erosion control measures.

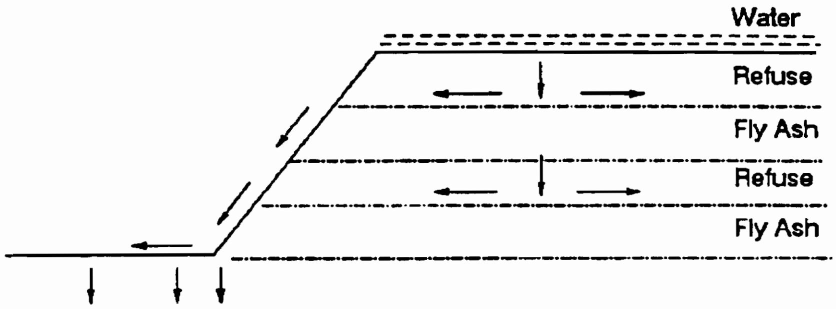
The other potential scenario is one of incorporating refuse within a pile would be to place large "cells" (>3m in depth) of fly ash within a refuse pile mass (see figure 14). These "cells" would be placed at least 1.0 m above the groundwater table. The areal extent of such an ash block could be placed away from the pile faces to prevent lateral drainage reaching the pile outslopes. In such a scenario, there may be two kinds of flows occuring within a gob pile. Portions of the pile uninhibited by fly ash could have a flow rate governed by the permeability of refuse (around 10^{-3} cm/s). Where fly ash is present, perching of water on the fly ash layer may result. Most of the perched water may then flow laterally into the surrounding refuse material and drain vertically, as shown in figure 14. In such a case, the flow pattern would be changed and a small area of refuse may handle the flow of the entire pile. The limited amount of ponded water which flows through the fly ash would be limited by the permeability of fly ash (around 10^{-5} cm/s) along the depth of the fly ash cell. The benefit of using this option is the easy and economical placement of fly ash cells within a gob pile. Such an option may ensure slope stability, as there may not be any seepage along the outslope of the pile. However, the permeability of the pile may be relatively unaffected (10^{-3}

cm/s), except for localized spots of low permeability (10^{-5} cm/s). Thus, for this option to be an effective one, a number of cells may have to be installed at regular intervals within a single pile mass.

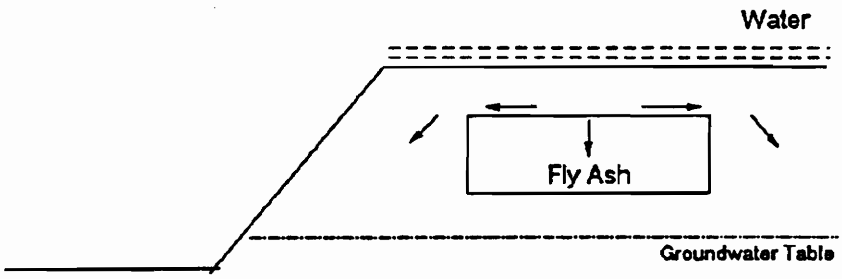
In summary, the ideal case of bulk-blending ash with refuse could result in low permeabilty (around 10^{-5} cm/s). However, this option may be uneconomical, unpractical and time consuming for many refuse pile operations particularly where the remediation of acid mine drainage via fly ash blending is not a management objective. Blending 20 cm lifts of fly ash in alternate layers with refuse may result in lower permeability for low to medium flows. In case of high flows, there could be variable permeability and possible zones of instability. The cheapest option would be the insertion of fly ash "cells" into gob piles. The slope stability of a pile may be largely unaffected by this option. However, the success of this option would depend on the number of fly ash "cells" and their mode of placement within a single pile mass. Therefore, depending on the site-specific conditions and desired parameters, one or more of these scenarios may be used to blend fly ash within a refuse pile.



Option 1: Refuse Bulk Blended With Fly Ash



Option 2: Layering of Fly Ash in a Refuse Pile with Alternate Layers of Refuse



Option 3: Fly Ash Compacted in "Cells" Within a Refuse Pile

Figure 14. Schematic of Various Scenarios of Blending Fly Ash in a Refuse Pile

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.10. Conclusions

The primary purpose of this study was to determine how fly ash additions to coal refuse would impact the geotechnical properties of refuse. This investigation was conducted with the Moss 3 refuse pile ("typical fill") as a model. Refuse, fly ash and refuse-fly ash blends were tested for compaction, permeability and shear strength. In addition, a grain size analysis was carried out for refuse and fly ash. The test results obtained were used to analyze the Moss 3 pile for slope stability. Also, the volume expansion characteristics of refuse were examined when refuse was blended with varying rates of fly ash. From the results of these investigations, the following conclusions are drawn:

1. The particle size analysis of refuse indicates that refuse is very coarse with few fines. Conversely, fly ash is a fine grained material. Thus, refuse and fly ash can be effectively physically bulk blended because of their differing gradation characteristics.

2. The blending of fly ash to refuse does not significantly alter the maximum dry density characteristics of refuse. Thus, even if 32% fly ash is bulk blended with a refuse pile, the estimated drop in the maximum dry density of refuse would only be 1.3 kN/m^3 (8 lb/ft^3). Thus, the addition of fly ash may not significantly affect the compactability of a typical pile.

3. The permeability of a refuse pile is considerably decreased with the addition of high amounts of fly ash. Therefore, if 32% fly ash were to be bulk blended in a typical fill, it is estimated that the permeability of the fill could decrease from about 10^{-3} cm/s to 10^{-5} cm/s.

Such a decrease in permeability could considerably lower acid mine drainage volumes.

4. The shear strength of refuse, which depends on c' and ϕ', remains nearly the same even if large amounts of fly ash are bulk blended.

a) Both coal refuse and fly ash are cohesionless materials. Therefore, the addition of fly ash to a typical refuse pile would have no impact on its cohesion (c' = 0).

b) The ϕ' value of refuse is marginally affected with the addition of fly ash. Thus, addition of 32% fly ash to refuse would lower the ϕ' by a maximum of 2°. Therefore, there is no practicable change in the shear strength of a typical refuse pile blended with fly ash.

5. The optimum permeability was achieved for test blends containing 32% fly ash. Such a blend yielded a marginal decline in compaction and shear strength of refuse but improved its permeability characteristics considerably. If a 32% blend were to be used on a typical pile, the leachate volume from that pile could decrease considerably with a possible reduction in acidity of the leachate, thus minimizing aquatic and groundwater impacts. Moreover, large amounts of fly ash could be beneficially reused at little cost, thus helping the environment.

6. Addition of 32% fly ash may impact on the slope stability of Moss 3 pile in the short term because of the possible reduction in the pile shear strength due to undrained conditions within the pile. However, for long term drained conditions, slope stability of the pile may not be significantly affected, with the addition of even 32% fly ash.

7. There is a negligible expansion (0.035 m^3/Mg) in the refuse volume with the addition of fly ash to refuse. This is because most of the fly ash is embedded in the large refuse void spaces after compaction, thus limiting the total expansion of blended refuse. Therefore,

volume change for a typical refuse pile would be marginal if it were bulk blended with fly ash.

In summary, it is felt that fly ash has a beneficial reuse potential from a physical standpoint and it could be used in a co-disposal scenario in refuse piles with little adverse impacts. It's use on refuse piles could minimize disposal space and costs for the individual materials, reduce overall disposal costs, reduce pile leachate volume, and possibly reduce acid mine drainage concentrations. Moreover, its reuse would help in the conservation of the environment and in the reduction of adverse water quality impacts.

6.20. Recommendations:

Based on this study the following recommendations are proposed:

1. The scope of this study should be enlarged to include refuse piles from West Virginia and Pennsylvania. This study should also be expanded to include Class C and Class F fly ashes from various locations in Virginia, West Virginia and Pennsylvania.
2. The tests carried out in this investigation should also be conducted on a weathered pile to study the impacts of pyrite oxidation and other chemical reactions on the physical properties of the pile.
3. Leachate toxicity studies need to be carried out for leachates from a refuse pile blended with 32% fly ash, in order to determine the effects of these leachates on plant and animal life.

REFERENCES

Adams, L. M., Capp, J. P., and Gillmore, D. W., 1972. Coal Mine Spoil and Refuse Bank Reclamation with Power Plant Fly Ash. *In* M. A. Schwartz (ed.), Proc. 3rd Mineral Waste Utilization Symposium. USDI Bureau of Mines and IIT Research Institute, Illinois.

Adriano, D. C., Page, A. L., Elseewi, A. A, and Chang, A. C., Straughan, I., 1980. Utilization and Disposal of Fly Ash and Other Coal Residues in Terrestrial Ecosystems: A Review. *In* Journal of Environmental Quality 9: 333-344.

ASA., 1990. Methods of Soil Analysis, Part I. Physical and Mineralogical Methods. Second Edition. Arnold Klute (editor). American Society of Agronomy (ASA), Number 9 (PartI) in the Series Agronomy, pp. 383-409.

ASTM., 1992. 1992 Annual Book of ASTM Standards, Section 4, Construction., Volume 04.08, Soil and Rock; Dimension Stone; Geosynthetics. Publication Code No (PCN):01-040892-38. Philadelphia, Pennsylvania.

Bacon, L. D., 1976. Fly Ash for Construction of Highway Embankments. *In* Proceedings, 4th International Ash Utilization Symposium, St. Louis, Montana. March 24-25, 1976. Energy Research and Development Administration, Morgantown, West Virginia.

Bell, J. C., Daniels, W. L. and Zipper C. E., 1989. The Practice of "Approximate Original Contour" in the Central Appalachians. I. Slope Stability and Erosion Potential. Landscape and Urban Planning, 18 (1989), Pp 127-138. Elsevier Science Publishers B. V., Amsterdam.

Bishop, A. W., 1955. The Use of the Slip Circle in the Stability Analysis of Earth Slopes. *In* Geotechnique, 4:128-152.

Bishop C. S., and Simon N. R., 1976. Selected Soil Mechanics Properties of Kentucky Coal Preparation Plant Refuse. *In* Proceedings of the Second Kentucky Coal Refuse Disposal and Utilization Seminar, Pineville, Kentucky, pp. 61-67.

Busch, R. A., Backer, R. R., and Atkins, L. A., 1974. Physical Property Data on Coal Waste Embankment Materials. US Bureau of Mines. Report Investigation 7964.

Buttermore, W. H., Simcoe, E. J., and Malloy, M. A., 1978. Characterization of Coal Refuse. Technical Report No. 159, Coal Research Bureau. West Virginia University, Morgantown, West Virginia.

Carlson, C. L., and Adriano, D. C., 1993. Environmental Impacts of Coal Combustion

Residues. *In* Journal of Environmental Quality 22 : 227-247 (1993).

Caruccio, F. T., Ferm, J. C., Horne J., Geidel, G., and Baganz, B., 1977. Paleoenvironment of Coal and its Relation to Drainage Quality. EPA-600/7-77-067.

Chang, A. C., Lund, L. J., Page, A. L., and Warneke, J. E., 1977. Physical Properties of Fly Ash Amended Soils. *In* Journal of Environmental Quality, 6:267-270.

Cherkauer, D. S., 1980. The Effect of Fly Ash Disposal on a Shallow Ground Water System. Groundwater, 18: 544 -550.

Chirapuntu, S., 1975. The Role of Fill Strength in the Stability of Embankments on Soft Clay Foundations. Doctoral Thesis Presented to the University of California, Berkeley, in 1975.

Chu, T. Y. J., Krenkel, P. A. and Ruane, R. J., 1976. Reuse of Ash sluicing Water in Coal Fired Power Plants, Tennessee Valley Authority, Chattanooga, TN. Prepared for the Third National Conference on Complete Water Reuse, Cincinnati, Ohio, June 27-30, 1976. 29p.

Daniels, W. L., Haering, K., Dove, D., 1992. Long Term Strategies for Reclaiming and Managing Coal Refuse Disposal Areas. Virginia Coal and Energy Quarterly., pp 45-59.

Daniels, W. L., Stewart, B. R., and Jackson, M. L., 1993. Utilization of Fly Ash to Prevent Acid Mine Drainage from Coal Refuse. Proceedings: Tenth International Ash Use Symposium. January 18-21, 1993. Orlando, FL. Am. Coal Ash Assoc., Washington D.C.

D'Appolonia, E., 1975. Engineering and Design Manual for Coal Refuse Facilities. Prepared for the U.S. Dept. of the Interior, MESA, Washington, D.C.

Davidson, W. A., 1974. Reclaiming Refuse Banks from Underground Bituminous Mines in Pennsylvania. *In* Proceedings , First Symposium on Mine and Preparation Plant Disposal, Louisville, KY, 22-24 Oct. 1974. National Coal Association and Bituminous Coal Research Inc., Washington D.C.

Davison, R. L., Natusch, D. F. S., Wallace, J. R., and Evans, C. A., Jr., 1974. Trace Elements in Fly Ash-Dependence of Concentration on Particle Size. *In* environmental Science and Technology, Vol. 8 (No 13):1107-1113, December 1974.

Day, P. R., 1965. Particle Fractionation and Particle Size Analysis. *In* C. A. Black (ed.). Methods of Soil Analysis, Part I, Agronomy 9: 545-556.

Delp, C. H., 1975. Soil Morphology Characteristics, Genesis and Classification of West

Virginia Coal mine Refuse. M.S. Thesis. West Virginia University, Morgantown, WVa.

Doran, J. W. and Martens, D. C., 1972. Molybdenum Availability as Influenced by Application of Fly Ash to Soil. Journal of Environmental Quality, Vol. 1, No 2: 186-189.

Drake, L. D., 1991. Self Attenuation of Fly Ash Landfill Leachates. *In* XIIth National Symposium on Mining, University of Kentucky, Lexington, KY. Sept. 22-27, 1991.

Duncan, J. M. and Wright, S. G., 1980. The Accuracy of Equilibrium Methods of Slope Stability Analysis. *In* S. L. Koh (ed.), Mechanisms of Landslides and Slope Stability. Engineering Geology, 16:5-17.

Duncan, J. M., Low, B. K., and Schaeffer, V. R., 1985. STABGM: A Computer Program for Slope Stability Analysis of Reinforced Embankments and Slopes; Microcomputer Version. Virginia Tech, Blacksburg, Va.

Fail, J. L. and Wochok, Z. S., 1977. Soyabean Growth on Fly Ash-Amended Strip Mine Soils. Plant and Soil 48:473-484.

Ferguson, G., 1993. Use of Self-Cementing Fly Ashes As a Soil Stabilization Agent. *In* Fly Ash for Soil Improvement. Proceedings, Am. Soc. of Civil Engineers (ASCE). Geotechnical Special Publication No. 36. Kevan D. Sharp (editor). Dallas, TX. October 24-28, 1993.

Golden, D. M., 1983. Water Pollution Arising from Solid Waste (Coal Fly Ash, Slag) Disposal, and Measures to Prevent Water Pollution. Water Science and Technology, 15: 1-10.

Haering, K. C., and Daniels, W. L., 1991. Fly Ash: Characteristics and Use in Mined Land Reclamation- A Literature Review. Virginia Center for Coal and Energy Research. *In* Virginia Coal and Energy Journal, (Summer 1991), 3:33-45.

Harries, J. R., and Ritchie, A. I. M., 1987. the Effect of Rehabilitation on the Rate of Oxidation of Pyrite in a Mine Waste Rock Dump. Environ. Geochem. Health 9(2):27-36.

Hayes, R. J., and Klimstra, W. D., 1975. Some Properties of Coal Spoilbank and Refuse Materials Resulting from Surface Mining Coal in Illinois. State of IL, Institute for Environmental Quality.

Head, K. H., 1982. Manual of Soil Laboratory Testing , Vols 1, 2 and 3. Published for ELE International Limited. A Halsted Press Book. John Wiley & Sons, New York.

Hecht, N. L. and Duvale, D. S., 1975. Characterization and Utilization of municipal and Utility Sludges and Ashes, Vol. II: Utility Coal Ash. University of Dayton, Dayton, Ohio. Publication No PB 244 312. environmental Protection Agency. May 1975. 66p.

Jackson, M. L., 1993. Influence of Fly Ash and Other Treatments on Acid Mine Drainage from Coal Refuse. M.S. Thesis. Virginia Tech, Blacksburg, VA.

Joshi, R. C., Duncan, D. M., and Durbin, W. L., 1976. Performance Record of Fly Ash As A Construction Material. *In* Proceedings, 4th International Ash Utilization Symposium, St. Louis, Montana. March 24-25, 1976. Energy Research and Development Administration, Morgantown, WV.

Keefer, D. H., Singh, R. N., Doonan, F., Khawaja, A. R. and Horvath, D. J., 1980. Application of Fly Ash and Other Wastes to Mine Soils as an Aid to Revegetation. *In* J. D. Spencer and C. E. Wieldon, Jr.(ed.), Proc. 5th International Ash Utilization Symposium. METC/SP-79-10. Morgantown Energy Technical Center. Morgantown, WV.

Keystone Coal Industry Manual., 1988. Robert Lick Publisher. Maclean Hunter Publishing Co. Chicago, Illinois, pp.530-537.

Khan, L. A., Bhagwat, S. B., and Baxter, J. W., 1986. Economics of Secondary Recovery of Coal. In D. J. Graves (ed.) proceedings, 1986. Symposium of Surface Mining, Hydrology, Sedimentology and Reclamation. university of Kentucky, Lexington, KY.

Klein, D. H., Andren, A. W., Carter, J. A., Emery, J. F., Feldman, C., Fulkerson, W., Lyon, W. S., Ogle, J. C.,Taimi, Y., Van Hook, R. I., and Bolton, N., 1975. Pathway of 37 Trace Elements Through Coal Fired Power Plants. Environmental Science and Technology 9: 973-979.

Lamb, D. W., 1973. Ash Use in Structural Fill. *In* J. H. Faber, W. E. Eckhard, and J. D. Spencer (ed.), Proc. of the Third International Fly Ash Utilization Symposium, St. Louis, MO, March 24, 1973. Reproduced in Torrey, S., 1978. Coal Ash Utilization: Fly Ash, Bottom Ash and Slag, Pollution Tech. Review No. 48, Noyes Data Corp., NJ, pp. 81-122.

Lamb, D. W., Herrmann W., and Pizella, J., 1976. Fly Ash as Construction Material for Water Retaining Structures. *In* Proceedings, 4th International Ash Utilization Symposium, St. Louis, Montana. March 24-25, 1976. Energy Research and Development Administration, Morgantown, WV.

Lowson, R. T., 1982. Aqueous Oxidation of Pyrite by Molecular Oxygen. Chem. Rev. 82(5):471-496.

Mattigod, S. V., Rai, D., Eary, L. E., and Ainsworth C. C., 1990. Geochemical Factors Controlling the Mobilization of Inorganic Constituents from Fossil Fuel Combustion Residues: I. Review of Major Elements. Journal of Environmental Quality, 19:188-201.

Moulton, L. K., Anderson, D. A., Hussain, S. M., and Seals, R. K., 1974. Coal Mine Refuse: An Engineering Material. *In* Proceedings, First Symposium on Mine and Preparation Plant Refuse Disposal, Louisville, KY. October, pp. 1-25.

Muraka, I. P., and McIntosh, D. A., 1987. Solid Waste Environmental Studies (SWES): Description, Status and Available Results, EPRI-EA-5322-SR: Electric Power Research Institute, Palo Alto, CA.

Natush, D. F. S., Bauer, C. F., Matusiewics, H., Evans, C. A., Baker, J., Loh, A., Lonlen, R. W., and Hopke, P. K., 1977. Characterization of Trace Elements in Fly Ash . University of Illinois Institute for Environmental Studies Research Report No. 3. Champaign, IL.

Nawrot, J. R., Warburton, D. B., and Klimstra, W. B., 1986. Coarse Refuse Reclamation: Alkaline Enhancement for Direct Vegetation Establishment. *In* Proceedings of the National Mined Land Reclamation Conference. St. Louis, MO. October 28-29.

Nicholson, P. G., and Kashyap, V., 1993. Fly Ash Stabilization of Tropical Hawaiian Soils. *In* Fly Ash for Soil Improvement. Proceedings, Am. Soc. of Civil Engineers (ASCE). Geotechnical Special Publication No. 36. Kevan D. Sharp (editor). Dallas, TX. October 24-28, 1993.

Page, A. L., Elseewi, A. A., and Straughan, I. R., 1979. Physical and Chemical Properties of Fly Ash from Coal Fired Power Plants with Reference to Environmental Impacts. Residue Reviews 71: 83-120. *In* Carlson, C. L., and Adriano, D. C., 1993. Environmental Impacts of Coal Combustion Residues. *In* Journal of Environmental Quality 22 : 227-247 (1993).

Peffer, J. R., 1983. Fly Ash Disposal in a limestone Quarry, Groundwater, 20, 267-273, 1983.

Plass, W. T., and Capp, J. P., 1974. Physical and Chemical Characteristics of Surface Mine Spoil treated with Fly Ash. *In* Journal of Soil and Water Conservation 20: 119-121.

Plumley, A. L., 1971. Fossil Fuel and the Environment- Present System and their Emissions. *In* Combustion:36-43, October 1971.

Randolph, J., Jones, J. R., and Prelaz, L. J., 1990. Virginia Coal. Virginia Center for Coal and energy Research, Virginia Tech, Blacksburg, Va.

Ray, S. S., and Parker, F. G., 1978. Coal Ash Characterization. *In* Torrey, S., 1978. Coal Ash Utilization: Fly Ash, Bottom Ash and Slag. Pollution Tech. Review No 48, Noyes Data Corp., NJ, pp. 1-26.

Roy, W. R., Thiery, R. G., Schuller, R. M., Suloway, J. J., 1981. Coal Fly Ash: A Review of the Literature and Proposed Classification System with Emphasis on Environmental Impacts. *In* Environmental Geology Notes 96. Illinois State Geological Survey. Champaign, Illinois.

Smith, R. L., 1993. Stabilization of Industrial Wastes. *In* Fly Ash for Soil Improvement. Proceedings, Am. Soc. of Civil Engineers (ASCE). Geotechnical Special Publication No. 36. Kevan D. Sharp (editor). Dallas, TX. October 24-28, 1993.

South African Coal Processing Society (SACPS), 1977. Coal Preparation Course, Volume I. Coal Processing Society, Johannesburg, South Africa.

Stewart, B. R., 1990. Physical and Chemical Properties of Coarse Coal Refuse from Southwest Virginia. M.S. Thesis. Department of Crops and Soil Environmental Sciences, VPI & SU, Blacksburg, VA.

Stewart, B. R., Daniels, W. L. and Jackson, M. L., 1992. Utilization of Fly Ash as an Ammendment for Coal Refuse Piles and Mine Soils. *In* Proceedings 1992 Powell River Project Symposium, Research Division, Virginia Tech.

Stewart, B. R., Jackson, M. L. and Daniels, W. L., 1994. The Effects of Fly Ash Blending Rates and Ash Properties on Leachate Quality from Fly Ash/ Coal Refuse Mixtures. The International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acid Mine Drainage. Pittsburg, PA. April 24-29, 1994. USDI Bureau of Mines, Special Publication 06C-94.

Taylor, E. M. and Schumann, G. E., 1988. Fly Ash and Lime Amendment of Acidic Coal Spoil to aid Revegetation. *In* Journal of Environmental Quality 17:120-124.

Theis, T. L. and Wirth, J. L., 1977. Sorptive behavior of Trace Metals on Fly Ash in Aqueous Systems. *In* Environmental Science and Technology 11:1096-1100.

Tolle, D. A., Arthur, M. F. and Pomeroy, S. E., 1982. Fly Ash Use for Agriculture and Land Reclamation: A Critical Literature Review and Identification of Additional Research Needs. RP-1224-5. Battelle Columbus Laboratories. Columbus, Ohio.

United States Environmental Protection Agency (USEPA), 1988. Wastes from the

Combustion of Coal by Electric Utility Power Plants. USEPA Rep. 530-SW-88-002. USEPA, Washington D.C.

United States Environmental Protection Agency (USEPA), 1993. 40 CFR Part 261. "Final Regualtory Determination on Four Large Volume Wastes from the Combustion of Coal by Electric Utility Power Plants". *In* Federal Register. EPA, Washington D.C.

Usmen, M. A., and Bowders, J. J., Jr., 1988. Stabilization Characteristics of Class F Fly Ash. Transportation Research Record, pp. 59-69. *Cited In* Fly Ash for Soil Improvement. Proceedings, Am. Soc. of Civil Engineers (ASCE). Geotechnical Special Publication No. 36. Kevan D. Sharp (editor). Dallas, Texas. October 24-28, 1993.

Vogel, W. G., 1987. A Manual for Training Reclamation Inspectors in the Fundamentals of Soils and Revegetation. Prepared for the Office of Surface Mining and Reclamation, Jackson, Mississippi, pp. 123-130.

Watzlaf, G. R., and Hammack, R. W., 1989. The Effect of Oxygen, Iron Oxidizing Bacteria and Leaching Frequency on Pyrite Oxidation. *In* Proceedings, 9th Annual WV Surface Mine Drainage Task Force Symposium, Morgantown, West Virginia.

Whitman, R. V. and Bailey, W. A., 1967. Use of Computers for Slope Stability Analysis. JSMFD, ASCE. 93:SM4:519-541.

APPENDIX A
COMPACTION TEST DATA

COMPACTION TEST DATA

Table A1. Nomenclature of Samples

Sample 1 = 100% Coal refuse

Sample 2 = Coal refuse + 8% fly ash

Sample 3 = Coal refuse + 16% fly ash

Sample 4 = Coal refuse + 24% fly ash

Sample 5 = Coal refuse + 32% fly ash

Sample 6 = 100% fly ash

Table A2. Terms Used in the Compaction Test

A = Weight of sample + mold, (g)

B = Weight of mold, (g)

(A-B) = Weight of the sample, (g)

V = Volume of the Sample, (cubic cm)

WD = Wet density = (A-B)/V, (g/cubic cm)

MC = Average moisture moisture, (%)

γ_D = Dry density = WD/ (1+MC), (kN/m^3)

Table A3. Results of Compaction Test for Sample 1

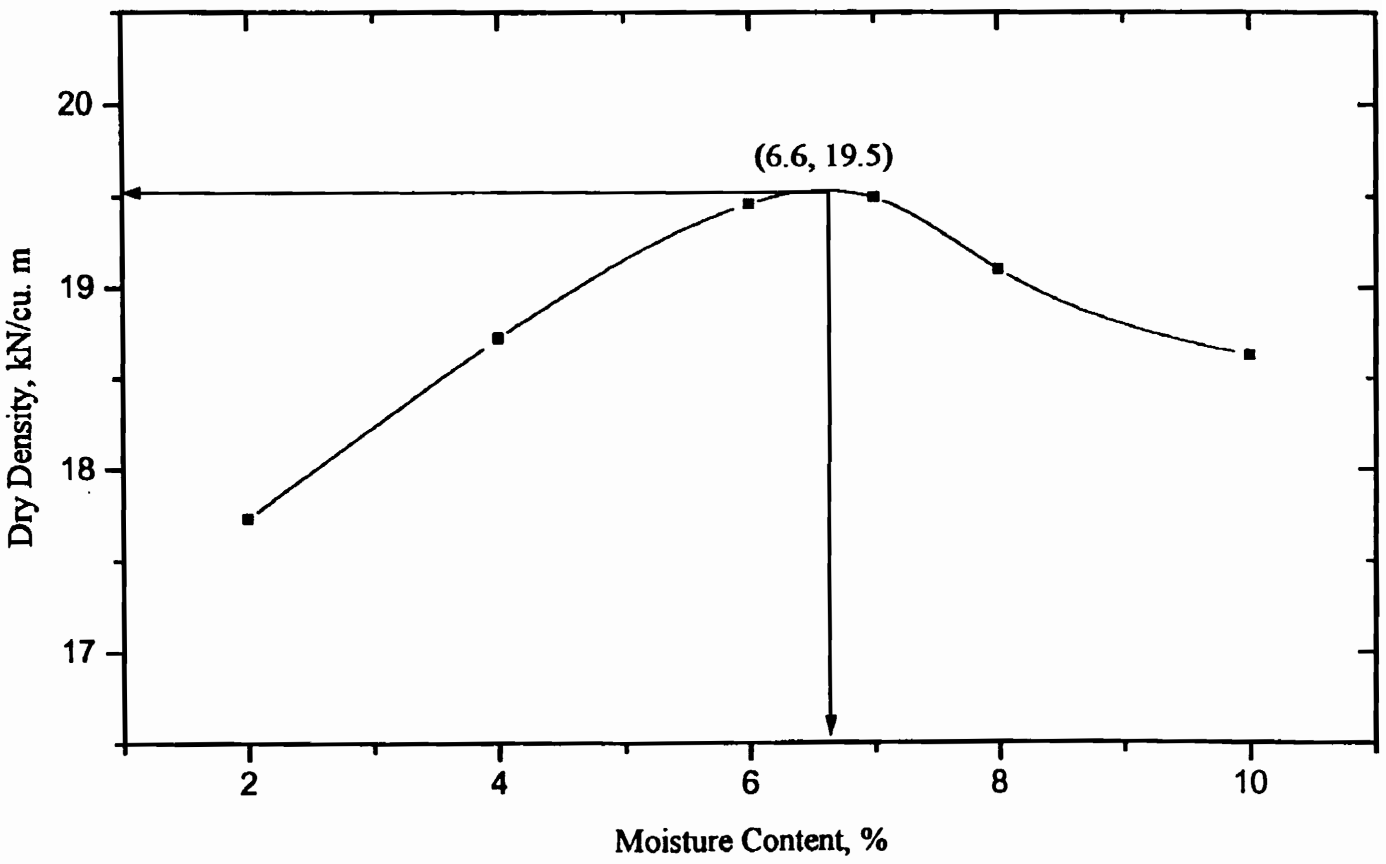
A (g)	B (g)	A-B (g)	V (cm^3)	WD (g/cm^3)	MC (%)	γ_D (kN/m^3)	γ_D (lb/ft^3)
10035	6120	3915	2124	1.84322	2	17.727	112.8123
10335	6120	4215	2124	1.98446	4	18.719	119.1212
10585	6120	4465	2124	2.10217	6	19.455	123.8056
10635	6120	4515	2124	2.12571	7	19.489	124.022
10585	6120	4465	2124	2.10217	8	19.095	121.5129
10555	6120	4435	2124	2.08804	10	18.622	118.5020

Table A4. Results of Compaction Test for Table 2

A (g)	B (g)	A-B (g)	V (cm^3)	WD (g/cm^3)	MC (%)	γ_D (kN/m^3)	γ_D (lb/ft^3)
10180	6120	4060	2124	1.91149	2	18.384	116.9905
10290	6120	4170	2124	1.96328	4	18.519	117.8494
10565	6120	4445	2124	2.09275	6	19.368	123.2510
10555	6120	4435	2124	2.08804	8	18.966	120.6965
10495	6120	4375	2124	2.05979	10	18.370	116.8988

Table A5. Results of Compaction Test for Sample 3

A (g)	B (g)	A-B (g)	V (cm^3)	WD (g/cm^3)	MC (%)	γ_D (kN/m^3)	γ_D (lb/ft^3)
10010	6120	3890	2124	1.83145	2	17.614	112.0919
10230	6120	4110	2124	1.93503	4	18.252	116.1537
10380	6120	4260	2124	2.00565	6	18.562	118.1214
10485	6120	4365	2124	2.05508	8	18.667	118.7915
10400	6120	4280	2124	2.01507	10	17.791	114.3604
10340	6120	4220	2124	1.98682	12	17.402	110.7437



Compaction characteristics: Sample 1

Figure A1. Compaction Test Sample 1

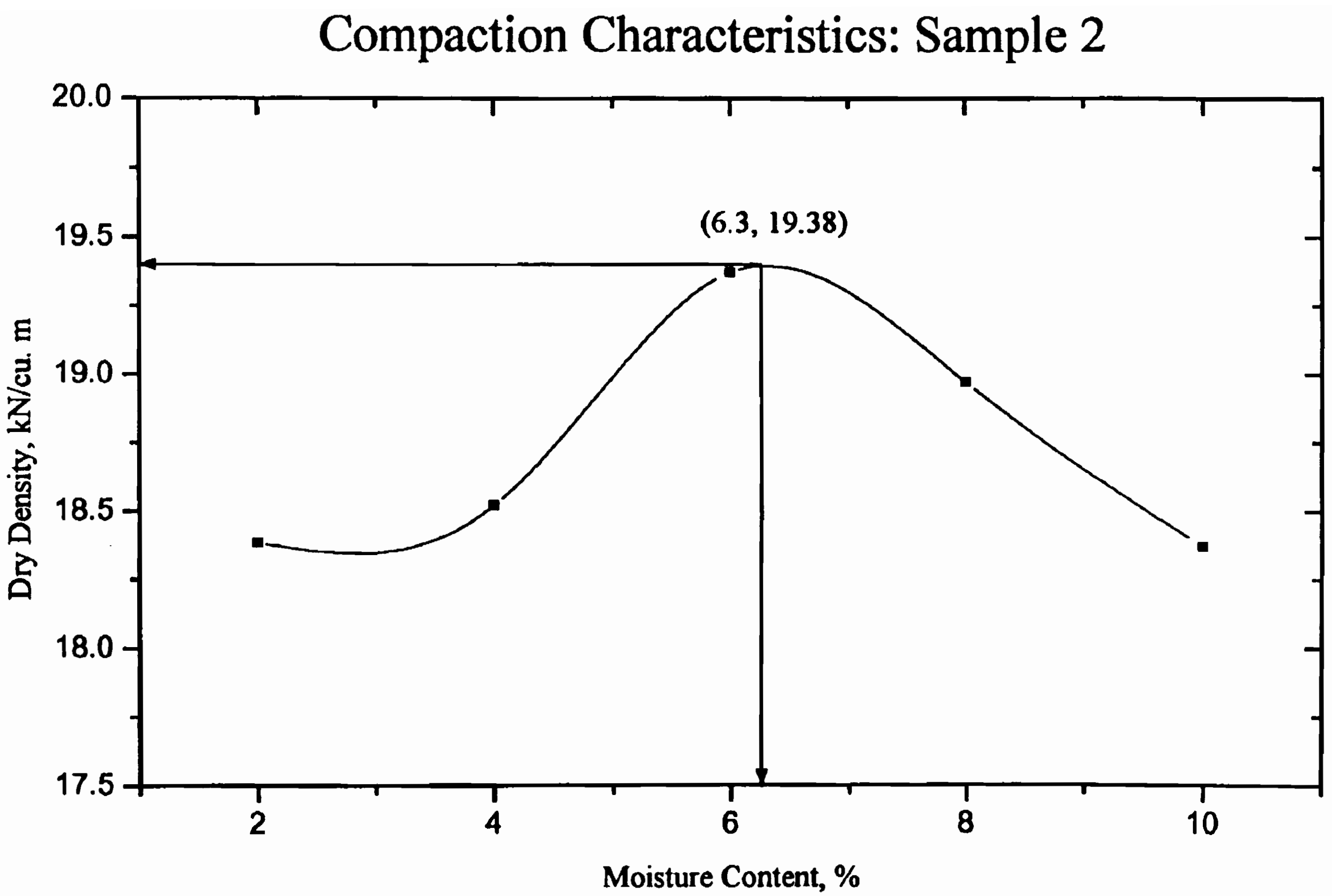


Figure A2. Compaction Test Sample 2

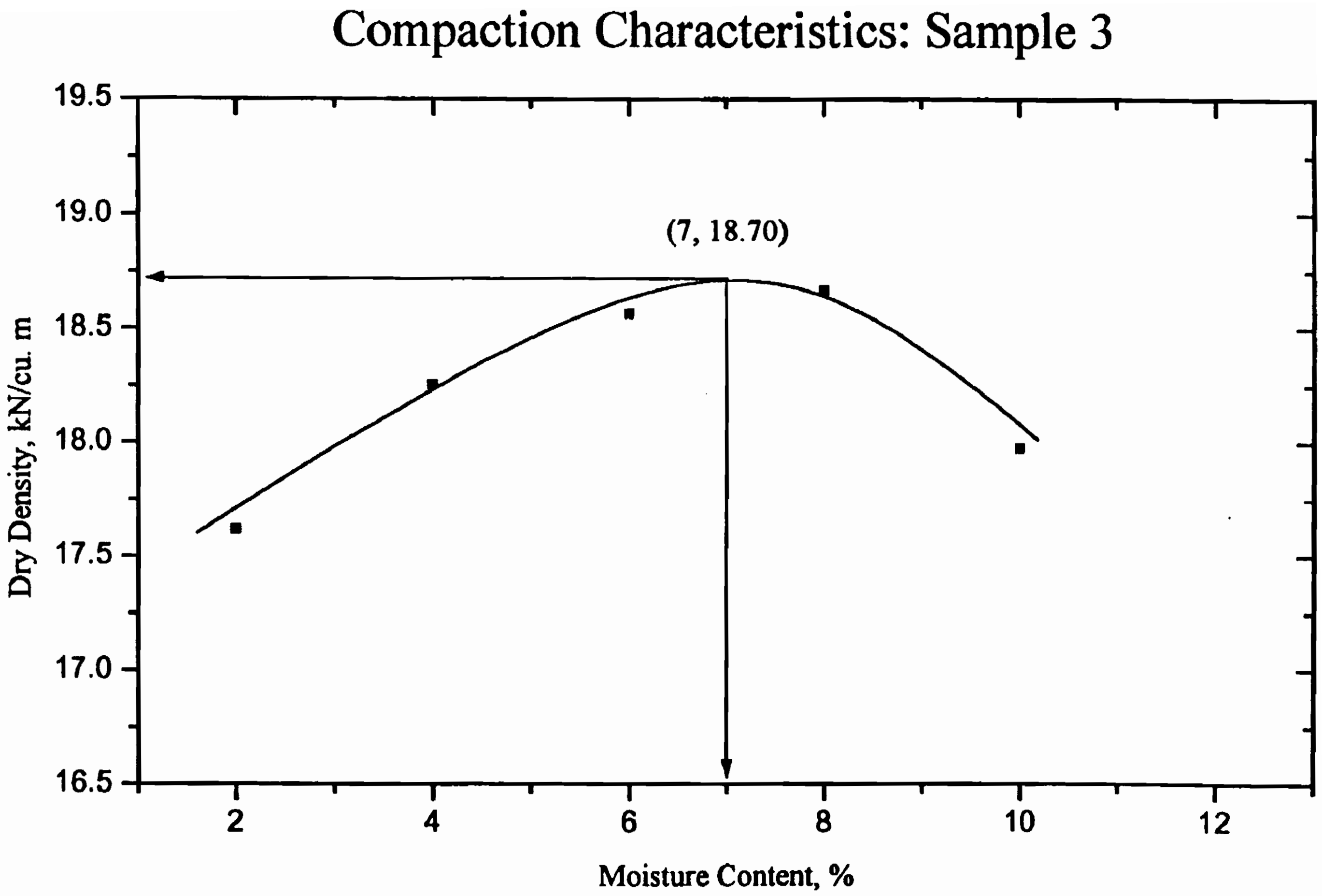


Figure A3. Compaction Test Sample 3

Table A6. Results of Compaction Test for Sample 4

A (g)	B (g)	A-B (g)	V (cm^3)	WD (g/cm^3)	MC (%)	γ_D (kN/m^3)	γ_D (lb/ft^3)
10015	6120	3895	2124	1.83380	4	17.298	110.0776
10150	6120	4030	2124	1.89736	6	17.560	111.7439
10430	6120	4310	2124	2.02919	8	18.432	117.2947
10430	6120	4310	2124	2.02919	10	18.097	115.1620
10390	6120	4270	2124	2.01036	12	17.607	112.0559
10275	6120	4155	2124	1.95621	14	16.833	107.1250

Table A7. Results of Compaction Test for Sample 5

A (g)	B (g)	A-B (g)	V (cm^3)	WD (g/cm^3)	MC (%)	γ_D (kN/m^3)	γ_D (lb/ft^3)
9965	6120	3845	2124	1.81026	4	17.076	108.6645
10105	6120	3985	2124	1.87618	6	17.364	110.4962
10370	6120	4250	2124	2.00094	8	18.175	115.6618
10385	6120	4265	2124	2.00800	10	17.908	113.9596
10400	6120	4280	2124	2.01507	12	17.650	112.3183
10350	6120	4230	2124	1.99153	14	17.138	109.0587

Table A8. Results of Compaction Test for Sample 6

A (g)	B (g)	A-B (g)	V (cm^3)	WD (g/cm^3)	MC (%)	γ_D (kN/m^3)	γ_D (lb/ft^3)
8990	6120	2870	2124	1.35122	8	12.274	78.10572
9215	6120	3095	2124	1.45716	12	12.763	81.22082
9370	6120	3250	2124	1.53013	16	12.940	82.34744
9575	6120	3455	2124	1.62665	20	13.298	84.62361
9680	6120	3560	2124	1.67608	25	13.154	83.70757
9780	6120	3660	2124	1.72316	30	13.003	82.74894

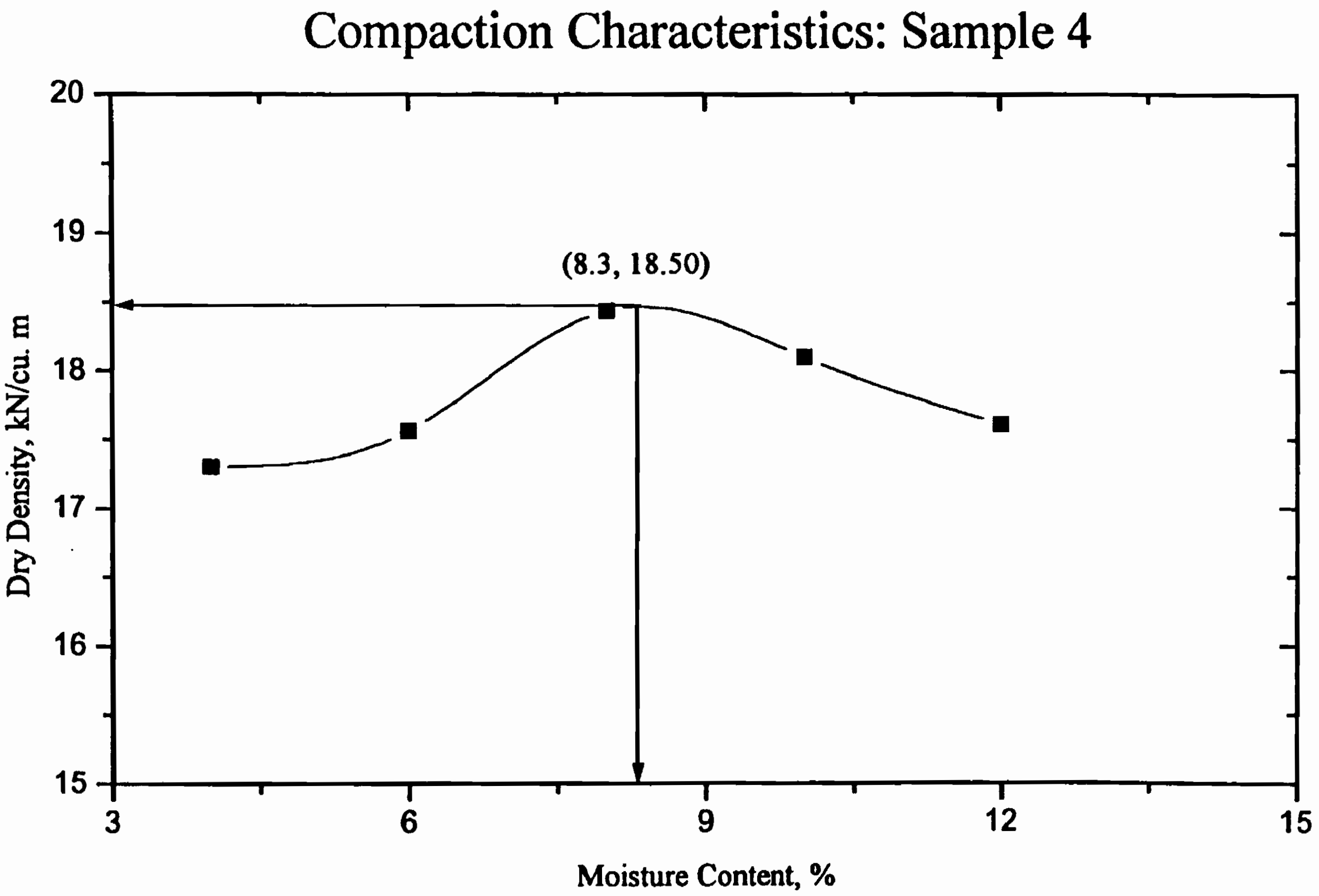


Figure A4. Compaction Test Sample 4

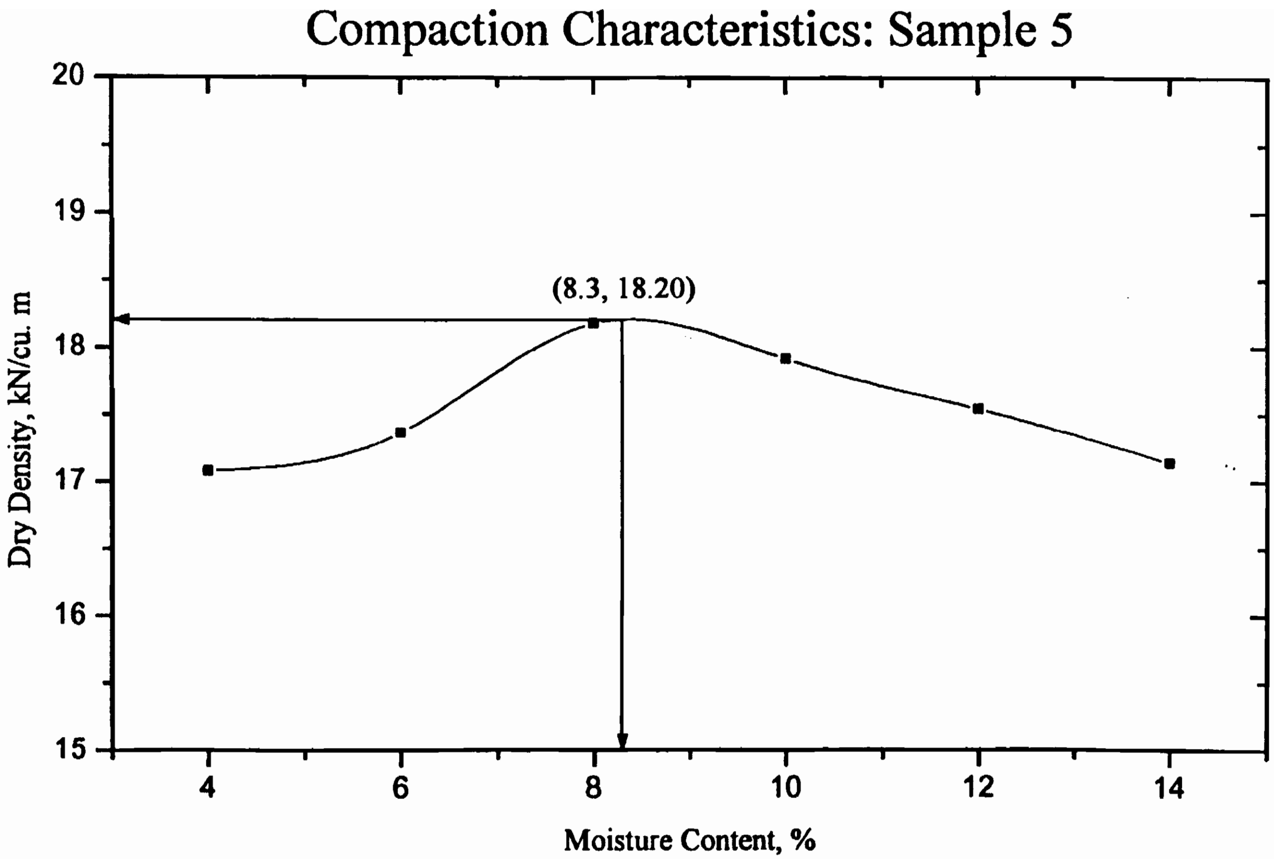


Figure A5. Compaction Test Sample 5

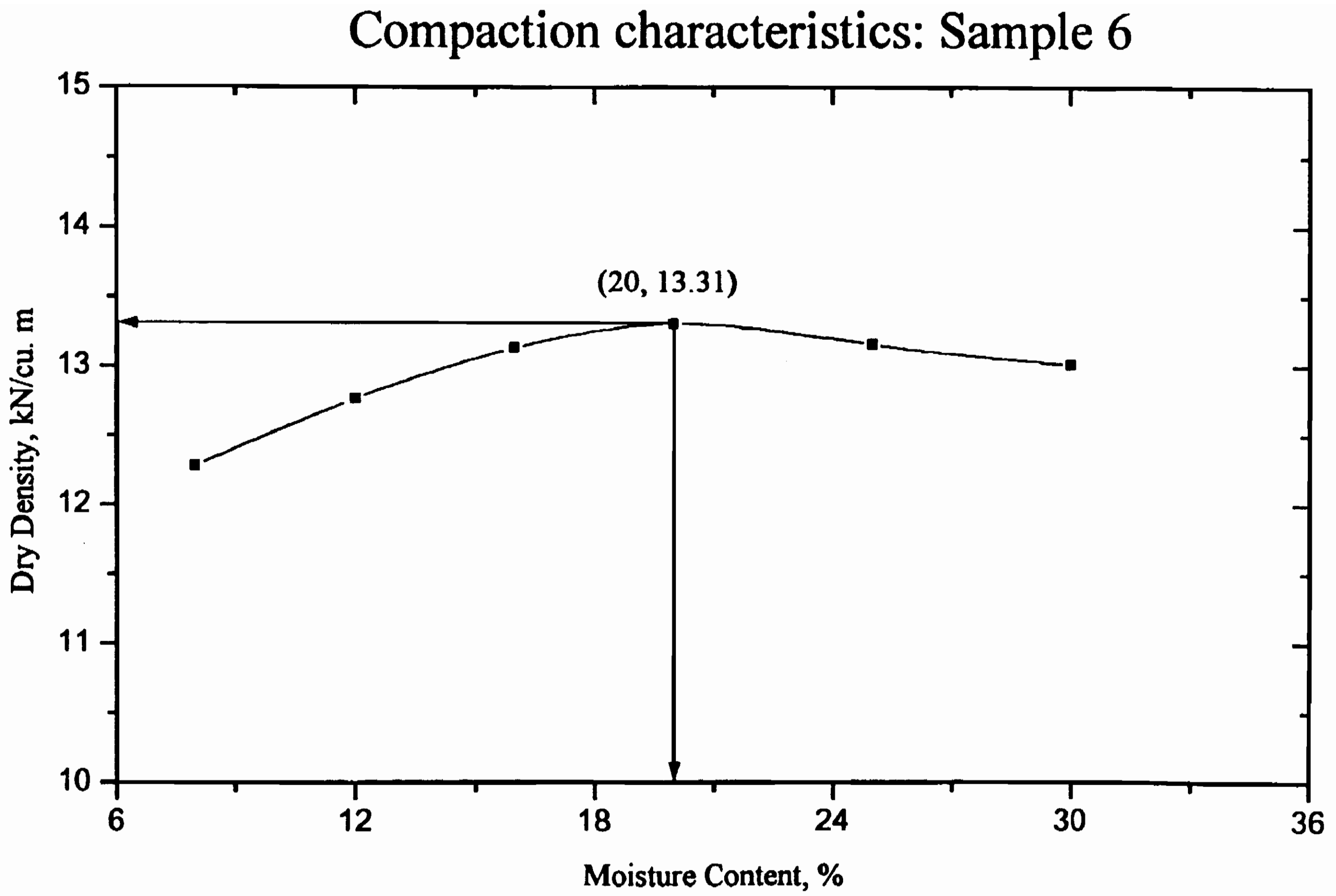


Figure A6. Compaction Test Sample 6

APPENDIX B
PERMEABILITY TEST DATA

PERMEABILITY TEST DATA

Table B.1 - Dimensions of Sample and Burette

Length of samples, L = 22.86 cm
Diameter of samples, D = 20.32 cm
Area of Samples, A = 324.29 cm^2
Diameter of burette, d = 5.05 cm
Area of burette, a = 20.03 cm^2

Table B.2 - Explanation of Abbreviations for Permeability Test

C = Conversion constant (= aL/A = 1.412 cm)
h_1 = Initial height of water in burette
h_2 = Final height of water in burette
h = Height of water at the outlet
H_1 = Initial hydraulic head across the sample
H_2 = Final hydraulic head across the sample
T = Elapsed time of test
K = Coefficient of permeability

Table B.3 - Summary of Permeability Results for Sample 1

C	h_1 cm	h_2 cm	H_1 cm	H_2 cm	Log_n (H_1/H_2)	T sec	K cm/sec
1.412	64.77	30.48	91.44	50.8	0.58778	300	2.77E-03
1.412	64.77	54.61	91.44	81.28	0.11778	57	2.91E-03
1.412	64.77	49.53	91.44	76.2	0.18232	92	2.80E-03
1.412	64.77	44.45	91.44	71.12	0.25131	125	2.84E-03
1.412	64.77	39.37	91.44	66.04	0.32542	164	2.81E-03
1.412	64.77	34.29	91.44	60.96	0.40547	208	2.75E-03
1.412	64.77	59.69	91.44	86.36	0.05716	28	2.88E-03
1.412	64.77	45.72	91.44	73.66	0.21622	108	2.83E-03

Average = 2.83 E-03
Standard Dev. = 5.00 E-05

Table B.4 - Summary of Permeability Results for Sample 2

C	h_1 cm	h_2 cm	H_1 cm	H_2 cm	Log_n (H_1/H_2)	T sec	K cm/sec
1.412	78.74	53.54	104.14	78.74	0.2796	390	1.01E-03
1.412	78.74	68.58	104.14	93.98	0.1027	145	9.99E-04
1.412	78.74	40.64	104.14	66.04	0.4555	615	1.05E-03
1.412	78.74	27.94	104.14	53.34	0.6690	945	9.97E-04
1.412	78.74	48.26	104.14	73.66	0.3463	485	1.01E-03
1.412	78.74	15.24	104.14	40.64	0.9410	1290	1.03E-03
1.412	78.74	33.02	104.14	58.42	0.5781	815	9.99E-04
1.412	78.74	17.78	104.14	43.18	0.8804	1245	1.0E-03

Average = 1.01E-03
Standard Dev. = 1.80E-05

Table B.5 - Summary of Permeability Results for Sample 3

C	h_1 cm	h_2 cm	H_1 cm	H_2 cm	Log_n (H_1/H_2)	T sec	K cm/sec
1.412	71.12	53.34	96.52	78.74	0.2036	1145	2.51E-04
1.412	71.12	10.16	96.52	35.56	0.9985	5400	2.61E-04
1.412	71.12	40.64	96.52	66.04	0.3795	2120	2.53E-04
1.412	71.12	45.72	96.52	71.12	0.3054	1665	2.59E-04
1.412	71.12	22.86	96.52	48.26	0.6931	3795	2.58E-04
1.412	71.12	5.08	96.52	30.48	1.1527	6410	2.54E-04
1.412	71.12	48.26	96.52	73.66	0.2703	1495	2.55E-04
1.412	71.12	33.02	96.52	58.42	0.5021	2760	2.57E-04

Average = 2.56 E-04
Standard Dev. = 3.10E-06

Table B.6 - Summary of Permeability Results for Sample 4

C	h_1 cm	h_2 cm	H_1 cm	H_2 cm	Log_n (H_1/H_2)	T sec	K cm/sec
1.412	63.5	58.42	88.90	83.82	0.05884	490	1.70E-04
1.412	63.5	33.02	88.90	58.42	0.41985	3370	1.76E-04
1.412	63.5	48.26	88.90	73.66	0.18805	1620	1.64E-04
1.412	63.5	25.40	88.90	50.80	0.55961	4675	1.69E-04
1.412	63.5	12.70	88.90	38.10	0.84730	6875	1.74E-04
1.412	63.5	40.64	88.90	66.04	0.29725	2500	1.68E-04
1.412	63.5	10.16	88.90	35.56	0.91629	7350	1.76E-04
1.412	63.5	35.56	88.90	60.96	0.37729	3095	1.72E-04

Average = 1.71 E-04
Standard Dev. = 3.90E-06

Table B.7 - Summary of Permeability Results for Sample 5

C	h_1 cm	h_2 cm	H_1 cm	H_2 cm	Log_n (H_1/H_2)	T sec	K cm/sec
1.412	68.58	27.94	93.98	53.34	0.56639	10190	7.85E-05
1.412	68.58	55.88	93.98	81.28	0.14518	2630	7.79E-05
1.412	68.58	38.10	93.98	63.5	0.39204	6990	7.92E-05
1.412	68.58	20.32	93.98	45.72	0.72055	12895	7.89E-05
1.412	68.58	43.18	93.98	68.58	0.31508	5660	7.86E-05
1.412	68.58	7.62	93.98	33.02	1.04597	18740	7.88E-05
1.412	68.58	30.48	93.98	55.88	0.51988	9340	7.86E-05
1.412	68.58	48.26	93.98	73.66	0.24362	4320	7.96E-05

Average = 7.88 E-05
Standard Dev. = 4.70E-07

Table B.8 - Summary of Permeability Results for Sample 6

C	h_1 cm	h_2 cm	H_1 cm	H_2 cm	Log_n (H_1/H_2)	T sec	K cm/sec
1.412	71.12	33.02	96.52	58.42	0.50209	12330	5.75 -05
1.412	71.12	53.34	96.52	78.74	0.20360	4950	5.81E-05
1.412	71.12	17.78	96.52	43.18	0.80437	20135	5.64E-05
1.412	71.12	25.4	96.52	50.80	0.64185	15520	5.84E-05
1.412	71.12	48.26	96.52	73.66	0.27029	6545	5.83E-05
1.412	71.12	40.64	96.52	66.04	0.37949	9255	5.79E-05
1.412	71.12	45.72	96.52	71.12	0.30538	7565	5.70E-05
1.412	71.12	20.32	96.52	45.72	0.74721	18035	5.85E-05

Average = 5.78E-05
Standard Dev. = 7.00E-07

APPENDIX C
CU (SHEAR) TEST DATA

CU TEST - EXPERIMENT 1

SAMPLE 1 - COAL REFUSE
Sigma 3= 45 psi
u= 35 psi
Sigma 3' = 10 psi
October 31, 1993

Load div	Load P lbs	Strain div	Strain in	Strain E	Strain %	Ac=12.122 12.1227/(1-	Deviator S =P/Acc	Sigma 1	Pore pres psi	mod. pp	Sig1'	Sig3'	Sig1'/sig3'	p'	q	A
0	0	0	0	0	0	12.1227	0	45	35	0	10	10	1	10	0	0
10	25	8	0.008	0.001333	0.133333	12.13889	2.059497	47.0595	35.5	0.5	11.5595	9.5	1.216789	10.52975	1.029749	0.242778
20	50	9	0.009	0.0015	0.15	12.140911	4.118307	49.11831	36	1	13.11831	9	1.45759	11.05915	2.059153	0.242819
30	75	18	0.018	0.003	0.3	12.159178	6.16818	51.16818	36.5	1.5	14.66818	8.5	1.725668	11.58409	3.08409	0.243184
40	100	40	0.04	0.006667	0.666667	12.20406	8.193994	53.19399	37	2	16.19399	8	2.024249	12.097	4.096997	0.244081
50	125	70	0.07	0.011667	1.166667	12.265801	10.19094	55.19094	37.75	2.75	17.44094	7.25	2.405646	12.34547	5.095468	0.269848
60	150	100	0.1	0.016667	1.666667	12.328169	12.16728	57.16728	38.5	3.5	18.66728	6.5	2.871889	12.58364	6.083638	0.287657
70	175	145	0.145	0.024167	2.416667	12.422921	14.08686	59.08686	40	5	19.08686	5	3.817373	12.04343	7.043432	0.354941
80	200	186	0.186	0.031	3.1	12.510526	15.98654	60.98654	40.5	5.5	20.48654	4.5	4.552564	12.49327	7.993269	0.344039
90	225	210	0.21	0.035	3.5	12.562383	17.91061	62.91061	40	5	22.91061	5	4.582123	13.95531	8.955307	0.279164
100	250	255	0.255	0.0425	4.25	12.660783	19.74601	64.74601	39.5	4.5	25.24601	5.5	4.590184	15.37301	9.873007	0.227894
110	275	300	0.3	0.05	5	12.760737	21.55048	66.55048	39	4	27.55048	6	4.591747	16.77524	10.77524	0.185611
120	300	336	0.336	0.056	5.6	12.841843	23.36113	68.36113	38.5	3.5	29.86113	6.5	4.59402	18.18057	11.68057	0.149822
140	325	402	0.402	0.067	6.7	12.993248	25.01299	70.01299	38	3	32.01299	7	4.573284	19.5065	12.5065	0.119938
150	350	455	0.455	0.075833	7.583333	13.117439	26.68204	71.68204	37.5	2.5	34.18204	7.5	4.557605	20.84102	13.34102	0.093696
160	400	564	0.564	0.094	9.4	13.380464	29.89433	74.89433	36.75	1.75	38.14433	8.25	4.623555	23.19717	14.94717	0.05854
170	425	630	0.63	0.105	10.5	13.544916	31.37708	76.37708	36.25	1.25	40.12708	8.75	4.585952	24.43854	15.68854	0.039838
180	450	675	0.675	0.1125	11.25	13.65938	32.94438	77.94438	35.75	0.75	42.19438	9.25	4.561555	25.7222	16.4722	0.022766
190	475	750	0.75	0.125	12.5	13.854514	34.28486	79.28486	35.25	0.25	44.03486	9.75	4.516396	26.89243	17.14243	0.007292
200	500	798	0.798	0.133	13.3	13.982353	35.75936	80.75936	35	0	45.75936	10	4.575936	27.87968	17.87968	0
212	530	890	0.89	0.148333	14.83333	14.23408	37.23456	82.23456	34.25	-0.75	47.98456	10.75	4.463679	29.36728	18.61728	-0.02014
210	525	960	0.96	0.16	16	14.431786	36.37803	81.37803	33.75	-1.25	47.62803	11.25	4.233603	29.43902	18.18902	-0.03436
205	512.5	990	0.99	0.165	16.5	14.518204	35.30051	80.30051	33.5	-1.5	46.80051	11.5	4.06961	29.15026	17.65026	-0.04249
200	500	1040	1.04	0.173333	17.33333	14.664556	34.09581	79.09581	33	-2	46.09581	12	3.841318	29.04791	17.04791	-0.05866
195	487.5	1120	1.12	0.186667	18.66667	14.904959	32.70724	77.70724	32.5	-2.5	45.20724	12.5	3.616579	28.85362	16.35362	-0.07644
190	475	1200	1.2	0.2	20	15.153375	31.34615	76.34615	32	-3	44.34615	13	3.411242	28.67308	15.67308	-0.09571

SAMPLE NO 2 - COAL REFUSE
Sigma3 = 55 psi
u= 35psi
2 November, 1993

Load div	Load P lbs	Strain div	Strain in	Strain E	Strain %	Ac =12.07 Acc=12.07	Deviator S =P/Acc	Sigma 1	Pore pres psi	mod. pp	Sig1'	Sig3'	Sig1'/sig3'	p'	q	A
2	5	4	0.004	0.000667	0.066667	12.080325	0.41389	55.4139	35	0	20.4139	20	1.020695	20.20695	0.206945	0
20	50	20	0.02	0.003333	0.333333	12.118663	4.125868	59.12587	35.5	0.5	23.62587	19.5	1.211583	21.56293	2.062934	0.121187
40	100	43	0.043	0.007167	0.716667	12.165454	8.219998	63.22	36.25	1.25	26.97	18.75	1.4384	22.86	4.109999	0.152068
60	150	60	0.06	0.01	1	12.200271	12.29481	67.29481	37	2	30.29481	18	1.683045	24.1474	6.147405	0.16267
80	200	77	0.077	0.012833	1.283333	12.235267	16.34616	71.34616	37.75	2.75	33.59616	17.25	1.947604	25.42308	8.173081	0.168236
95	237.5	100	0.1	0.016667	1.666667	12.282984	19.33569	74.33569	38.5	3.5	35.83569	16.5	2.17186	26.16785	9.667846	0.181012
110	275	120	0.12	0.02	2	12.324763	22.3128	77.3128	39.25	4.25	38.0628	15.75	2.416686	26.9064	11.1564	0.190474
120	300	141	0.141	0.0235	2.35	12.368938	24.25431	79.25431	40	5	39.25431	15	2.616954	27.12716	12.12716	0.206149
130	325	160	0.16	0.026667	2.666667	12.409178	26.19028	81.19028	41.5	6.5	39.69028	13.5	2.940021	26.59514	13.09514	0.248184
140	350	180	0.18	0.03	3	12.451823	28.10833	83.10833	43	8	40.10833	12	3.342361	26.05417	14.05417	0.284613
150	375	198	0.198	0.033	3.3	12.490453	30.02293	85.02293	44.5	9.5	40.52293	10.5	3.859327	25.51147	15.01147	0.316425
160	400	220	0.22	0.036667	3.666667	12.537984	31.90303	86.90303	45.75	10.75	41.15303	9.25	4.448976	25.20151	15.95151	0.336959
170	425	240	0.24	0.04	4	12.581526	33.77968	88.77968	45.25	10.25	43.52968	9.75	4.464582	26.63984	16.88984	0.303437
180	450	255	0.255	0.0425	4.25	12.614379	35.67358	90.67358	44.75	9.75	45.92358	10.25	4.480349	28.08679	17.83679	0.273312
190	475	280	0.28	0.046667	4.666667	12.669512	37.49158	92.49158	44.25	9.25	48.24158	10.75	4.487589	29.49579	18.74579	0.246722
200	500	300	0.3	0.05	5	12.713968	39.32683	94.32683	43.75	8.75	50.57683	11.25	4.495718	30.91342	19.66342	0.222494
210	525	320	0.32	0.053333	5.333333	12.756734	41.14828	96.14828	43.25	8.25	52.89828	11.75	4.501982	32.32414	20.57414	0.200494
220	550	343	0.343	0.057167	5.716667	12.810808	42.93317	97.93317	42.75	7.75	55.18317	12.25	4.504748	33.71658	21.46658	0.180513
230	575	360	0.36	0.06	6	12.848221	44.74878	99.74878	42.25	7.25	57.49878	12.75	4.509708	35.1244	22.3744	0.162012
240	600	380	0.38	0.063333	6.333333	12.894948	46.52986	101.5299	41.75	6.75	59.77986	13.25	4.511687	36.51493	23.26493	0.145068
250	625	400	0.4	0.066667	6.666667	12.941001	48.29611	103.2961	41.25	6.25	62.04611	13.75	4.512444	37.89806	24.14806	0.12941
260	650	425	0.425	0.070833	7.083333	12.999033	50.00372	105.0037	40.75	5.75	64.25372	14.25	4.509033	39.25186	25.00186	0.114991
270	675	450	0.45	0.075	7.5	13.057587	51.69408	106.6941	40	5	66.69408	15	4.446272	40.84704	25.84704	0.096723
280	700	475	0.475	0.079167	7.916667	13.116671	53.3672	108.3672	39.5	4.5	68.8672	15.5	4.443046	42.1836	26.6836	0.084321
290	725	500	0.5	0.083333	8.333333	13.176282	55.02307	110.0231	39	4	71.02307	16	4.438942	43.51153	27.51153	0.072697
300	750	525	0.525	0.0875	8.75	13.236456	56.66188	111.6617	38.25	3.25	73.41188	16.75	4.382787	45.08094	28.33094	0.057358
310	775	550	0.55	0.091667	9.166667	13.297178	58.28306	113.2831	37.75	2.75	75.53306	17.25	4.378728	46.39153	29.14153	0.047184
320	800	575	0.575	0.095833	9.583333	13.358453	59.88717	114.8872	37.25	2.25	77.63717	17.75	4.373925	47.69358	29.94358	0.037571
330	825	600	0.6	0.1	10	13.420290	61.47406	116.474	36.5	1.5	79.97406	18.5	4.322921	49.23702	30.73702	0.024401
340	850	628	0.628	0.104667	10.46667	13.480247	63.00848	118.0085	36	1	82.00848	19	4.316236	50.50424	31.50424	0.015871
350	875	650	0.65	0.108333	10.83333	13.545721	64.59604	119.596	35.5	0.5	84.09604	19.5	4.312618	51.79802	32.29802	0.00774
360	900	675	0.675	0.1125	11.25	13.609316	66.13117	121.1312	34.75	-0.25	86.38117	20.25	4.265737	53.31558	33.06558	-0.00378
370	925	705	0.705	0.1175	11.75	13.686423	67.58562	122.5856	34.25	-0.75	88.33562	20.75	4.257139	54.54281	33.79281	-0.0111
380	950	725	0.725	0.120833	12.08333	13.738314	69.14968	124.1497	33.75	-1.25	90.39968	21.25	4.254102	55.82484	34.57484	-0.01808
390	975	750	0.75	0.125	12.5	13.803736	70.63306	125.6331	33.25	-1.75	92.38306	21.75	4.247497	57.06653	35.31653	-0.02478
400	1000	775	0.775	0.129167	12.91667	13.869781	72.09919	127.0992	32.75	-2.25	94.34919	22.25	4.240413	58.2996	36.0496	-0.03121
410	1025	800	0.8	0.133333	13.33333	13.936463	73.54807	128.5481	32.25	-2.75	96.29807	22.75	4.232882	59.52404	36.77404	-0.03739
420	1050	828	0.828	0.138	13.8	14.011912	74.93624	129.9362	31.75	-3.25	98.18624	23.25	4.223064	60.71812	37.46812	-0.04337
430	1075	850	0.85	0.141667	14.16667	14.071788	76.39409	131.3941	31.25	-3.75	100.1441	23.75	4.216593	61.94705	38.19705	-0.04909
440	1100	875	0.875	0.145833	14.58333	14.140411	77.79123	132.7912	30.75	-4.25	102.0412	24.25	4.207886	63.14562	38.89562	-0.05463
450	1125	905	0.905	0.150833	15.08333	14.223672	79.0936	134.0936	30.25	-4.75	103.8436	24.75	4.195701	64.2968	39.5468	-0.06006
460	1150	930	0.93	0.155	15.5	14.293808	80.45442	135.4544	29.75	-5.25	105.7044	25.25	4.186314	65.47721	40.22721	-0.06525
470	1175	975	0.975	0.1625	16.25	14.421812	81.47381	136.4738	29.25	-5.75	107.2238	25.75	4.164031	66.4869	40.7369	-0.07057
465	1162.5	1015	1.015	0.169167	16.91667	14.537534	79.96542	134.9654	28.75	-6.25	106.2154	26.25	4.046302	66.23271	39.98271	-0.07816
460	1150	1065	1.065	0.1775	17.75	14.684824	78.31214	133.3121	28	-7	105.3121	27	3.90045	66.15607	39.15607	-0.08939
455	1137.5	1110	1.11	0.185	18.5	14.810061	76.75458	131.7546	27.5	-7.5	104.2546	27.5	3.791076	65.87729	38.37729	-0.09771
450	1125	1140	1.14	0.19	19	14.911442	75.44542	130.4454	27	-8	103.4454	28	3.694479	65.72271	37.72271	-0.10604
445	1112.5	1190	1.19	0.198333	19.83333	15.066446	73.83957	128.8396	26.5	-8.5	102.3396	28.5	3.590862	65.41979	36.91979	-0.11511
440	1100	1235	1.235	0.205833	20.58333	15.208732	72.32687	127.3269	26	-9	101.3269	29	3.49403	65.16344	36.16344	-0.12444

CU TEST - EXPERIMENT 1

SAMPLE 3 - COAL REFUSE
Sigma3= 69 psi
u= 39 psi
Sig 3'= 30 psi
Del V = 34 cc
November 3, 1993

Load div	Load P lbs	Strain div	Strain in	Strain E	Strain %	11.911308 Acc=11.91	Deviator =P/Acc	Sigma 1	Pore pres psi	mod. pp	Sig1'	Sig3'	Sig1'/sig3'	p'	q	A
0	0	0	0	0		11.911308	0	69	39	0	30	30	1	30	0	0
20	50	10	0.01	0.001667	0.166667	11.931193	4.190696	73.1907	39.25	0.25	33.9407	29.75	1.140864	31.84535	2.095348	0.059656
40	100	35	0.035	0.005833	0.583333	11.981198	8.346411	77.34641	39.75	0.75	37.59641	29.25	1.285347	33.42321	4.173205	0.089859
60	150	55	0.055	0.009167	0.916667	12.021506	12.47764	81.47764	40.25	1.25	41.22764	28.75	1.434005	34.98882	6.23882	0.100179
80	200	78	0.078	0.013	1.3	12.068194	16.57249	85.57249	40.75	1.75	44.82249	28.25	1.586637	36.53624	8.286244	0.105597
100	250	100	0.1	0.016667	1.666667	12.113194	20.63865	89.63865	41	2	48.63865	28	1.737095	38.31933	10.31933	0.096906
120	300	121	0.121	0.020167	2.016667	12.156463	24.67823	93.67823	41.5	2.5	52.17823	27.5	1.89739	39.83912	12.33912	0.101304
140	350	143	0.143	0.023833	2.383333	12.202126	28.68353	97.68353	42.5	3.5	55.18353	26.5	2.082397	40.84176	14.34176	0.122021
160	400	165	0.165	0.0275	2.75	12.248131	32.65804	101.658	43.5	4.5	58.15804	25.5	2.280708	41.82902	16.32902	0.137791
180	450	185	0.185	0.030833	3.083333	12.290257	36.61437	105.6144	44.75	5.75	60.86437	24.25	2.509871	42.55718	18.30718	0.157042
200	500	205	0.205	0.034167	3.416667	12.332674	40.54271	109.5427	46	7	63.54271	23	2.762726	43.27136	20.27136	0.172657
220	550	226	0.226	0.037667	3.766667	12.377528	44.43537	113.4354	47	8	66.43537	22	3.019789	44.21768	22.21768	0.180037
240	600	247	0.247	0.041167	4.116667	12.422708	48.29864	117.2986	48.25	9.25	69.04864	20.75	3.327646	44.89932	24.14932	0.191517
260	650	270	0.27	0.045	4.5	12.472574	52.11434	121.1143	50.5	11.5	70.61434	18.5	3.816992	44.55717	26.05717	0.220669
280	700	290	0.29	0.048333	4.833333	12.51626	55.92725	124.9272	50.75	11.75	74.17725	18.25	4.064507	46.21362	27.96362	0.210094
300	750	315	0.315	0.0525	5.25	12.571301	59.6597	128.6597	51	12	77.6597	18	4.314428	47.82985	29.82985	0.201141
315	787.5	330	0.33	0.055	5.5	12.604558	62.4774	131.4774	50	11	81.4774	19	4.288284	50.2387	31.2387	0.176064
330	825	346	0.346	0.057667	5.766667	12.640226	65.26781	134.2678	49.25	10.25	85.01781	19.75	4.304699	52.38391	32.63391	0.157046
345	862.5	359	0.359	0.059833	5.983333	12.669358	68.07764	137.0776	48.5	9.5	88.57764	20.5	4.320861	54.53882	34.03882	0.139547
360	900	371	0.371	0.061833	6.183333	12.696366	70.88642	139.8864	47.75	8.75	92.13642	21.25	4.335832	56.69321	35.44321	0.123437
375	937.5	385	0.385	0.064167	6.416667	12.728023	73.65636	142.6564	47	8	95.65636	22	4.348017	58.82818	36.82818	0.108612
390	975	400	0.4	0.066667	6.666667	12.762115	76.39798	145.398	46	7	99.39798	23	4.321652	61.19899	38.19899	0.091625
405	1012.5	412	0.412	0.068667	6.866667	12.789522	79.16637	148.1664	45.25	6.25	102.1664	23.75	4.301742	62.95819	39.20819	0.078948
420	1050	428	0.428	0.071333	7.133333	12.826247	81.86339	150.8634	44.25	5.25	105.6134	24.75	4.267208	65.18169	40.43169	0.064131
435	1087.5	440	0.44	0.073333	7.333333	12.853929	84.60448	153.6045	43.25	4.25	109.3545	25.75	4.246776	67.55224	41.80224	0.050234
450	1125	456	0.456	0.076	7.6	12.891026	87.27001	156.27	42.5	3.5	113.02	26.5	4.264906	69.76001	43.26001	0.040105
465	1162.5	471	0.471	0.0785	7.85	12.925999	89.93502	158.935	41.75	2.75	116.435	27.25	4.272846	71.84251	44.59251	0.030578
480	1200	485	0.485	0.080833	8.083333	12.958812	92.60106	161.6011	41	2	119.8511	28	4.280396	73.92554	45.92554	0.021598
495	1237.5	502	0.502	0.083667	8.366667	12.998881	95.2005	164.2005	40	1	123.2005	29	4.248293	76.10025	47.10025	0.010504
510	1275	517	0.517	0.086167	8.616667	13.034442	97.81776	166.8178	39.5	0.5	126.8178	29.5	4.298907	78.15888	48.65888	0.005112
525	1312.5	532	0.532	0.088667	8.866667	13.070189	100.4193	169.4193	38.5	-0.5	129.9193	30.5	4.259649	80.20964	49.70964	-0.00498
540	1350	547	0.547	0.091167	9.116667	13.106152	103.0051	172.0051	38.75	-0.25	133.5051	30.25	4.413391	81.87753	51.62753	-0.00243
555	1387.5	562	0.562	0.093667	9.366667	13.142303	105.5751	174.5751	37.25	-1.75	135.8251	31.75	4.277956	83.78756	52.03756	-0.01658
570	1425	577	0.577	0.096167	9.616667	13.178456	108.1294	177.1294	36.5	-2.5	139.8794	32.5	4.303981	86.1897	53.6897	-0.02312
585	1462.5	592	0.592	0.098667	9.866667	13.215208	110.6679	179.6679	36	-3	143.1679	33	4.338423	88.08397	55.08397	-0.02711
600	1500	605	0.605	0.100833	10.08333	13.247052	113.2327	182.2327	35.5	-3.5	146.2327	33.5	4.365156	89.86637	56.36637	-0.03091
615	1537.5	617	0.617	0.102833	10.28333	13.276583	115.8054	184.8054	34.75	-4.25	149.3054	34.25	4.359282	91.7777	57.5277	-0.0367
630	1575	635	0.635	0.105833	10.58333	13.321127	118.2332	187.2332	34.25	-4.75	152.4832	34.75	4.388007	93.61662	58.86662	-0.04017
645	1612.5	650	0.65	0.108333	10.83333	13.358476	120.7099	189.7099	33.5	-5.5	155.4599	35.5	4.379151	95.47994	59.97994	-0.04556
660	1650	662	0.662	0.110333	11.03333	13.388506	123.24	192.24	32.75	-6.25	158.74	36.25	4.379035	97.49502	61.24502	-0.05071
675	1687.5	675	0.675	0.1125	11.25	13.421192	125.734	194.734	32.5	-6.5	161.984	36.5	4.437918	99.242	62.742	-0.0517
690	1725	700	0.7	0.116667	11.66667	13.484499	127.9247	196.9247	31.75	-7.25	164.4247	37.25	4.414086	100.8373	63.58733	-0.05667
705	1762.5	725	0.725	0.120833	12.08333	13.548407	130.0891	199.0891	31	-8	167.3391	38	4.40366	102.6696	64.66956	-0.0615
720	1800	750	0.75	0.125	12.5	13.612923	132.2273	201.2273	30.5	-8.5	170.2273	38.5	4.421488	104.3636	65.86365	-0.06428
735	1837.5	775	0.775	0.129167	12.91667	13.678057	134.3393	203.3393	30	-9	172.8393	39	4.431776	105.9196	66.91963	-0.06699
750	1875	800	0.8	0.133333	13.33333	13.743817	136.425	205.425	29.5	-9.5	175.425	39.5	4.441139	107.4625	67.96249	-0.06964
765	1912.5	830	0.83	0.138333	13.83333	13.823568	138.3507	207.3507	29	-10	177.8507	40	4.446267	108.9253	68.92534	-0.07228
780	1950	858	0.858	0.143	14.3	13.898842	140.2995	209.2995	28.5	-10.5	180.2995	40.5	4.451838	110.3997	69.89973	-0.07484
795	1987.5	900	0.9	0.15	15	14.013303	141.8295	210.8295	28	-11	182.3295	41	4.447061	111.6648	70.66476	-0.07756
810	2025	940	0.94	0.156667	15.66667	14.12408	143.3722	212.3722	27.5	-11.5	184.3722	41.5	4.442703	112.9361	71.43608	-0.08021
825	2062.5	977	0.977	0.162833	16.28333	14.22812	144.9594	213.9594	27	-12	186.4594	42	4.43951	114.2297	72.22971	-0.08278
840	2100	1020	1.02	0.17	17	14.350973	146.3315	215.3315	26.5	-12.5	188.3315	42.5	4.43133	115.4158	72.91577	-0.08542
850	2125	1060	1.06	0.176667	17.66667	14.467175	146.8842	215.8842	26.25	-12.75	189.3842	42.75	4.430041	116.0671	73.31712	-0.0868
845	2112.5	1097	1.097	0.182833	18.28333	14.57635	144.9265	213.9265	25.75	-13.25	187.6765	43.25	4.339342	115.4633	72.21327	-0.09143
840	2100	1140	1.14	0.19	19	14.705318	142.8055	211.8055	25.5	-13.5	186.0555	43.5	4.277137	114.7777	71.27774	-0.09453
835	2087.5	1178	1.178	0.196333	19.63333	14.821204	140.8456	209.8456	25.25	-13.75	184.3456	43.75	4.213612	114.0478	70.29775	-0.09762
830	2075	1230	1.23	0.205	20.5	14.982777	138.4924	207.4924	25	-14	182.2424	44	4.141872	113.1212	69.12118	-0.10109
825	2062.5	1275	1.275	0.2125	21.25	15.12547	136.3594	205.3594	24.75	-14.25	180.3594	44.25	4.075918	112.4297	67.9297	-0.1045
820	2050	1320	1.32	0.22	22	15.270907	134.2422	203.2422	24.5	-14.5	178.4922	44.5	4.01106	89.24609	89.24609	-0.10801

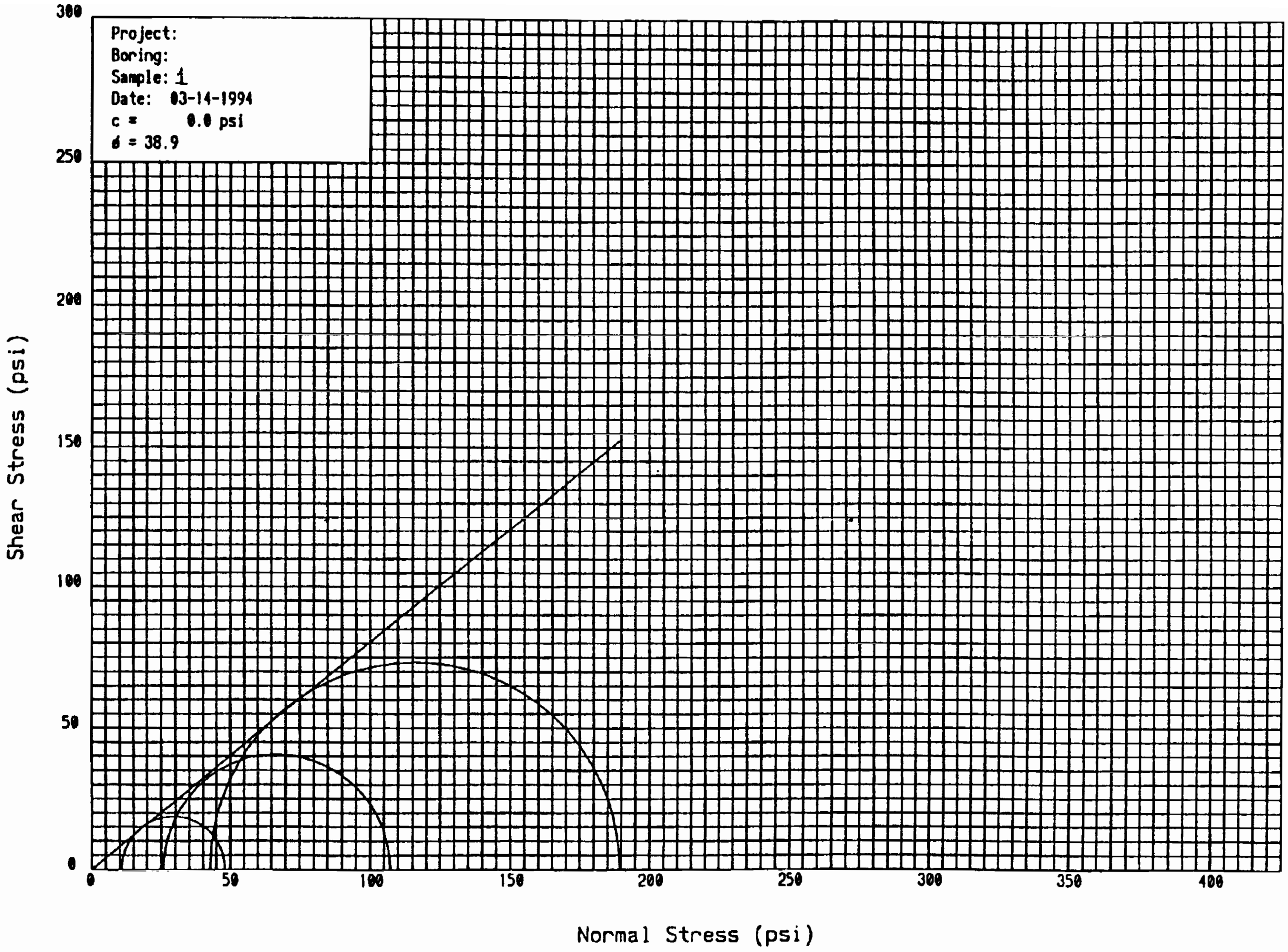


Figure C1. Mohr Circle Data for Sample 1

CU TEST - EXPERIMENT 2

SAMPLE 1 - COAL REFUSE + 0% FA

sigma 3= 45 psi
u= 35
sig. 3' =10 psi
Consolidating vol (delta V) = 40 ml

Load div	Load P lbs	Strain div	Strain in	Strain E	Ac=12.22 12.22616	Deviator =P/Acc	Sigma 1	Pore pres psi	mod. pp	Sig1'	Sig3'	Sig1'/sig3	p'	q	A
0	0	0	0	0	12.2262	0	45	35	0	10	10	1	10	0	0
20	50	12	0.012	0.002	12.2507	4.08141	49.0814	35.5	0.5	13.5814	9.5	1.42962	11.5407	2.0407	0.12251
40	100	35	0.035	0.00583	12.2979	8.13147	53.1315	36	1	17.1315	9	1.9035	13.0657	4.06573	0.12298
60	150	58	0.058	0.00967	12.3455	12.1502	57.1502	36.5	1.5	20.6502	8.5	2.42943	14.5751	6.07508	0.12346
80	200	100	0.1	0.01667	12.4334	16.0857	61.0857	38.25	3.25	22.8357	6.75	3.38307	14.7929	8.04286	0.20204
100	250	150	0.15	0.025	12.5397	19.9367	64.9367	39	4	25.9367	6	4.32278	15.9684	9.96837	0.20063
115	287.5	180	0.18	0.03	12.6043	22.8097	67.8097	38	3	29.8097	7	4.25853	18.4048	11.4048	0.13152
130	325	209	0.209	0.03483	12.6674	25.6564	70.6564	37.25	2.25	33.4064	7.75	4.3105	20.5782	12.8282	0.0877
145	362.5	255	0.255	0.0425	12.7688	28.3894	73.3894	36.25	1.25	37.1394	8.75	4.2445	22.9447	14.1947	0.04403
160	400	305	0.305	0.05083	12.8809	31.0536	76.0536	35.5	0.5	40.5536	9.5	4.2688	25.0268	15.5268	0.0161
175	437.5	350	0.35	0.05833	12.9835	33.6966	78.6966	34.75	-0.25	43.9466	10.25	4.28748	27.0983	16.8483	-0.00742
185	462.5	405	0.405	0.0675	13.1112	35.2753	80.2753	34.25	-0.75	46.0253	10.75	4.28142	28.3876	17.6376	-0.02126
195	487.5	460	0.46	0.07667	13.2413	36.8166	81.8166	33.75	-1.25	48.0666	11.25	4.27259	29.6583	18.4083	-0.03395
205	512.5	542	0.542	0.09033	13.4403	38.1317	83.1317	33.25	-1.75	49.8817	11.75	4.24525	30.8158	19.0658	-0.04589
200	500	690	0.69	0.115	13.8149	36.1928	81.1928	32.25	-2.75	48.9428	12.75	3.83865	30.8464	18.0964	-0.07598
195	487.5	760	0.76	0.12667	13.9994	34.8228	79.8228	31.75	-3.25	48.0728	13.25	3.62814	30.6614	17.4114	-0.09333
190	475	840	0.84	0.14	14.2165	33.4119	78.4119	31.25	-3.75	47.1619	13.75	3.42996	30.456	16.706	-0.11224
185	462.5	925	0.925	0.15417	14.4546	31.9968	76.9968	30.75	-4.25	46.2468	14.25	3.24539	30.2484	15.9984	-0.13283
180	450	1030	1.03	0.17167	14.76	30.4878	75.4878	30	-5	45.4878	15	3.03252	30.2439	15.2439	-0.164
175	437.5	1135	1.135	0.18917	15.0786	29.0148	74.0148	29.5	-5.5	44.5148	15.5	2.87192	30.0074	14.5074	-0.18956

SAMPLE 2 - COAL REFUSE + 0% FA

Sigma 3=50 psi
u= 30 psi
Sigma 3' = 20 psi
Delta V =60 ml

Load div	Load P lbs	Strain div	Strain in	Strain E	Ac=12.14 12.14878	Deviator =P/Acc	Sigma 1	Pore pres psi	mod. pp	Sig1'	Sig3'	Sig1'/sig3	p'	q	A
0	0	0	0	0	12.1488	0	50	30	0	20	20	1	20	0	0
25	62.5	10	0.01	0.00167	12.1701	5.13553	55.1355	30.5	0.5	24.6355	19.5	1.26336	22.0678	2.56777	0.09736
50	125	28	0.028	0.00467	12.2089	10.2384	60.2384	31.75	1.75	28.4884	18.25	1.56101	23.3692	5.1192	0.17093
75	187.5	52	0.052	0.00867	12.255	15.2999	65.2999	32.75	2.75	32.5499	17.25	1.88695	24.8999	7.64995	0.17974
100	250	75	0.075	0.0125	12.3036	20.3193	70.3193	33.5	3.5	36.8193	16.5	2.23147	26.6597	10.1597	0.17225
120	300	93	0.093	0.0155	12.3411	24.3081	74.3081	34.5	4.5	39.8081	15.5	2.56826	27.6541	12.1541	0.18512
140	350	123	0.123	0.0205	12.4041	28.2166	78.2166	35.75	5.75	42.4666	14.25	2.98011	28.3583	14.1083	0.20378
160	400	148	0.148	0.02467	12.4571	32.1103	82.1103	38.5	8.5	43.6103	11.5	3.7922	27.5551	16.0551	0.26471
180	450	180	0.18	0.03	12.5256	35.9266	85.9266	39	9	46.9266	11	4.26605	28.9633	17.9633	0.25051
200	500	205	0.205	0.03417	12.5786	39.7468	89.7468	37.75	7.75	51.9968	12.25	4.24464	32.1234	19.8734	0.19498
220	550	233	0.233	0.03883	12.6407	43.5103	93.5103	36.5	6.5	57.0103	13.5	4.22298	35.2552	21.7552	0.14939
240	600	265	0.265	0.04417	12.7112	47.2024	97.2024	35.25	5.25	61.9524	14.75	4.20017	38.3512	23.6012	0.11122
260	650	300	0.3	0.05	12.7892	50.824	100.824	34.25	4.25	66.574	15.75	4.22692	41.162	25.412	0.08362
280	700	337	0.337	0.05617	12.8728	54.3781	104.378	33.25	3.25	71.1281	16.75	4.24646	43.9391	27.1891	0.05977
300	750	375	0.375	0.0625	12.96	57.8713	107.871	32	2	75.8713	18	4.21507	46.9357	28.9357	0.03456
315	787.5	420	0.42	0.07	13.0643	60.2788	110.279	31.25	1.25	79.0288	18.75	4.21487	48.8894	30.1394	0.02074
330	825	459	0.459	0.0765	13.1563	62.7078	112.708	30.5	0.5	82.2078	19.5	4.21579	50.8539	31.3539	0.00797
345	862.5	505	0.505	0.08417	13.2664	65.014	115.014	29.75	-0.25	85.264	20.25	4.21057	52.757	32.507	-0.00385
360	900	547	0.547	0.09117	13.3686	67.3221	117.322	29	-1	88.3221	21	4.20582	54.6611	33.6611	-0.01485
375	937.5	598	0.598	0.09967	13.4948	69.4713	119.471	28	-2	91.4713	22	4.15779	56.7357	34.7357	-0.02879
390	975	654	0.654	0.109	13.6361	71.5012	121.501	27	-3	94.5012	23	4.10875	58.7506	35.7506	-0.04196
380	950	710	0.71	0.11833	13.7806	68.9381	118.938	26	-4	92.9381	24	3.87242	58.469	34.469	-0.05802
370	925	765	0.765	0.1275	13.9253	66.426	116.426	25	-5	91.426	25	3.65704	58.213	33.213	-0.07527
360	900	823	0.823	0.13717	14.0813	63.9147	113.915	24	-6	89.9147	26	3.45826	57.9573	31.9573	-0.09388
355	887.5	890	0.89	0.14833	14.2659	62.2113	112.211	22.75	-7.25	89.4613	27.25	3.28298	58.3556	31.1056	-0.11654
350	875	963	0.963	0.1605	14.4727	60.4588	110.459	21.5	-8.5	88.9588	28.5	3.12136	58.7294	30.2294	-0.14059

SAMPLE 3 - COAL REFUSE + 0% FA

Sigma 3 = 50 psi
u=20 psi
Sigma 3' = 30 psi

Load div	Load P lbs	Strain div	Strain in	Strain E	Ac=12.00 12.00560	Deviator =P/Acc	Sigma 1	Pore pres psi	mod. pp	Sig1'	Sig3'	Sig1'/sig3	p'	q	A
0	0	0	0	0	12.0056	0	50	20	0	30	30	1	30	0	0
40	100	18	0.018	0.003	12.0417	8.30446	58.3045	21	1	37.3045	29	1.28636	33.1522	4.15223	0.12042
80	200	42	0.042	0.007	12.0902	16.5423	66.5423	22.5	2.5	44.0423	27.5	1.60154	35.7711	8.27114	0.15113
120	300	65	0.065	0.01083	12.1371	24.7178	74.7178	24.5	4.5	50.2178	25.5	1.96932	37.8589	12.3589	0.18206
160	400	98	0.098	0.01633	12.2048	32.7736	82.7736	28.5	8.5	54.2736	21.5	2.52435	37.8868	16.3868	0.25936
200	500	130	0.13	0.02167	12.2716	40.7448	90.7448	31	11	59.7448	19	3.14447	39.3724	20.3724	0.26997
240	600	163	0.163	0.02717	12.3409	48.618	98.618	32.25	12.25	66.368	17.75	3.7391	42.059	24.309	0.25196
280	700	205	0.205	0.03417	12.4303	56.314	106.314	33.25	13.25	73.064	16.75	4.36203	44.907	28.157	0.23529
310	775	235	0.235	0.03917	12.495	62.0248	112.025	32.25	12.25	79.7748	17.75	4.49436	48.7624	31.0124	0.1975
340	850	275	0.275	0.04583	12.5823	67.5553	117.555	30.5	10.5	87.0553	19.5	4.46437	53.2777	33.7777	0.15543
370	925	317	0.317	0.05283	12.6753	72.9767	122.977	29	9	93.9767	21	4.47508	57.4884	36.4884	0.12333
400	1000	360	0.36	0.06	12.7719	78.2968	128.297	27.5	7.5	100.797	22.5	4.47986	61.6484	39.1484	0.09579
430	1075	400	0.4	0.06667	12.8631	83.5721	133.572	25.75	5.75	107.822	24.25	4.44627	66.0361	41.7861	0.0688
460	1150	443	0.443	0.07383	12.9627	88.7163	138.716	24	4	114.716	26	4.41216	70.3581	44.3581	0.04509
490	1225	488	0.488	0.08133	13.0686	93.7368	143.737	22.5	2.5	121.237	27.5	4.40861	74.3684	46.8684	0.02667
520	1300	535	0.535	0.08917	13.1808	98.6278	148.628	20.5	0.5	128.128	29.5	4.34331	78.8138	49.3138	0.00507
550	1375	588	0.588	0.098	13.31	103.306	153.306	18.25	-1.75	135.056	31.75	4.25373	83.403	51.653	-0.01694
580	1450	637	0.637	0.10617	13.4316	107.955	157.955	16.5	-3.5	141.455	33.5	4.22253	87.4773	53.9773	-0.03242
610	1525	690	0.69	0.115	13.5656	112.418	162.418	14.5	-5.5	147.918	35.5	4.16672	91.7092	56.2092	-0.04892
600	1500	756	0.756	0.126	13.7364	109.199	159.199	12.25	-7.75	146.949	37.75	3.89269	92.3495	54.5995	-0.07097
590	1475	822	0.822	0.137	13.9115	106.028	156.028	9.5	-10.5	146.528	40.5	3.61797	93.5139	53.0139	-0.09903
580	1450	895	0.895	0.14917	14.1104	102.761	152.761	7.25	-12.75	145.511	42.75	3.40377	94.1306	51.3806	-0.12407
570	1425	970	0.97	0.16167	14.3208	99.5057	149.506	5.5	-14.5	144.006	44.5	3.23608	94.2528	49.7528	-0.14572
565	1412.5	1048	1.048	0.17467	14.5464	97.1033	147.103	4.25	-15.75	142.853	45.75	3.12248	94.3017	48.5517	-0.1622
560	1400	1135	1.135	0.18917	14.8066	94.5531	144.553	3.75	-16.25	140.803	46.25	3.04439	93.5266	47.2766	-0.17186

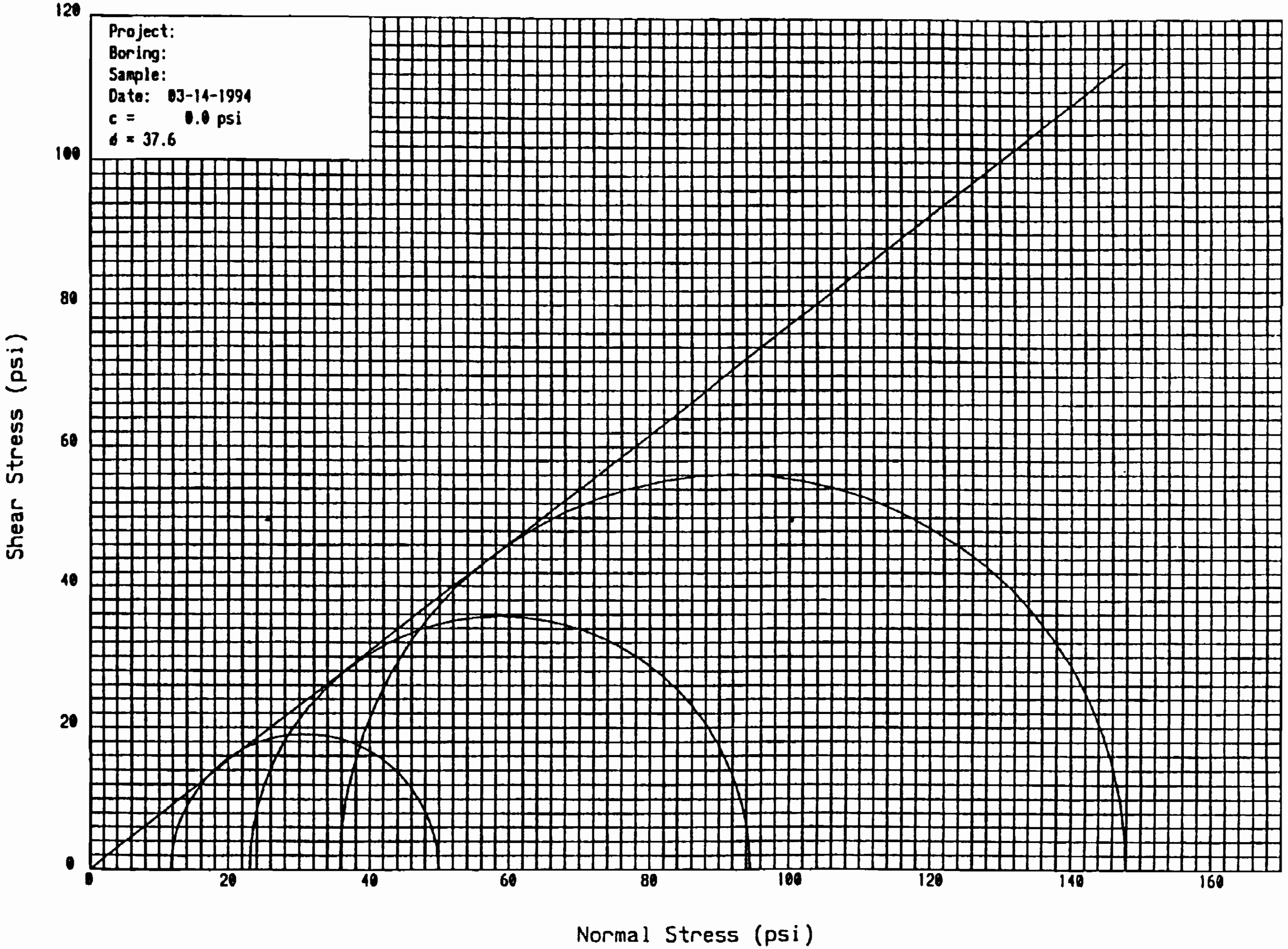


Figure C2. Mohr Circle Data for Sample 2

CU TEST - EXPERIMENT 3

SAMPLE 1- COAL REFUSE + 10% FA
Sigma 3 = 45 psi
u = 35 psi
Sigma 3' = 10 psi
Delta V = 46 ml

Load div	Load P lbs	Strain div	Strain in	Strain E	Strain %	Ac=12.23 12.2331V	Deviator =P/Acc	Sigma 1 psf	Pore pres psi	mod. pp psi	Sig1' psf	Sig3' psf	Sig1'/sig3'	p'	q	A
0	0	0	0	0	0	12.23311	0	45	35	0	10	10	1	10	0	0
20	50	3	0.003	0.0005	0.05	12.23923	4.085224	49.08522	35.75	0.75	13.33522	9.25	1.441646	11.29261	2.042612	0.183588
40	100	8	0.008	0.001333	0.133333	12.24944	8.163637	53.16364	36.5	1.5	16.66364	8.5	1.960428	12.58182	4.081818	0.183742
60	150	15	0.015	0.0025	0.25	12.26377	12.23115	57.23115	37	2	20.23115	8	2.528894	14.11557	6.115575	0.163517
70	175	24	0.024	0.004	0.4	12.28224	14.24822	59.24822	37.5	2.5	21.74822	7.5	2.899762	14.62411	7.124108	0.175461
80	200	40	0.04	0.006667	0.666667	12.31521	16.24008	61.24008	39	4	22.24008	6	3.70668	14.12004	8.120038	0.246304
90	225	62	0.062	0.010333	1.033333	12.36084	18.20265	63.20265	39.25	4.25	23.95265	5.75	4.165678	14.85132	9.101324	0.233483
100	250	85	0.085	0.014167	1.416667	12.4089	20.14683	65.14683	38.75	3.75	26.39683	6.25	4.223492	16.32341	10.07341	0.186134
110	275	107	0.107	0.017833	1.783333	12.45523	22.07908	67.07908	38.25	3.25	28.82908	6.75	4.270975	17.78954	11.03954	0.147198
120	300	135	0.135	0.0225	2.25	12.51469	23.97183	68.97183	37.5	2.5	31.47183	7.5	4.196244	19.48591	11.98591	0.104289
130	325	167	0.167	0.027833	2.783333	12.58336	25.82778	70.82778	36.75	1.75	34.07778	8.25	4.130641	21.16389	12.91389	0.067756
140	350	205	0.205	0.034167	3.416667	12.66586	27.63334	72.63334	36.25	1.25	36.38334	8.75	4.158096	22.56667	13.81667	0.045236
150	375	250	0.25	0.041667	4.166667	12.76498	29.37724	74.37724	35.5	0.5	38.87724	9.5	4.092341	24.18862	14.68862	0.01702
160	400	298	0.298	0.049667	4.966667	12.87244	31.07414	76.07414	35	0	41.07414	10	4.107414	25.53707	15.53707	0
170	425	340	0.34	0.056667	5.666667	12.96796	32.77308	77.77308	34.5	-0.5	43.27308	10.5	4.121246	26.88654	16.38654	-0.01526
180	450	385	0.385	0.064167	6.416667	13.07189	34.42502	79.42502	34	-1	45.42502	11	4.129547	28.21251	17.21251	-0.02905
190	475	432	0.432	0.072	7.2	13.18223	36.03336	81.03336	33.5	-1.5	47.53336	11.5	4.133336	29.51668	18.01668	-0.04163
195	487.5	475	0.475	0.079167	7.916667	13.28483	36.696	81.696	33	-2	48.696	12	4.058	30.348	18.348	-0.0545
192	480	530	0.53	0.088333	8.833333	13.4184	35.77177	80.77177	32.5	-2.5	48.27177	12.5	3.861742	30.38589	17.88589	-0.06989
190	475	595	0.595	0.099167	9.916667	13.57977	34.9785	79.9785	32	-3	47.9785	13	3.690654	30.48925	17.48925	-0.08577
185	462.5	663	0.663	0.1105	11.05	13.75279	33.62953	78.62953	31.5	-3.5	47.12953	13.5	3.491076	30.31477	16.81477	-0.10408
180	450	738	0.738	0.123	12.3	13.94881	32.26081	77.26081	31	-4	46.26081	14	3.304343	30.1304	16.1304	-0.12399
175	437.5	810	0.81	0.135	13.5	14.14232	30.93551	75.93551	30.5	-4.5	45.43551	14.5	3.133483	29.96776	15.46776	-0.14546

SAMPLE 2 - COAL REFUSE + 10% FA
Sigma 3= 50 psi
u=30 psi
sigma3'=20 psi
Delta V = 56 ml

Load div	Load P lbs	Strain div	Strain in	Strain E	Strain %	Ac=12.16 12.16368	Deviator =P/Acc	Sigma 1 psf	Pore pres psi	mod. pp psi	Sig1' psf	Sig3' psf	Sig1'/sig3'	p'	q	A
0	0	0	0	0		12.16368	0	50	30	0	20	20	1	20	0	0
25	62.5	9	0.009	0.0015	0.15	12.18196	5.13054	55.13054	30.5	0.5	24.63054	19.5	1.263106	22.06527	2.56527	0.097456
50	125	20	0.02	0.003333	0.333333	12.20436	10.24224	60.24224	31	1	29.24224	19	1.539065	24.12112	5.12112	0.097636
75	187.5	43	0.043	0.007167	0.716667	12.25148	15.30427	65.30427	32.25	2.25	33.05427	17.75	1.862212	25.40213	7.652136	0.147018
100	250	70	0.07	0.011667	1.166667	12.30727	20.3132	70.3132	34.25	4.25	36.0632	15.75	2.289727	25.9066	10.1566	0.209224
120	300	100	0.1	0.016667	1.666667	12.36985	24.25253	74.25253	36	6	38.25253	14	2.732323	26.12626	12.12626	0.247397
140	350	120	0.12	0.02	2	12.41192	28.1987	78.1987	38.25	8.25	39.9487	11.75	3.399889	25.84936	14.09936	0.292567
160	400	145	0.145	0.024167	2.416667	12.46492	32.09007	82.09007	39.5	9.5	42.59007	10.5	4.056197	26.54503	16.04503	0.296042
180	450	179	0.179	0.029833	2.983333	12.53772	35.89168	85.89168	38.75	8.75	47.14168	11.25	4.190372	29.19584	17.94584	0.243788
200	500	205	0.205	0.034167	3.416667	12.59399	39.70152	89.70152	37.5	7.5	52.20152	12.5	4.176122	32.35076	19.85076	0.18891
220	550	230	0.23	0.038333	3.833333	12.64854	43.48327	93.48327	36.25	6.25	57.23327	13.75	4.16242	35.49164	21.74164	0.143733
240	600	250	0.25	0.041667	4.166667	12.69254	47.27187	97.27187	35	5	62.27187	15	4.151458	38.63594	23.63594	0.105771
260	650	270	0.27	0.045	4.5	12.73684	51.03307	101.0331	34	4	67.03307	16	4.189567	41.51654	25.51654	0.078381
275	687.5	290	0.29	0.048333	4.833333	12.78146	53.78888	103.7889	33	3	70.78888	17	4.164052	43.89444	26.89444	0.055774
290	725	309	0.309	0.0515	5.15	12.82412	56.53408	106.5341	32.25	2.25	74.28408	17.75	4.185019	46.01704	28.26704	0.039799
300	750	330	0.33	0.055	5.5	12.87162	58.26772	108.2677	31.75	1.75	76.51772	18.25	4.192752	47.38386	29.13386	0.030034
320	800	350	0.35	0.058333	5.833333	12.91718	61.93301	111.933	30.5	0.5	81.43301	19.5	4.176052	50.4665	30.9665	0.008073
330	825	368	0.368	0.061333	6.133333	12.95847	63.66494	113.6649	30	0	83.66494	20	4.183247	51.83247	31.83247	0
340	850	390	0.39	0.065	6.5	13.00928	65.33796	115.338	29.25	-0.75	86.08796	20.75	4.148817	53.41898	32.66898	-0.01148
350	875	409	0.409	0.068167	6.816667	13.05349	67.03186	117.0319	28.75	-1.25	88.28186	21.25	4.15444	54.76593	33.51593	-0.01865
360	900	430	0.43	0.071667	7.166667	13.10271	68.68809	118.6881	28.25	-1.75	90.43809	21.75	4.158073	56.09404	34.34404	-0.02548
370	925	448	0.448	0.074667	7.466667	13.14519	70.36795	120.368	27.5	-2.5	92.86795	22.5	4.127465	57.68398	35.18398	-0.03553
380	950	482	0.482	0.080333	8.033333	13.22618	71.82722	121.8272	26.75	-3.25	95.07722	23.25	4.089343	59.16361	35.91361	-0.04525
390	975	528	0.528	0.088	8.8	13.33737	73.10287	123.1029	26	-4	97.10287	24	4.045953	60.55144	36.55144	-0.05472
385	962.5	575	0.575	0.095833	9.583333	13.45292	71.54581	121.5458	25.25	-4.75	96.29581	24.75	3.89074	60.52291	35.77291	-0.06639
380	950	635	0.635	0.105833	10.58333	13.60337	69.83563	119.8356	24.5	-5.5	95.33563	25.5	3.738652	60.41782	34.91782	-0.07876
375	937.5	700	0.7	0.116667	11.66667	13.7702	68.08178	118.0818	23.75	-6.25	94.33178	26.25	3.593591	60.29089	34.04089	-0.0918
370	925	765	0.765	0.1275	12.75	13.94118	66.35019	116.3502	23	-7	93.35019	27	3.457414	60.17509	33.17509	-0.1055
365	912.5	833	0.833	0.138833	13.88333	14.12465	64.60335	114.6034	22.25	-7.75	92.35335	27.75	3.328049	60.05168	32.30168	-0.11996
360	900	895	0.895	0.149167	14.91667	14.2962	62.9536	112.9536	21.5	-8.5	91.4536	28.5	3.208898	59.9768	31.4768	-0.13502
355	887.5	972	0.972	0.162	16.2	14.51513	61.14309	111.1431	20.75	-9.25	90.39309	29.25	3.090362	59.82154	30.57154	-0.15128
350	875	1050	1.05	0.175	17.5	14.74386	59.34676	109.3468	20	-10	89.34676	30	2.978225	59.67338	29.67338	-0.1685
345	862.5	1135	1.135	0.189167	18.91667	15.00146	57.49442	107.4944	19.25	-10.75	88.24442	30.75	2.869737	59.49721	28.74721	-0.18697
340	850	1225	1.225	0.204167	20.41667	15.28421	55.61296	105.613	18.5	-11.5	87.11296	31.5	2.765491	59.30648	27.80648	-0.20679

SAMPLE 3 - COAL REFUSE + 10% FA
Sigma 3=50 psi
u = 20 psi
Sigma 3' = 30 psi
Delta V = 77 ml

Load div	Load P lbs	Strain div	Strain in	Strain E	Strain %	Ac=12.03 12.03176	Deviator =P/Ace	Sigma 1 psi	Pore pres psi	mod. pp psi	Sig1' psi	Sig3' psi	Sig1'/sig3'	p'	q	A
0	0	0	0	0	0	12.03177	0	50	20	0	30	30	1	30	0	0
30	75	10	0.01	0.001667	0.166667	12.05185	6.22311	56.22311	20.5	0.5	35.72311	29.5	1.210953	32.61155	3.111555	0.080346
60	150	25	0.025	0.004167	0.416667	12.08211	12.41506	62.41506	22	2	40.41506	28	1.443395	34.20753	6.207528	0.161096
85	212.5	42	0.042	0.007	0.7	12.11656	17.53795	67.53795	24	4	43.53795	26	1.674537	34.76897	8.768975	0.228077
110	275	60	0.06	0.01	1	12.1533	22.6276	72.6276	26	6	46.6276	24	1.942817	35.3138	11.3138	0.265163
135	337.5	80	0.08	0.013333	1.333333	12.19436	27.67674	77.67674	28	8	49.67674	22	2.258033	35.83837	13.83837	0.289051
160	400	102	0.102	0.017	1.7	12.23984	32.68016	82.68016	29.5	9.5	53.18016	20.5	2.594154	36.84008	16.34008	0.290696
185	462.5	120	0.12	0.02	2	12.27731	37.67111	87.67111	30.75	10.75	56.92111	19.25	2.956941	38.08556	18.83556	0.285365
210	525	142	0.142	0.023667	2.366667	12.32342	42.60181	92.60181	31.75	11.75	60.85181	18.25	3.334346	39.5509	21.3009	0.27581
235	587.5	165	0.165	0.0275	2.75	12.372	47.48626	97.48626	32	12	65.48626	18	3.638126	41.74314	23.74314	0.252705
260	650	187	0.187	0.031167	3.116667	12.41882	52.33992	102.3399	32.75	12.75	69.58992	17.25	4.034198	43.41996	26.16996	0.2436
285	712.5	210	0.21	0.035	3.5	12.46815	57.1456	107.1456	31.5	11.5	75.6456	18.5	4.088951	47.0728	28.5728	0.20124
310	775	230	0.23	0.038333	3.833333	12.51137	61.94368	111.9437	30	10	81.94368	20	4.097183	50.97183	30.97183	0.161437
335	837.5	250	0.25	0.041667	4.166667	12.55489	66.7071	116.7071	28.5	8.5	88.2071	21.5	4.102656	54.85355	33.35355	0.127423
360	900	270	0.27	0.045	4.5	12.59871	71.4359	121.4359	27	7	94.4359	23	4.105908	58.71795	35.71795	0.09799
385	962.5	290	0.29	0.048333	4.833333	12.64284	76.13007	126.1301	25.5	5.5	100.6301	24.5	4.10735	62.56503	38.06503	0.072246
410	1025	310	0.31	0.051667	5.166667	12.68728	80.78961	130.7896	24	4	106.7896	26	4.107293	66.3948	40.3948	0.049511
435	1087.5	328	0.328	0.054667	5.466667	12.72754	85.44465	135.4446	22.5	2.5	112.9446	27.5	4.107078	70.22232	42.72232	0.029259
460	1150	355	0.355	0.059167	5.916667	12.78841	89.92515	139.9251	21	1	118.9251	29	4.100867	73.96257	44.96257	0.01112
480	1200	370	0.37	0.061667	6.166667	12.82249	93.5856	143.5856	19.75	-0.25	123.8356	30.25	4.093739	77.0428	46.7928	-0.00267
500	1250	400	0.4	0.066667	6.666667	12.89118	96.96554	146.9655	18.75	-1.25	128.2155	31.25	4.102897	79.73277	48.48277	-0.01289
520	1300	430	0.43	0.071667	7.166667	12.96061	100.3039	150.3039	17.5	-2.5	132.8039	32.5	4.086274	82.65195	50.15195	-0.02492
535	1337.5	460	0.46	0.076667	7.666667	13.03079	102.6415	152.6415	16.75	-3.25	135.8915	33.25	4.086962	84.57074	51.32074	-0.03166
550	1375	495	0.495	0.0825	8.25	13.11364	104.8526	154.8526	15.75	-4.25	139.1026	34.25	4.061391	86.67632	52.42632	-0.04053
560	1400	530	0.53	0.088333	8.833333	13.19756	106.0803	156.0803	15	-5	141.0803	35	4.030866	88.04015	53.04015	-0.04713
570	1425	560	0.56	0.093333	9.333333	13.27033	107.3824	157.3824	14.25	-5.75	143.1324	35.75	4.003704	89.4412	53.6912	-0.05355
565	1412.5	595	0.595	0.099167	9.916667	13.35626	105.7556	155.7556	13.25	-6.75	142.5056	36.75	3.877704	89.62782	52.87782	-0.06383
560	1400	635	0.635	0.105833	10.58333	13.45584	104.044	154.044	12	-8	142.044	38	3.738001	90.02201	52.02201	-0.07689
555	1387.5	689	0.689	0.114833	11.48333	13.59266	102.0772	152.0772	11	-9	141.0772	39	3.617364	90.03859	51.03859	-0.08817
550	1375	737	0.737	0.122833	12.28333	13.71662	100.2433	150.2433	10	-10	140.2433	40	3.506083	90.12166	50.12166	-0.09976
545	1362.5	785	0.785	0.130833	13.08333	13.84288	98.42608	148.4261	9	-11	139.4261	41	3.400636	90.21304	49.21304	-0.11176
540	1350	837	0.837	0.1395	13.95	13.9823	96.55066	146.5507	8	-12	138.5507	42	3.298825	90.27533	48.27533	-0.12429
535	1337.5	889	0.889	0.148167	14.81667	14.12455	94.69325	144.6933	7	-13	137.6933	43	3.202169	90.34663	47.34663	-0.13729
530	1325	940	0.94	0.156667	15.66667	14.26692	92.87221	142.8722	6	-14	136.8722	44	3.110732	90.4361	46.4361	-0.15074
525	1312.5	995	0.995	0.165833	16.58333	14.4237	90.9961	140.9961	5	-15	135.9961	45	3.022135	90.49805	45.49805	-0.16484
520	1300	1057	1.057	0.176167	17.61667	14.60461	89.01298	139.013	4.25	-15.75	134.763	45.75	2.945638	90.25649	44.50649	-0.17694
515	1287.5	1125	1.125	0.1875	18.75	14.80833	86.94432	136.9443	3.75	-16.25	133.1943	46.25	2.879877	89.72216	43.47216	-0.1869

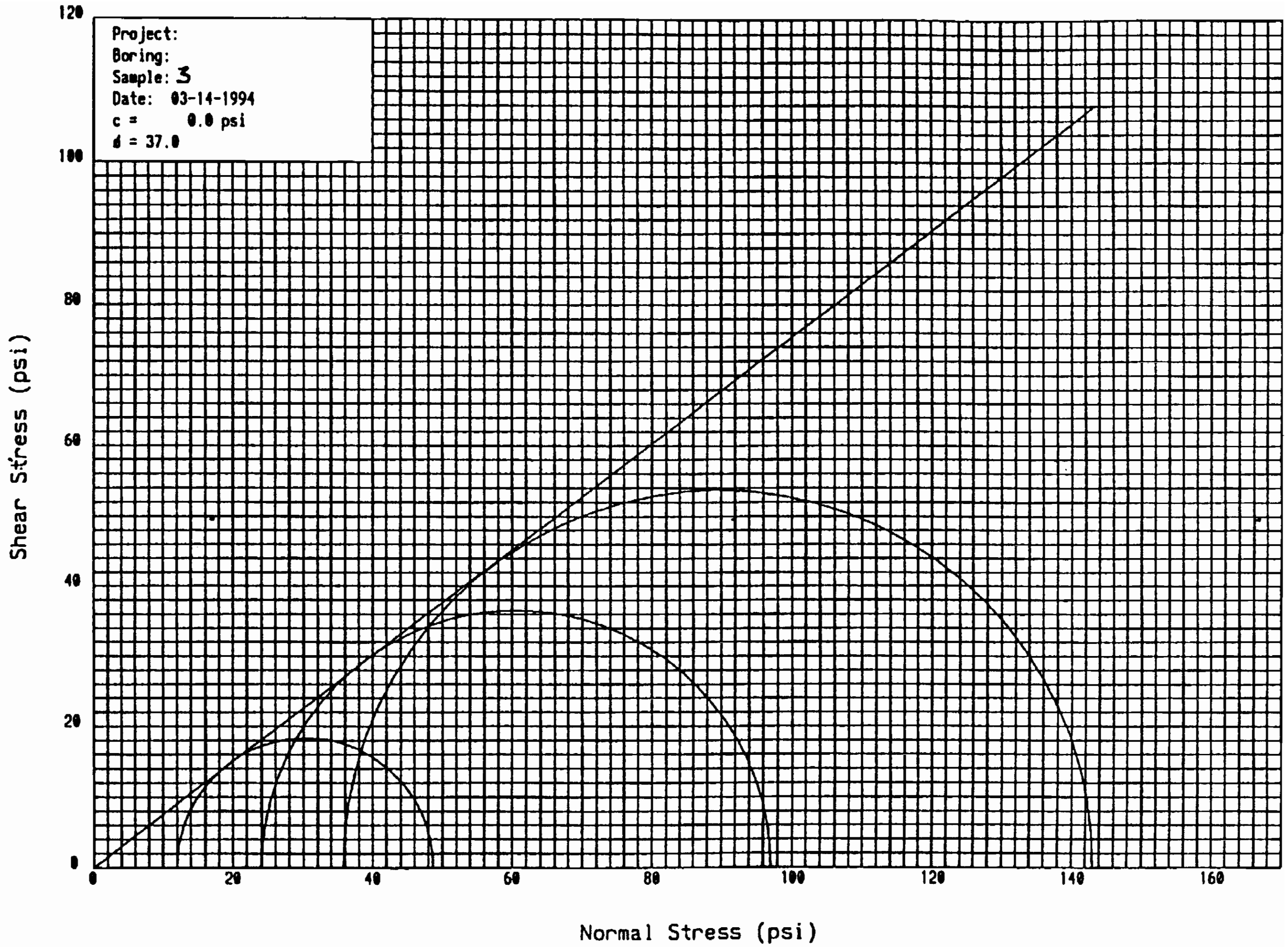


Figure C3. Mohr Circle Data for Sample 3

CU TEST - EXPERIMENT 4

SAMPLE 1 - COAL REFUSE + 30% FA
Sigma 3 = 40 psi
u = 30 psi
Sig. 3' = 10 psi
Delta V = 41 ml

Load div	Load P lbs	Strain div	Strain in	Strain E	Strain %	Ac=12.20 12.20171	Deviator =P/Ac	Sigma 1 psf	Pore pres psi	mod. pp psi	Sig1' psf	Sig3' psf	Sig1'/Sig3'	p' psf	q psf	A
0	0	0	0	0	0	12.20171	0	40	30	0	10	10	1	10	0	0
25	62.5	18	0.018	0.003	0.3	12.31867	5.073691	45.0736	30.75	0.75	14.3236	9.25	1.548497	11.7868	2.5368	0.147824
50	125	50	0.05	0.008333	0.833333	12.30482	10.15892	50.15892	34	4	16.15892	6	2.693153	11.07946	5.07946	0.393817
75	190	80	0.08	0.013333	1.333333	12.44708	15.26308	55.26308	35	5	20.26308	5	4.052770	12.63154	7.631544	0.327671
95	237.5	125	0.125	0.020833	2.083333	12.54362	18.93463	58.93463	33.75	3.75	25.18463	6.25	4.029572	15.71741	9.467414	0.198048
110	275	170	0.17	0.028333	2.833333	12.55904	21.7568	61.7568	32.75	2.75	29.0068	7.25	4.000911	18.1283	10.8783	0.126398
125	312.5	215	0.215	0.035833	3.583333	12.73816	24.53288	64.53288	31.75	1.75	32.78288	8.25	3.973646	20.51628	12.26628	0.071334
140	350	265	0.265	0.044167	4.416667	12.84922	27.23901	67.23901	30.75	0.75	36.48901	9.25	3.944758	22.86951	13.61951	0.027534
155	387.5	310	0.31	0.051667	5.166667	12.95084	29.92084	69.92084	30	0	39.92084	10	3.992084	24.96042	14.96042	0
170	425	360	0.36	0.06	6	13.06686	32.52604	72.52604	29.25	-0.75	43.27604	10.75	4.025664	27.01302	16.26302	-0.02306
185	462.5	440	0.44	0.073333	7.333333	13.25364	34.89606	74.89606	28.5	-1.5	46.39606	11.5	4.03444	28.94803	17.44803	-0.04298
180	450	515	0.515	0.085833	8.583333	13.43467	33.49483	73.49483	27.5	-2.5	45.99483	12.5	3.679586	29.24742	16.74742	-0.07464
175	437.5	610	0.61	0.101667	10.16667	13.67186	32.0006	72.0006	26.5	-3.5	45.5006	13.5	3.370407	29.50026	16.00026	-0.10937
170	425	680	0.68	0.113333	11.33333	13.86156	30.66240	70.66240	26	-4	44.66240	14	3.191606	29.33124	15.33124	-0.13057
165	412.5	725	0.725	0.120833	12.08333	13.96972	29.52816	69.52816	25.5	-4.5	44.02816	14.5	3.036424	29.26408	14.76408	-0.1524
160	400	770	0.770	0.128333	12.83333	14.1118	28.34667	68.34667	25	-5	43.34667	15	2.889711	29.17334	14.17334	-0.17638
155	387.5	845	0.845	0.140833	14.08333	14.29491	27.10786	67.10786	24.5	-5.5	42.60786	15.5	2.748894	29.05393	13.55393	-0.2029
150	375	915	0.915	0.1525	15.25	14.49108	25.87808	65.87808	24	-6	41.87808	16	2.617380	28.93904	12.93904	-0.23187
		985	0.985	0.164167	16.41667	14.59807			23.5	-6.5						

SAMPLE 2 - COAL REFUSE + 30% FA
Sigma 3 = 50 psi
u = 30 psi
Sig. 3' = 20 psi
Delta V= 63 ml

Load div	Load P lbs	Strain div	Strain in	Strain E	Strain %	Ac=12.19 12.19836	Deviator =P/Ac	Sigma 1 psf	Pore pres psi	mod. pp psi	Sig1' psf	Sig3' psf	Sig1'/Sig3'	p' psf	q psf	A
0	0	0	0	0	0	12.1984	0	50	30	0	20	20	1	20	0	0
25	62.5	7	0.007	0.001167	0.116667	12.21264	5.117647	55.11765	30.5	0.5	24.61765	19.5	1.262443	22.05882	2.558823	0.097701
50	125	18	0.018	0.003	0.3	12.2351	10.21661	60.21661	31.25	1.25	28.96661	18.75	1.54488	23.85831	5.108306	0.122361
75	187.5	48	0.048	0.008	0.8	12.29836	15.2684	65.2684	32.75	2.75	32.5184	17.25	1.885128	24.8842	7.6342	0.180111
100	250	68	0.068	0.011333	1.133333	12.33823	20.26223	70.26223	34.25	4.25	36.01223	15.75	2.286491	25.88111	10.13111	0.20976
125	312.5	95	0.095	0.015833	1.583333	12.39464	25.2126	75.2126	35.75	5.75	39.4626	14.25	2.769298	26.8563	12.6063	0.228061
150	375	119	0.119	0.019833	1.983333	12.44523	30.13204	80.13204	37.75	7.75	42.38204	12.25	3.459756	27.31602	15.06602	0.257201
174	435	140	0.14	0.023333	2.333333	12.48963	34.82936	84.82936	38.5	8.5	46.32936	11.5	4.028862	28.91468	17.41468	0.244046
200	500	160	0.16	0.026667	2.666667	12.5326	39.89616	89.89616	36.75	6.75	53.14616	13.25	4.011016	33.19808	19.94808	0.16919
225	562.5	185	0.185	0.030833	3.083333	12.58648	44.69081	94.69081	35	5	59.69081	15	3.979388	37.34541	22.34541	0.11188
250	625	210	0.21	0.035	3.5	12.64082	49.44298	99.44298	33.5	3.5	65.94298	16.5	3.996544	41.22149	24.72149	0.070789
275	687.5	243	0.243	0.0405	4.05	12.71329	54.07729	104.0773	31.75	1.75	72.32729	18.25	3.963139	45.28865	27.03865	0.032361
300	750	270	0.27	0.045	4.5	12.77319	58.71674	108.7167	30.25	0.25	78.46674	19.75	3.972999	49.10837	29.35837	0.004258
325	812.5	302	0.302	0.050333	5.033333	12.84492	63.25446	113.2546	28.75	-1.25	84.50446	21.25	3.976666	52.87728	31.62728	-0.01976
350	875	336	0.336	0.056	5.6	12.91176	67.72678	117.7268	27.75	-2.25	89.97678	22.25	4.043866	56.11339	33.86339	-0.03322
375	937.5	377	0.377	0.062833	6.283333	13.01626	72.02636	122.0264	26.75	-3.25	95.27636	23.25	4.097908	59.26318	36.01318	-0.04512
395	987.5	430	0.43	0.071667	7.166667	13.1401	75.15162	125.1516	25.75	-4.25	99.40162	24.25	4.099036	61.82581	37.57581	-0.05655
405	1012.5	485	0.485	0.080833	8.083333	13.27116	76.29333	126.2933	24.75	-5.25	101.5433	25.25	4.021516	63.39666	38.14666	-0.06881
395	987.5	543	0.543	0.0905	9.05	13.4122	73.627	123.627	23.75	-6.25	99.877	26.25	3.804838	63.0635	36.8135	-0.08489
385	962.5	605	0.605	0.100833	10.08333	13.56633	70.94708	120.9471	22.75	-7.25	98.19708	27.25	3.603563	62.72354	35.47354	-0.10219
375	937.5	663	0.663	0.1105	11.05	13.71377	68.36196	118.362	21.75	-8.25	96.61196	28.25	3.419892	62.43098	34.18098	-0.12068
365	912.5	740	0.74	0.123333	12.33333	13.91482	65.57898	115.579	20.75	-9.25	94.82898	29.25	3.242016	62.03949	32.78949	-0.14105
355	887.5	812	0.812	0.135333	13.53333	14.10763	62.90823	112.9082	19.75	-10.25	93.15823	30.25	3.079644	61.70411	31.45411	-0.16293
350	875	890	0.89	0.148333	14.83333	14.32297	61.09068	111.0907	18.75	-11.25	92.34068	31.25	2.954902	61.79534	30.54534	-0.18416

SAMPLE 3 - COAL REFUSE + 30% FA
Sigma 3 = 60 psi
u = 30 psi
Sig. 3' = 30 psi

Load div	Load P lbs	Strain div	Strain in	Strain E	Strain %	Ac=12.12 12.12066	Deviator =P/Ac	Sigma 1 psf	Pore pres psi	mod. pp psi	Sig1' psf	Sig3' psf	Sig1'/Sig3'	p' psf	q psf	A
0	0	0	0	0	0	12.12067	0	60	30	0	30	30	1	30	0	0
25	62.5	8	0.008	0.001333	0.133333	12.14516	5.146083	65.14608	31	1	34.14608	29	1.177451	31.57304	2.573041	0.194325
50	125	25	0.025	0.004167	0.416667	12.17172	10.26207	70.26207	32.5	2.5	37.76207	27.5	1.373189	32.63104	5.131035	0.243616
75	187.5	45	0.045	0.0075	0.75	12.22062	15.34292	75.34292	33.5	3.5	41.84292	26.5	1.578978	34.17146	7.671460	0.228116
100	250	70	0.07	0.011667	1.166667	12.27214	20.37134	80.37134	35	5	45.37134	25	1.814854	35.18567	10.18567	0.245443
125	312.5	95	0.095	0.015833	1.583333	12.3241	25.35662	85.35662	35.75	5.75	49.60662	24.25	2.045634	36.92831	12.67831	0.226761
150	375	115	0.115	0.019167	1.916667	12.36588	30.32613	90.32613	37.75	7.75	52.57613	22.25	2.362927	37.41306	15.16306	0.255564
175	437.5	130	0.13	0.021667	2.166667	12.39788	35.28914	95.28914	38.75	8.75	56.53914	21.25	2.660665	38.89457	17.64457	0.247952
200	500	156	0.156	0.026	2.6	12.44387	40.18304	100.1830	40.25	10.25	59.93304	19.75	3.034584	39.84152	20.09152	0.255015
225	562.5	175	0.175	0.029167	2.916667	12.49336	45.02393	105.0239	43	13	62.02393	17	3.648466	39.51196	22.51196	0.288736
250	625	204	0.204	0.034	3.4	12.55587	49.77753	109.7775	43.5	13.5	66.27753	16.5	4.01682	41.38876	24.88876	0.271207
275	687.5	225	0.225	0.0375	3.75	12.60162	54.55692	114.5569	42	12	72.55692	18	4.030940	45.27846	27.27846	0.219952
300	750	250	0.25	0.041667	4.166667	12.65631	59.25898	119.259	40.5	10.5	78.75898	19.5	4.038921	49.12949	29.62949	0.177189
325	812.5	275	0.275	0.045833	4.583333	12.71188	63.91009	123.9101	39	9	84.91009	21	4.043338	52.95505	31.95505	0.140826
350	875	300	0.3	0.05	5	12.76733	68.53428	128.5343	37.5	7.5	91.03428	22.5	4.045968	56.76714	34.26714	0.109434
375	937.5	325	0.325	0.054167	5.416667	12.82360	73.10762	133.1076	36	6	97.10762	24	4.046151	60.55381	36.55381	0.082071
400	1000	345	0.345	0.0575	5.75	12.86063	77.75664	137.7566	34.5	4.5	103.2566	25.5	4.049278	64.37832	38.87832	0.05787
415	1037.5	370	0.37	0.061667	6.166667	12.92607	80.26412	140.2641	33.5	3.5	106.7641	26.5	4.028836	66.63206	40.13206	0.043606
430	1075	395	0.395	0.065833	6.583333	12.98373	82.79604	142.796	32.5	2.5	110.296	27.5	4.010761	68.89802	41.39802	0.030196
445	1112.5	415	0.415	0.069167	6.916667	13.03122	85.37042	145.3704	31.75	1.75	113.6204	28.25	4.022846	70.93521	42.68521	0.020497
460	1150	435	0.435	0.0725	7.25	13.07708	87.94030	147.9403	31	1	116.9403	29	4.032424	72.97016	43.97016	0.011371
475	1187.5	465	0.465	0.0775	7.75	13.14893	90.31036	150.3104	30	0	120.3104	30	4.010345	75.15518	45.15518	0
490	1225	495	0.495	0.0825	8.25	13.21968	92.66559	152.6656	29.25	-0.75	123.4156	30.75	4.013514	77.08279	46.33279	-0.00809
505	1262.5	515	0.515	0.085833	8.583333	13.26779	95.15628	155.1563	28.5	-1.5	126.6563	31.5	4.020836	79.07815	47.57815	-0.01576
520	1300	545	0.545	0.090833	9.083333	13.34078	97.44578	157.4458	27.75	-2.25	129.6958	32.25	4.021575	80.97289	48.72289	-0.02309
515	1287.5	585	0.585	0.0975	9.75	13.4303	95.88113	155.8811	26.5	-3.5	129.3811	33.5	3.862123	81.44057	47.94057	-0.03650
510	1275	620	0.62	0.103333	10.33333	13.52673	94.25782	154.2578	25.5	-4.5	128.7578	34.5	3.732111	81.62891	47.12891	-0.04774
495	1237.5	662	0.662	0.110333	11.03333	13.63316	90.77133	150.7713	24.25	-5.75	126.5213	35.75	3.539060	81.13567	45.38567	-0.06335
490	1225	703	0.703	0.117167	11.71667	13.73868	89.1643	149.1643	23.25	-6.75	125.9143	36.75	3.426230	81.33216	44.58216	-0.0757
485	1212.5	745	0.745	0.124167	12.41667	13.84048	87.56469	147.5647	22	-8	125.5647	38	3.304334	81.78234	43.78234	-0.09137
480	1200	793	0.793	0.132167	13.21667	13.97616	85.86057	145.8606	20.75	-9.25	125.1106	39.25	3.18753	82.18028	42.93028	-0.10773
475	1187.5	835	0.835	0.139167	13.91667	14.0898	84.28084	144.2808	19.5	-10.5	124.7808	40.5	3.081009	82.64042	42.14042	-0.12458
470	1175	880	0.88	0.146667	14.66667	14.21363	82.66711	142.6671	18.25	-11.75	124.4171	41.75	2.980061	83.08356	41.33356	-0.14214
465	1162.5	932	0.932	0.155333	15.53333	14.35775	80.96702	140.967	17	-13	123.967	43	2.882953	83.48351	40.48351	-0.16056
460	1150	985	0.985	0.164167	16.41667	14.51123	79.24898	139.249	15.75	-14.25	123.499	44.25	2.790938	83.87449	39.62449	-0.17981
455	1137.5	1041	1.041	0.1735	17.35	14.6751	77.51227	137.5123	14.5	-15.5	123.0123	45.5	2.703566	84.25613	38.75613	-0.19997
450	1125	1100	1.1	0.183333	18.33333	14.8416	75.74041	135.7404	13.25	-16.75	122.4904	46.75	2.620087	84.62021	37.87021	-0.22115

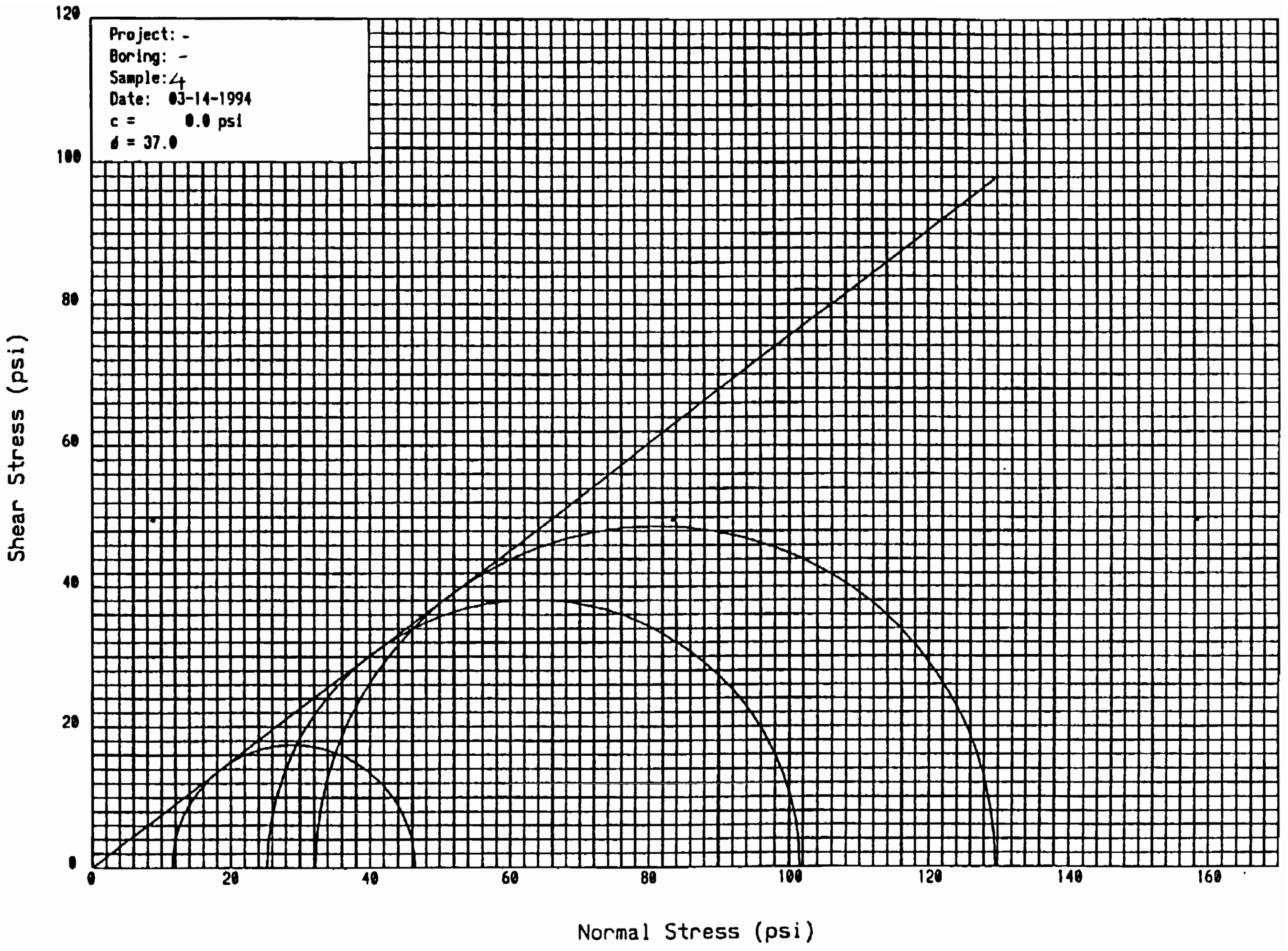


Figure C4. Mohr Circle Data for Sample 4

APPENDIX D
SLOPE STABILITY DATA

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STABGM   Version  9.85 (MS-DOS)
Slope Stability Analysis of Reinforced Slopes
Bishop's Modified Method  and/or Ordinary Method of Slices


SLOPE STABILITY MODEL FOR COAL REFUSE WITH FLY ASH (30FT DEEP)


                    C O N T R O L   D A T A

      NUMBER OF SPECIFIED CENTERS . . . . . . .. . . . . . . . . . .  0
      NUMBER OF DEPTH LIMITING TANGENTS . . . . . . . . . .   1
      NUMBER OF VERTICAL SECTIONS . . . . . . . . . . . . . . . . . .  6
      NUMBER OF SOIL LAYER BOUNDARIES . . . . . . . . . . . . .  4
       NUMBER OF PORE PRESSURE LINES . . . . . . . . . . . . . . . .  0
      NUMBER OF POINTS DEFINING COHESION PROFILE  .   0
      NUMBER OF REINFORCING LAYERS  . . . . . . . . . . . . . . . . 0
      SEISMIC COEFFICIENTS, S1, S2  . . . . . . . . . . . . . . . . . . . . . ..0  0
      UNIT WEIGHT OF WATER  . . . . . . . . . . . . . . . . . . . . . . . . . 62.40


SEARCH IS BASED ON BISHOP MODIFIED METHOD
SEARCH STARTS AT CENTER (1744.0, -4.0) WITH FINAL GRID OF  8.0
ALL CIRCLES TANGENT TO DEPTH 1150.0

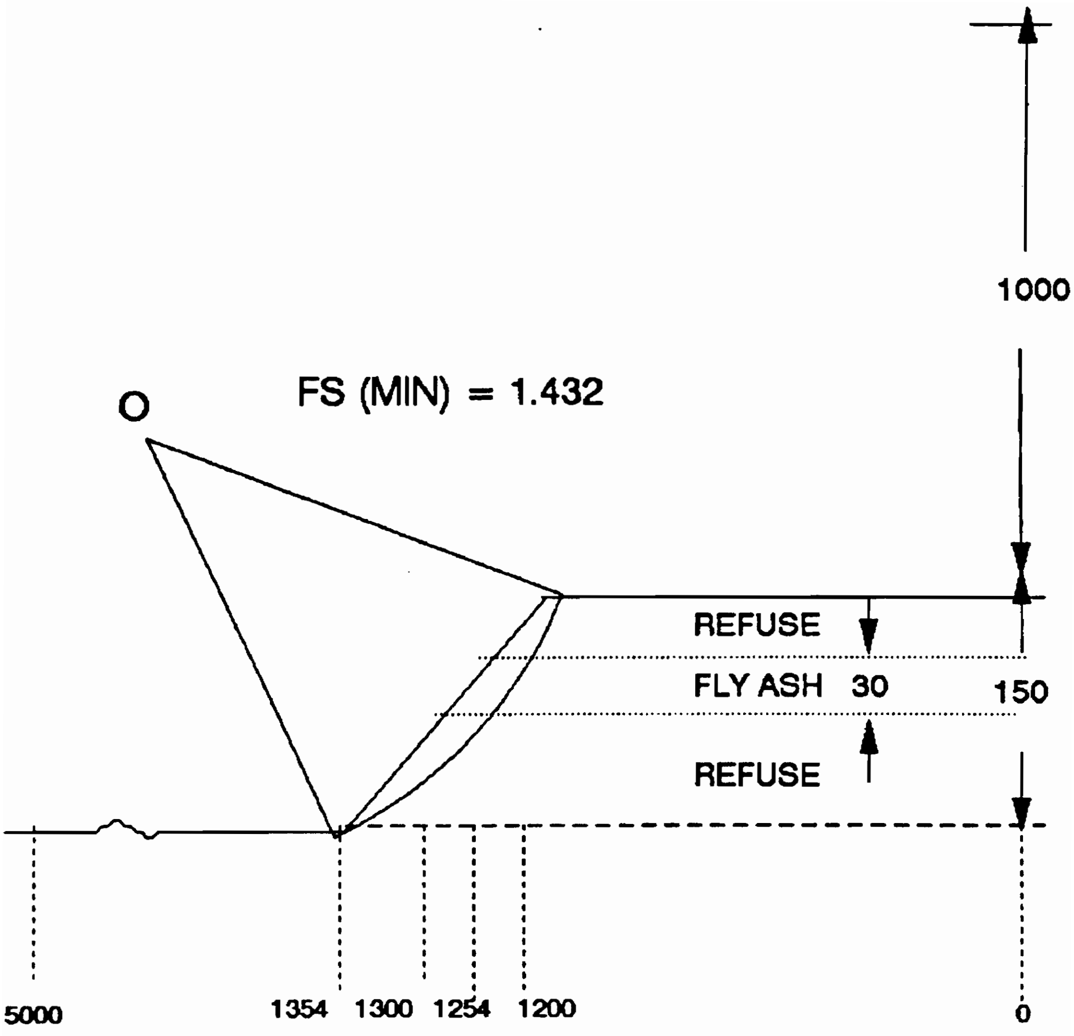

GEOMETRY
SECTIONS           1200.0  1253.9  1300.0  1354.0  5000.0
T. CRACKS         1000.0  1000.0  1060.0  1090.0  1150.0  1150.0
W IN CRACK        1000.0  1000.0  1060.0  1090.0  1150.0  1150.0
BOUNDARY 1        1000.0  1000.0  1060.0  1090.0  1150.0  1150.0
BOUNDARY 2        1060.0  1060.0  1060.0  1090.0  1150.0  1150.0
BOUNDARY 3        1090.0  1090.0  1090.0  1090.0  1150.0  1150.0
BOUNDARY 4        1150.0  1150.0  1150.0  1150.0  1150.0  1150.0


SOIL PROPERTIES
LAYER        COHESION            FRICTION ANGLE          DENSITY
   1               0                      39.0                 118.8
   2               0                      37.0                  80.8
   3               0                      39.0                 118.8
```

SLOPE STABILITY MODEL FOR COAL REFUSE WITH FLY ASH (30 FT DEEP)

N0	TGT	RADIUS	(X) CENTER	(Y) CENTER	FS(BISHOP)	FS(OMS)
1	1150.0	1154.0	1744.0	-4.0	1.512	1.512
2	1150.0	1154.0	1728.0	-4.0	1.567	1.566
3	1150.0	1170.0	1744.0	-20.0	1.538	1.538
4	1150.0	1154.0	1760.0	-4.0	1.459	1.459
5	1150.0	1138.0	1744.0	12.0	1.487	1.486
6	1150.0	1154.0	1752.0	-4.0	1.486	1.485
7	1150.0	1162.0	1760.0	-12.0	1.472	1.472
8	1150.0	1154.0	1768.0	-4.0	1.432	1.432
9	1150.0	1146.0	1760.0	4.0	1.446	1.446
10	1150.0	1162.0	1768.0	-12.0	1.445	1.445
11	1150.0	1162.0	1760.0	-12.0	1.472	1.472
12	1150.0	1146.0	1760.0	4.0	1.446	1.446

F.S. MINIMUM= 1.432 FOR THE CIRCLE OF CENTER (1768.0, -4.0)



NOT TO SCALE

Figure D1. Data Used for STABGM Slope Model

APPENDIX E
INFORMATION ON COAL PREP. PROCESSES

COAL PREPARATION

The following sections (E1 to E5) on various processes occuring in a coal preparation plant are reproduced from Coal Preparation Course-Volume 1 by the South African Coal Processing Society (SACPS, 1977).

E.1 FUNDAMENTAL OPERATIONS

The fundamental operations in coal preparation are sizing, size reduction, cleaning,dewatering and handling. These processes are described in the subsequent sections as follows:

E.1.1 Sizing

Sizing (screening, or grading) is the separation of coal (clean or raw) into different sizes. The term "grading", properly applied, means making a coal between two size limits. Basically, a screen consists of a sieve, either static or moving, over which the material to be sized is passed to obtain oversize and undersize products. Screening is widely employed in coal preparation with each type of screening job having certain screens which are suitable. The uses of screens can be broadly divided into three sections: prescreening; drainage; and classifying. These sections are presented as follows:

E.1.1.1 Prescreening

Prescreening, or primary screening, is carried out on the run-of-mine (ROM) coal for two main reasons: to screen out the very largest sizes in the ROM so that these may be crushed to a size suitable for treatment; and to remove the fine sizes that may not require to be washed at all.

Type of deck

With regard to the type of deck used, for prescreening of large sizes (100mm-75mm) punched plate is frequently used; though some woven wire decks are still in use. For small sizes, punched plate may be used, unless the coal is damp (as most ROM coal is). If the coal is damp then special woven wire types of deck may be employed for sizes under about 10mm.

Wet screening

If prescreening is carried out at fine sizes, say 0,5mm (as in modern plants treating small sizes) then wet screening must be used. In this process, streams of water wash the fine particles through the deck apertures. The solids are recovered from the water at a later stage in the processing. Wet screening may be used at up to 6mm if particularly damp and difficult coal is being screened.

E.1.1.2 Drainage

After coal has been washed it must be freed from the associated washing liquid. This is carried out by passing the coal and liquid from the washer over screens with small aperture (about 0.5mm) decks. The coal is retained and the washing liquid passes through to be re-used.

E.1.1.3 Classification

This is the process whereby the clean coal is separated into the various size grades. If large coal is involved, then jigging screens may be used (see figure1). This is because these screens handle the large coal gently and also convey it to the loading devices with the minimum number of transfer points. Increasingly, however, vibrating screens are used for classification and there are some resonance screen installations. The decks employed on these screens may be perforated plate or woven wire.

E.1.1.4 General

The efficiency of screening is of fundamental importance to efficient preparation of coal for the market. If prescreening should be performed inefficiently and consequently the wrong size of raw coal sent to the washing vessel, the efficiency of washing will be seriously impaired, with perhaps dirt remaining with the clean coal. Equally if the dewatering screens should be faulty, quantities of small coal will be recirculated to the washing vessel, causing inefficient separation of coal from dirt. The most detrimental result of inefficient classifying screening is the production of badly graded coal for the market.

E.2 Size reduction

Size reduction is simply the crushing of pieces that are too large to be mechanically treated, or too large for the market into which the coal is being sold. The term "breaking" is usually applied to size reduction operations on large material (say plus 75 mm) and "crushing" to the size reduction operation carried out on sizes below about 75mm. For size reduction of very small sizes, e.g. treating from about 6mm downwards, the term "grinding" is usually employed. These terms however are only very loosely employed: for example a Jaw Breaker, used on large lumps of stone (though rarely on coal) may be called a jaw crusher. For treating large sizes of coal, double or single roll crushers, or swing hammer crushers, may be employed. Ball or rod mills are used for grinding. A general requirement in breaking and crushing operations is to achieve the size reduction without producing too much fine (say -6mm) material.

E.3 Cleaning

Cleaning is the general name given to the process of removing the unwanted material from the run-of-mine coal. The process can be simple or complex, depending on the nature of the coal, and the market requirements. The extent to which the various washing processes may be used is governed by the washability of the coal. This subject indicates how far the ash content of the coal changes with the relative density of the coal.

E.4 Dewatering

During the washing process, the washed solids, both clean coal and discard, become mixed up with a great deal of water or medium. To separate the solids from the liquids, dewatering techniques are used. These are usually employed in stages, the number and complexity of which depend on the size of coal being treated and the degree to which dewatering is required (i.e. the demands of the market). In its simplest form dewatering consists of a screen, which retains the coals and lets the liquids drain away. This sort of dewatering is usually adequate for coals above about 10mm. For -10mm coals, if further dewatering is required, then a centrifuge, (a sort of industrial scale spin drier) is used, which can reduce the moisture to about 6-7% free moisture. For still further moisture reduction, thermal dryers must be used. Other dewatering techniques include filters, used for the dewatering of suspensions, cyclones, and sieve bends. Thickeners, large tanks in which solids in suspension are given time to settle out, are also a form of dewatering device.

E.5 Handling

The raw coal, as well as the cleaned products and discard, must be transported from the mine to the plant, and from the plant to the market or to the dump. The blending of coal is another aspect cf handling. Either the raw coal may require to be blended, (if it comes from different source) or the cleaned products may require to be blended to ensure that the consumer gets a product that is of uniform consistency.

VITA

Allwyn J. J. de Albuquerque was born on December 7, 1968 in Goa, India to Jose and Ida Albuquerque. All of his primary and secondary school education was completed in Goa, India. In June 1990, he received his Bachelor's in Civil Engineering from the University of Goa where he graduated with top honors. Thereafter, he worked as a Civil Engineer with a consulting firm until December 1991. Subsequently, he came to the United States to pursue a Master's degree in Environmental Engineering from the Virginia Polytechnic Institute and State University.

He was employed by the Department of Crop and Soil Environmental Sciences at VPI & SU from May 1992 to September 1994 as a Graduate Assistant. During this time, he was mainly involved in research pertaining to the geoenvironmental aspects of coal refuse-fly ash blends.

He is a member of the American Society of Civil Engineers, Water Environment Federation and American Society for Surface Mining and Reclamation.

A. Albuquerque.