Final Report for TR-535

Applications for Reuse of Lime Sludge from Water Softening

by Rob J. Baker, J(Hans) van Leeuwen and David J. White
Iowa State University

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Co-sponsors

The City of Ames, the Cedar Rapids Water Department, the Des Moines Water Works, the Newton Water Works, and the West Des Moines Water Works co-funded this project.

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Disclaimer

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TR-535 **EXECUTIVE SUMMARY REPORT ON**

APPLICATIONS FOR REUSE OF LIME SLUDGE FROM WATER SOFTENING

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Lime sludge, an inert material mostly composed of calcium carbonate, is the result of softening hard water for distribution as drinking water. A large city such as Des Moines, Iowa, produces about 30,700 tons of lime sludge (dry weight basis) annually (Jones et al., 2005). Eight Iowa cities representing, according to the U.S. Census Bureau, 23% of the state's population of 3 million, were surveyed. They estimated that they collectively produce 64,470 tons of lime sludge (dry weight basis) per year, and they currently have 371,800 tons (dry weight basis) stockpiled. Recently, the Iowa Department of Natural Resources directed those cities using lime softening in drinking water treatment to stop digging new lagoons to dispose of lime sludge. Five Iowa cities with stockpiles of lime sludge funded this research. The research goal was to find useful and economical alternatives for the use of lime sludge. Feasibility studies tested the efficacy of using lime sludge in cement production, power plant SO_x treatment, dust control on gravel roads, wastewater neutralization, and in-fill materials for road construction. Applications using lime sludge in cement production, power plant SO_x treatment, and wastewater neutralization, and as a fill material for road construction showed positive results, but the dust control application did not.

Since the fill material application showed the most promise in accomplishing the project's goal within the time limits of this research project, it was chosen for further investigation. Lime sludge is classified as inorganic silt with low plasticity. Since it only has an unconfined compressive strength of approximately 110 kPa, mixtures with fly ash and cement were developed to obtain higher strengths. When fly ash was added at a rate of 50% of the dry weight of the lime sludge, the unconfined strength increased to 1600 kPa. Further, friction angles and California Bearing Ratios were higher than those published for soils of the same classification. However, the mixtures do not perform well in durability tests. The mixtures tested did not survive 12 cycles of freezing and thawing and wetting and drying without excessive mass and volume loss. Thus, these mixtures must be placed at depths below the freezing line in the soil profile. The results demonstrated that chemically stabilized lime sludge is able to contribute bulk volume to embankments in road construction projects.

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GENERAL INTRODUCTION

The Problem

Lime softening is the most common method used at water treatment plants in the United States to soften hard water. If the hardness in water is the primary constituent of concern for treatment, then there is no alternative that is more cost effective. Other methods for softening include reverse osmosis, ion exchange, nanofiltration, and electrodialysis (AWWA, 1999). The reagent for lime softening is purchased as unslaked lime (CaO), which is slaked with water to produce a solution of calcium hydroxide ($Ca(OH)_2$). This solution is dosed to the raw water to react with the ions that contribute to hardness. It is a single-ingredient reaction. The softening process produces a residual: lime sludge (mostly $CaCO_3$). From the beginning, since their treatment plants were built, the five Iowa cities that co-funded this research have used lagoons to dispose of the lime sludge they produce. New lagoons were excavated and filled as the need arose. This practice continued for decades, until recently, when the Iowa Department of Natural Resources (DNR) directed that no more new lagoons are to be built. These plants are therefore unable to increase their current level of storage for lime sludge.

Lime sludge could be disposed of in municipal solid waste (MSW) landfills. However, it is safe to assume that MSW landfills would not accept stockpiled lime sludge unless it was dried, because landfills need to minimize the amount of leachate they generate. Furthermore, if lime sludge were sent to a MSW landfill, the water treatment plant disposing of the sludge would need to pay for the costs of drying, loading, and transporting the sludge, plus tipping fees. It makes more sense to find alternative uses for lime sludge in which the consumer pays for the material. Part of solving this problem is processing the lime sludge to meet the consumer’s specifications.

Status of Lime Sludge Production

Table 1 shows the annual lime sludge production and existing stockpiles for some cities in Iowa responding to a March 2005 survey. It also summarizes how the sludge is processed before it is dry enough to be used for the applications discussed herein. The cities of Des Moines and West Des Moines use a filter press to dewater the sludge from a solids concentration of about 3% to a concentration of 50%. The disposal cost for the City of Des Moines is about $600,000 a year paid to a contractor, Kelderman Lime (Jones et al., 2005). The contractor retrieves the dewatered sludge and transports it to another site for further drying in a rotary kiln heated with natural gas. This contractor also transports the sludge produced in West Des Moines and Newton to this site for processing. The processed sludge product is sold as agricultural lime to a developing market of farmers. Since the material is sold to a consumer, the value of the product makes it possible to lower the disposal cost overall.

Table 1: Annual Lime Sludge Production and Existing Stockpiles for Selected Iowa Cities.

City (in Iowa)	Population	Dewatering Method	Drying Method	Dry Weight Produced, tons/y	Dry Weight Stockpiled, tons
Des Moines	400,000	Filter Press	Kiln, Air Dry	30,700	166,000
Cedar Rapids	128,000	Centrifuge, lagoon	Air dry	16,000	10,500
West Des Moines	52,000	Filter Press	Kiln, Air Dry	3600	500
Ames	50,000	Lagoon	Air Dry	5170	79,000
Newton	21,000	Lagoon	Kiln, Air Dry	3500	86,000
Boone	17,000	Lagoon	Air Dry	3300	14,700
Indianola	13,000	Lagoon	Air Dry	600	6000
Pella	9,900	Lagoon	Air Dry	1600	9100
Totals	690,900			64,470	371,800

The next most common sludge dewatering method is use of lagoons to settle the lime sludge and decant the water. The lime sludge from the water treatment clarifiers is transferred by pipe to a dewatering lagoon, e.g. at the plant in Ames. This plant has four operational lagoons, and of the four, three are set up for dewatering. The three dewatering lagoons are capable of decanting the water on top of the sludge (supernatant) to an adjacent wetland area.

The fourth lagoon is a storage lagoon and is not configured to decant. Figures 1, 2, and 3 illustrate the dewatering lagoons in use at the Ames Water Treatment Plant.

When one dewatering lagoon is filled with sludge, the sludge output is discharged into the next available dewatering lagoon. According to the workers of Biosolids Management Group (BMG), the contractor that processes the sludge from the Ames Water Treatment Plant, the sludge is retained in the lagoon for an average 10 months before it is excavated with a backhoe. Once the sludge is excavated from the dewatering lagoon, it can be dried in the sun during the summer in a week or two: the lime sludge is spread in windrows over a concrete pad and turned over as needed until it is dry. This windrow method takes about one week during the warm weather months (see Figure 4), but the length of the drying period depends on air temperature, sun exposure, and humidity.

The storage lagoon has roughly three times the surface area of one decanting lagoon. It was designed for final disposal before the current Iowa DNR policy prohibiting construction of new lime sludge lagoons was implemented. Workers from BMG occasionally empty this lagoon, when they are not working on the decanting lagoons. The fourth lagoon, according to observations over the last year and a half, does not appear to dewater much at all. The only mechanisms available for the storage lagoon to dewater lime sludge are evaporation of water to the air above the lagoon and infiltration of water into the soil beneath lagoon, and neither mechanism appears to dewater the sludge significantly.

According to Scott Adair (2005) at Kelderman Lime, even though Kelderman sells more lime sludge for agricultural purposes each year, they still have more than 100,000 tons (dry weight basis) stockpiled and waiting for use. Drying and selling lime sludge for agricultural lime is a desirable solution to the disposal problem, since the money made by the sale offsets the disposal cost paid by the water treatment plant: if the lime sludge were not sold as a product, no value for the material could be recovered. However, since not all of the lime sludge being produced by the cities funding this research is being sold as agricultural lime, there is a need to find additional uses for lime sludge that result in revenue upon disposal.

Figure 1: Dewatering Lagoon While Filling

Figure 2: Dewatering Lagoon after 3 Months Storage

Figure 3: Dewatering Lagoon after 10 Months Settling

Figure 4: Solar Drying of Sludge in Windrows

The Goal, Research Objectives, and Benefits

The Goal

The goal of this research was to identify alternative uses for water softening lime sludge that would ultimately reduce disposal costs.

Objectives

1. Evaluate the use of lime sludge as a replacement for limestone in the dry scrubbing process to treat SO_x compounds in flue gases of coal burning power plants.
2. Evaluate the use of lime sludge as a replacement for limestone in cement production.
3. Evaluate the use of lime sludge to neutralize acidic wastewater in food processing.
4. Evaluate the use of lime sludge for dust control on gravel roads.
5. Evaluate the engineering properties of lime sludge chemically stabilized with Class C fly ash or portland cement for the application of structural fill material.

Benefits

The practice of lime softening in Iowa is not going to be replaced by another treatment process unless the alternative is less expensive and just as effective, so it is a safe assumption that lime will continue to be used for water softening in the future. The five water treatment plants that co-funded this research hoped to identify alternative uses for lime sludge that would ultimately reduce or eliminate disposal costs. If successful, reduction or elimination of disposal costs will produce a “win” for drinking water customers, who currently bear the cost of sludge disposal. If new uses of lime sludge help the next consumer (i.e., a power plant, a road construction company, a food processing plant, etc.) to save money, a second “win” is accomplished by an Iowa business. A third “win” may be realized when the manufacturer that saved money by using lime sludge passes some of the savings on to the end user of the product. Therefore, developing practical and cost-effective solutions for using lime sludge can help both the people and the businesses of Iowa.

Background and Literature Review

This review provides a summary of previous research, including the scope, major findings, and background information for the specific applications discussed herein. This section is organized into three parts. First, the characteristics of lime sludge when it is precipitated at the water treatment plant will be discussed. Second, the results of studies done on the engineering properties of dried lime sludge will be presented. These properties are similar to those used to describe the engineering behavior of soil. Last, studies that describe potential applications for lime sludge use will be summarized.

Characteristics of Lime Sludge in the Liquid Form

Composition of Lime Sludge

To soften water, unslaked lime (CaO) is used. Before it is added to the raw water, the lime is hydrated with a small amount of water to form calcium hydroxide ($Ca(OH)_{(aq)}$). This provides the hydroxyl ions needed to raise the pH to about 10 or 11, depending on dosage. The ion that contributes the most to hardness is calcium. The reactions for removing hardness due to calcium are (Langelier, 1936):

$$Ca(OH)_2 + Ca^{2+} + 2HCO_3^- \rightarrow 2CaCO_{3(s)} + 2H_2O$$

Magnesium can be removed by the following reaction, but substantially only at pH values above 11:

$$2Ca(OH)_2 + Mg^{2+} + 2HCO_3^- \rightarrow Mg(OH)_2 + CaCO_{3(s)} + H_2O$$

Once the solids are precipitated, a settling process is used to separate the solids from the softened water. The solids are withdrawn from the settling process in a solid/liquid slurry called sludge. As with the lime sludge produced in Ames and Des Moines, Iowa, it is common for lime sludge to mostly consist of calcium carbonate (AWWA, 1999). Table 2 shows some common constituents found in municipal lime sludge from other cities in the United States.   If present in the raw water being treated, other metals can precipitate and end up in the sludge. Figure 5 shows a few common metals that are precipitated by calcium hydroxide.

Table 2: Composition of Dry Solids from Water Softening (Modified from O'Conner and Novak, 1978).

Constituent	Boulder City, Nevada	Miami, Florida	Cincinnati, Ohio
Silica, iron, and aluminum oxides	2.6	1.5	4.4
Magnesium oxide	7.0	2.8	2.3
Calcium carbonate	87.2	93.0	88.1
Other	3.2	2.7	5.2

Note: These values are a percentage by weight.

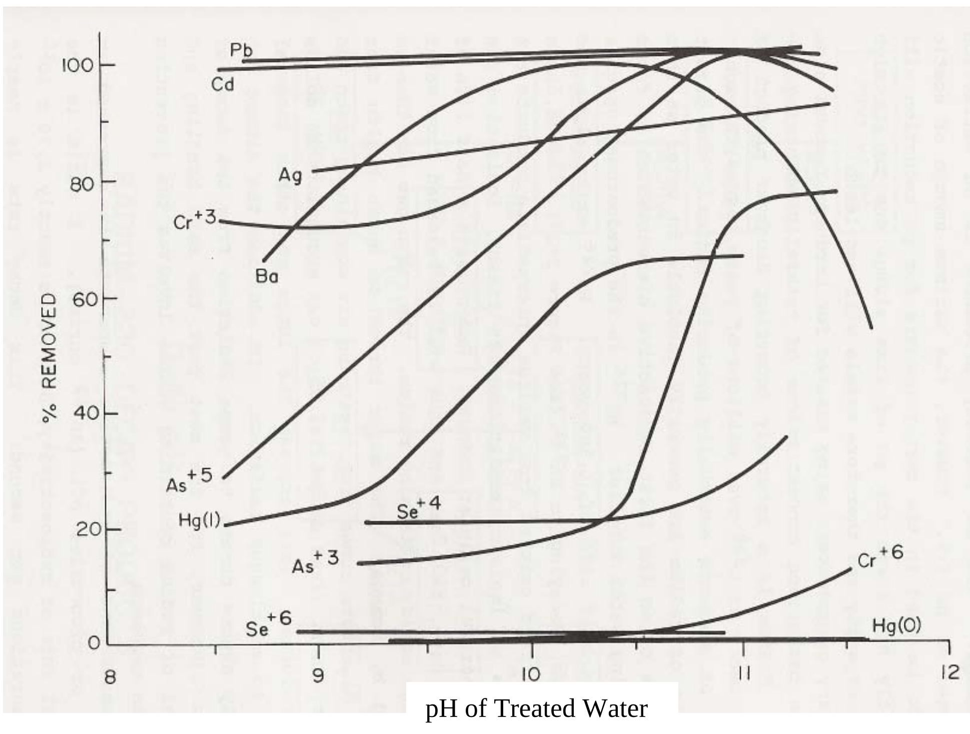

Figure 5: Removal of Inorganic Contaminants by Lime Softening (EPA, 1978)

Interaction of Solids and Water in Lime Sludge

Lime sludge is a mixture of water and precipitated solids. To understand the dewatering principle, a few simple concepts of how the water interacts with the solids will be helpful. Vesilind (1979) classified water and wastewater sludge in the categories as below.

1. *Free water* is not bound to solid particles and can be separated by gravitational forces.
2. Due to the shape of the floc formed, *floc water* becomes trapped between the floc particles as in the case of alum flocs. Since floc water is not attracted to the flocs, it is removed by simple mechanical forces.
3. *Capillary water* is water held by solid particles due to surface tension and is removed by compaction of the flocs.
4. *Bound water* is a part of the solid in that it is chemically bound to the particle, as in the case of aluminum hydroxides. It is only removed by sludge aging or with high heat.

Cornwell (1978) further expanded on this theory as below.

1. *Free water* can be removed by drainage or low-pressure mechanical methods.
2. *Hydrogen bound water* is attracted to the floc particle through hydrogen bonding. The attraction force is in the order of 0.13 kcal/mol.
3. *Chemically bound water* is bound to the floc in solution with strong chemical bonds.

According to Vesilind's definitions, free water and floc water are similar because they both require about the same amount of energy input to remove the water from the sludge. Comparison of the definitions of Vesilind and Cornwell shows that Cornwell's definition combines Vesilind's definitions for free water and floc water into one definition (free water) by making a slight change in the free water definition. Furthermore, the definitions of capillary water and hydrogen-bound water are similar relative to the amount of energy required to remove the water, as are bound water and chemically bound water.

There are two definitions frequently used in this paper to quantify how much water is present in the sludge. One is solids concentration (SC), and the other is moisture content (w). The relationship between the two is as follows:

$$SC = 1 / (1 + w)$$

Moisture content is defined differently depending on the discipline using it. In this paper and in geotechnical engineering, the definition of moisture content is the weight of water divided by the weight of solids for a given sample. This term is mostly used when describing the results of using lime sludge in fill materials. Solids concentration, which is commonly used by water treatment plant operators to describe the extent to which sludge is dewatered, is defined as the weight of the solids in the sample divided by the total weight of the sample.

Dewatering Lime Sludge

A property used by environmental engineers to quantify how difficult it is to dewater sludge is specific resistance. The specific resistance test is to apply a vacuum to the bottom of a Buchner funnel apparatus: the funnel is lined with filter paper and filled with sludge (as precipitated, not dewatered); the vacuum is applied and water drawn through the sludge; and the filtrate volume is recorded as a function of time. This data produces a value for the resistance offered by the solids cake to fluid flow per unit weight of dry solids. Generally, a high value for specific resistance means that it is difficult to dewater the sludge. Sludges with low values dewater more easily than those with higher values. Vandermeyden et al. (1997) tested nine samples of lime sludge for specific resistance, and the mean value was 5×10^{-12} m/kg. The same source reported that for 38 samples of alum sludge, the mean value was 1.58×10^{-13} m/kg.

Specific resistance is a function of the sludge particle’s shape, its specific surface area, its density, and the porosity of the sludge cake formed during dewatering (Cornwell, 1987). In order to approximate the size and shape of the sludge particle, Knocke and Wakeland (1983) looked at the particles under a microscope, noted the somewhat elliptical but irregular shape, and tried to approximate the shape of a sludge particle as an ellipsoid with major and minor axes. Since the specific resistance is a function of particle size and shape, this approximation was useful. The article presented evidence that supported the plausibility of assuming the solids to be elliptical for the purposes of estimation. It then demonstrated that major axis length was related to specific resistance. Sludge flocs with an elliptical major axis length of 30 μm correlated to the specific resistances the author reported for lime sludge.

Settled solids concentration refers to how dense the solids in sludge will get under the influence of gravity (settling). Sludge that has mostly free water will have high settled solids concentrations, and sludge with high percentages of chemically bound and hydrogen bound water will have low settled solids concentrations. Generally, as the magnesium concentration in the sludge increases, the settled solids concentration decreases (Cornwell, 1987). This makes the sludge harder to settle because metal hydroxides contribute to higher amounts of hydrogen bound water. Furthermore, metals such as iron and aluminum form complexes with water and tie up even more water molecules through bonding. This is why alum and iron sludges have low settled solids concentrations and high specific resistance values.

Water treatment plants employ different process units of devices to thicken and dewater lime sludge, and details of how these devices work and how to design them can be found in Cornwell (1987). Here, it is useful to know their limitations. Some lime sludge reuse applications require the sludge to be very dry (a moisture content of 2% or less). Table 3 shows a range of solids concentrations and the corresponding moisture contents obtainable with the dewatering technologies employed at water treatment plants. Therefore if the sludge needs to be drier to meet the criteria of the reuse application, further drying and processing will be required. This processing will add to the capital and operating costs of a given application.

Table 3: Efficacy of Dewatering Devices (Modified from Cornwell, 1987).

	Lime Sludge (solids concentration, %)	Lime Sludge (moisture content, %)
Gravity thickening	15 to 30	600 to 230
Scroll centrifuge	55 to 65	82 to 54
Belt filter press	10 to 15	90 to 57
Vacuum filter	45 to 65	122 to 54
Pressure filter	55 to 70	82 to 43
Sand drying beds	50	100
Storage lagoons	50 to 60	100 to 67

Engineering Properties of Dried Sludge (solids)

Not all lime sludges have similar properties. The dissolved ions in the raw water affect properties like specific gravity and particle size distribution. Three studies were selected to demonstrate differences in the engineering properties of water treatment sludges. A summary of the results that are of interest to this investigation are shown in Table 4. Particle size distributions were found to be either silt-sized or clay-sized material in all sludges. The specific gravity ranged from 1.9 to 3.43. No reasons were given for the wide range in specific gravity, but the raw waters that produced each sludge were different. For example, the water treated in the study by Maher et al. (1993) had high levels of zinc. The lime sludge in this study came from a groundwater remediation project, and the following elements and concentrations were present in the groundwater: zinc (125–150 ppm), aluminum (20–25 ppm), sulfate (225 ppm), and calcium (15–25 ppm). Wang et al. (1991) performed tests on three different sludges. Two were alum coagulant sludges that resulted from treating two raw waters with different levels color and turbidity. The third sludge resulted from an iron coagulant.

The sludges studied by Wang et al. (1991) and Maher et al. (1993) had high values for the liquid limit, plastic limit, and plasticity index. Limits such as these are common in expansive soils. Raghu et al. (1987) attempted these tests on the sludge they studied but were not able to report any values: in the liquid limit test, they could not find a moisture content that closed the gap in over 15 blows; in the plastic limit test, they were not able to roll out 1/8-inch diameter beads (for plastic limit). It is possible that small changes in moisture content resulted in large changes in the plasticity of the material, and that this was the reason why the properties could not be determined.

The maximum unit weights shown in Table 4 were all computed from moisture density relationships (ASDTM D698) and cover a wide range of values. Most soils yield a parabolic moisture density curve, facing downward; it is the maximum value of dry unit weight on the curve that is desired. For fill applications, it is important to know the moisture content that will result in maximum dry density when fill materials are placed and compacted. Raghu et al. (1987) and Wang et al. (1991) mentioned the difficulty of obtaining a maximum dry unit weight and corresponding moisture content. In essence, the curves from their studies were flat or irregularly shaped. Two of the sludges from Wang et al. (1991) yielded no maximum value, so only one value was listed. Maher et al. (1993) were able to produce characteristic moisture-density curves. Possible reasons for this success could be their using lime sludge with a higher specific gravity and mixing it with Class F fly ash.

The compression index, an indicator of soil compressibility, friction angle, and shear strength, was determined by Wang et al. (1991) while they were investigating the most efficient way to emplace water treatment sludges in storage areas. Shear strength was an important characteristic for this study since the authors wanted to know how steep the slopes could be when emplacing and compacting sludge: steeper slopes meant being able to store more material for a given surface area. The sludges studied by Wang et al. (1991) were coagulant ferric and aluminum sludges reported to have values for liquid limits, plasticity indexes, and compressibility indexes that were within the ranges of published values for expansive clays such as montmorillonite. Lime sludge is not expected to be as expansive as these coagulant sludges were due its low liquid limit and plasticity index.

The friction angles found by Wang et al. were determined using a triaxial shear test and were relatively high. Expected ranges of friction angle for materials classified as silts fall within the range of 26–35 degrees (Das, 2002). The friction angles reported by Wang et al. fell within the range for soils that classify as sands with angular grains. Wang et al. cited a friction angle of 76 degrees for paper-mill sludge (Charlie, 1977). Friction angles are important when characterizing a material for fill because it can be used to check a design for proper slope stability.

Lastly, the studies by Raghu et al. (1987) and Maher et al. (1993) reported values for permeability. However, these studies measured permeability to determine the material's applicability for use as a landfill liner material. The Environmental Protection Agency's (EPA) regulations for MSW landfills require any material used as a liner for MSW landfills to have a permeability of 1 x 10^{-7} cm/s or less (EPA, 2005). Both Raghu et al. and Maher et al. used consolidation tests to determine permeability and concluded that their material met the standards for landfill liners. After these papers were published, the EPA promulgated regulations requiring that permeability for liner materials be determined using the flexible wall permeameter (ASTM D5084) or equivalent (EPA, 2005). Permeability is important for fill applications because it indicates how well the fill will drain or resist the flow of water. The terms permeability and hydraulic conductivity will be used interchangeably in this thesis, as they refer to the same characteristic for the purposes of fill materials in road construction.

An interesting characteristic of lime sludge, pointed out by both Raghu et al. (1987) and Maher et al., is its ability to adsorb toxic substances—especially metals. There were no heavy metals or toxic organics in the sludge tested by Raghu et al., but since the researchers were investigating the feasibility of using this sludge as a landfill lining, its resistance to acidic leachates containing toxic materials was tested. It did not leach any heavy metals or toxic organic compounds that were known to be in the leachate: the sludge was able to fixate these substances of concern. In addition, a pinhole dispersion test was performed on sludge compacted 90% of maximum modified proctor, and it was found to be nondispersive.

Maher et al. (1993) did the third study that investigated the engineering properties of lime sludge and Class F fly ash. This is the only study that combined these two materials. The lime sludge used in this study was different than the lime sludge produced in Ames or Des Moines, Iowa: it was produced by using lime to treat contaminated groundwater. The fly ash was classified as Class F, which is different from the Class C fly ash produced in Iowa. The major difference between the two is the amount of calcium oxide they contain. The composition of Class C fly ash will be presented in the materials section of Part II of this thesis. For the Maher et al. (1993) study, the lime sludge was mixed with the fly ash in a range of mix ratios. The mix ratios were 2:1, 2.5:1, and 3:1, based on the ratio of the weight of dry fly ash to the weight of wet lime sludge.

Leachate with known amounts of dissolved metal ions was passed through the consolidated specimens from the permeability tests in the Maher et al. (1993) study; the permeate (liquid that passed through the sludge/fly ash specimen) was then tested for metals, but no significant concentrations of metals were found. It was concluded that the specimen had effectively fixated the metals since it was known that the leachate and lime sludge/fly ash mix contained significant concentrations of undesired ions.

Table 4: Summary of Results from Three Studies on Dried Water Treatment Sludge.

Property	Raghu et al. (1987)[a]	Wang et al. (1991)	Maher et al. (1993)[a]
Treatment chemicals	Lime, alum, polyamine	Iron, alum	Lime
Stabilizer	none	none	Class F Ash (no lime)
Metals in raw water	trace	trace	Zinc, Aluminum
Classification (UCS)	SM—silty sand	CH—expansive clay	CH—expansive clay
Specific gravity	1.9	2.26 to 2.72	3.43
Max dry unit weight, kN/m[c]	0.8 (sludge only)	11.3 (sludge only)	15.2 to 16.3 (w/fly ash in mix)
Liquid limit, %	*	108 to 550	294
Plastic limit, %	*	47 to 239	189
Plasticity index, %	*	61 to 311	105
Compression index	*	1.99 to 6.69	*
Swelling index	*	0.03 to 0.17	*
Unconfined compressive Strength, kPa	*	*	1160 to 1200
Undrained shear strength, kPa	*	1.24 to 17.9[d]	*
Effective friction angle, degrees	*	42 to 44	*
Permeability, cm/s	10×10^{-8} to 10×10^{-6} [b]	*	1×10^{-7} to 4×10^{-7} [b]

*Indicates no data.

Notes:
a. SI units were converted from standard units in the Raghu et al. and Maher et al. studies.
b. Permeability values obtained from consolidation tests
c. Triaxial Test (ASTM D2850) was done to find effective friction angles
d. Cone Penetration Test (ASTM D3441) was done for undrained shear strength

A significant finding from the study was that, based on permeability results and leach test results, these mixtures could be used as a landfill liner or cap material. Maher et al. also found that the material was a good, engineered fill. Unconfined compressive strength tests on the mixtures yielded values ranging from 1160 to 1200 kPa. According to Ferguson and Levorson (1999), if 50 psi (about 345 kPa) compressive strength can be achieved, then the potential for settlement in deep fills is significantly reduced.

Potential Uses for Lime Sludge

Lime sludge has the same main ingredient in it as mined limestone—calcium carbonate ($CaCO_3$). A useful approach to finding uses for lime sludge was to consider the current uses for mined limestone. One of the major producers of limestone in the United States is Martin Marietta Materials. According to their web site (http://www.martinmarietta.com), they mine and process materials used mostly for civil engineering projects such as road construction. Carmeuse, headquartered in Belgium, is an international lime supplier. Carmeuse's web site (http://www.carmeuse.be) lists the following possible uses for limestone: material for road construction; road foundations; buildings; dykes; cement and ceramics production; flue gas treatment; production of iron, glass, and steel; metallurgical and mining operations; the chemical industry; and the paper industry.

Unslaked lime or quicklime (CaO) is formed by heating limestone ($CaCO_3$) in a kiln. The water treatment plant managers from the cities that funded this study asked if lime sludge could be heated in a kiln to make lime. This was a good question since authors like Cornwell have suggested this as a potential application for lime sludge (Cornwell, 1987). However, some sources consider this an uneconomical effort due to sludge impurities, high fuel costs, high capital costs, and a reduction in kiln efficiency (Watt and Angelbeck, 1977). There is always a potential for this use, but research in this area would not be useful since no tests are needed to prove that lime (CaO) can be produced. Running kiln tests would only show the efficiency of a given kiln and a given lime sludge.

Using Lime Sludge for SO_x Removal in Coal Combustion Flue Gas

Ground limestone is used in some coal-fired power generation facilities to prevent the release of sulfur gases (SO_x) though the flue. SO_x gases include sulfur dioxide (SO_2), sulfur trioxide (SO_3), their acids, and the salts of their acids; the EPA mandates reductions of these gases through the Clean Air Act (EPA, 1990). In the year 2000, there will be a 40% reduction in annual SO_x emissions compared to those released in 1980. Davis and Cornwell (1991) reported the U. S. EPA limits of SO_x in acid rain were 0.03 ppm average per year and a maximum of 0.14 ppm during a 24-hour period. However, depending on how old the power plant is and how they use their emissions credits, the release limits for each plant are different. The process of removing SO_x is known as the flue gas scrubbing process, and is done as either a wet process or a dry process. In the wet process, a solid/liquid slurry, brought into intimate contact with the flue gas, absorbs and reacts with the SO_x gases. Calcium carbonate is the primary reagent, but calcium hydroxide is also effective. In the dry process, calcium carbonate is fed as a fine powder aerosol that reacts with the SO_x in the flue gas stream. It is vital that the powder moisture content be 2% or less (Witt, 2002) to avoid blocking pneumatic dry feeding systems.

According to Shannon et al. (1997), the calcium carbonate reacts with sulfur oxides in the gas to form hydrated calcium sulfite. Since hydrated calcium sulfite is difficult to dewater, fresh air is blown through the stream to oxidize the sulfite to sulfate during the scrubbing. The sulfate then reacts with calcium to form calcium sulfate. Shannon et al. also offer the following chemical reactions:

Just scrubbing with calcium carbonate:

$$SO_2 + H_2O \Leftrightarrow H_2SO_{3\,(aq)}$$

$$H_2SO_{3\,(aq)} \Leftrightarrow H^+ + HSO_3^-$$

$CaCO_{3(aq)} + H^+ \Leftrightarrow Ca^{2+} + HCO_3^-$

$Ca^{2+} + HCO_3^- + HSO_3^- \rightarrow Ca\ SO_{3(aq)} + CO_2 + H_2O$

With air stream added,

$HSO_3^- + \frac{1}{2} O_2 \rightarrow SO_4^{2-} + H^+$

$SO_4^{2-} + Ca^{2+} + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O_{(s)}$

The resulting solid is gypsum, which could be investigated for use in building materials like drywall.

A complete study using lime sludge rather than ground limestone in a wet scrubbing process was completed in Kansas (Shannon et al. 1999). The following is a summary of their findings:

1. Researchers found that the lime sludge slurry was more reactive and soluble than the limestone slurry normally used.
2. SO_2 removal was more effective when using lime sludge than when using ground limestone.
3. The power plant feeding mechanisms would need to be rebuilt to feed lime sludge rather than limestone.
4. One utility surveyed purchased limestone from a quarry 120 miles away because it was the only source whose limestone had the quality needed to operate efficiently in its scrubber. The cost of the limestone was $4 a ton, but the transportation costs doubled that amount.
5. The Lawrence Energy Center (a power plant used to test the lime sludge) showed that $60,000/year could be saved in materials cost due to savings from reduced reagent demand. Furthermore, not only was the amount of lime sludge required to treat the flue gases smaller than the amount of limestone required to treat the same amount of gases, but also the cost of using limestone was $10.71/ton, while and the cost of using lime sludge was $10.69/ton.

Using Lime Sludge in Fill Materials and for Road Construction

Maher et al. (1993) showed that when stabilized with fly ash, the properties of lime sludge as a fill material could be significantly improved, but this sludge was unusual with respect to the lime sludge resulting from drinking water treatment because of its high specific gravity (3.43). Watt and Angelbeck (1977), in a study of the effects of adding a very small amount of sludge (about 1 to 3%) to a road subbase aggregate, found that addition of 0.5 to 1.0% sludge produced maximum improvement to the seven-day cure and freeze/thaw unconfined compressive strengths. They further found that incorporation of up to 2% sludge did not significantly affect freeze/thaw durability.

Watt and Angelbeck worked with a sludge that came from treating Lake Erie surface water with alum for coagulation and lime for softening. The lime sludge composition was about 75% $CaCO_3$, and the metals present in the sludge were aluminum and magnesium. Although the classification of fly ash used was not indicated, lime (CaO) was added to their mixtures, so it is likely that it was Class F Ash. Class F ashes are more common in the Eastern United States because of their sources of coal, and the Class F ashes usually require additional lime to realize the same stabilization effects as Class C fly ash. The mix design was 86% aggregate, 11% fly ash, 3% lime, and 0 to 3% sludge solids. Watt and Angelbeck concluded that more research is needed on the effects of incorporating sludge solids in materials for road construction. They used the lime sludge in a subbase layer for road construction—an application that requires a higher grade of material than is needed fill applications, since it lies directly below the base course and pavement layer of a road. However, even with the higher quality standards required for this application, use of lime sludge in subbase layers can still be a constructive way to reduce lime sludge disposal costs.

Referencing his totals tabulated in January 2005, Ed Kasper, in the Office of Contracts of the Iowa Department of Transportation, helped define the amount of fill material used in DOT projects. He stated that the DOT projects used over 3 million cu. yd. (2.3 million m^3) of Class 10 Roadway and Borrow in 2004. He said the bid unit cost of excavation, transport, placement, and compaction of fill ranged from $0.82 to $30.00/cu. yd., and the average bid unit cost was $2.52/cu.yd. He stated that the wide range of unit costs was likely due to transportation costs, but sometimes excavation can be difficult, and therefore expensive, and at other times access to job sites may be difficult.

Many projects require Class 10 fill material to be transported from another site, so it was useful to look at these, since there will be transportation costs associated with any fill material used, regardless of source. An example is the replacement of the 63rd Street bridge over Interstate 235 in Des Moines, Iowa. To meet the design specifications for the new bridge and maintain the correct height above the roadway below it, it was necessary to elevate 63rd Street to the road elevation of the new bridge. Existing residential areas surround and are adjacent to the bridge construction site; in fact, the yards of residents were required to maneuver heavy construction equipment around the bridge construction site. Therefore, most of the fill needed to elevate the roadway was transported to the site from another borrow area. This project is a particularly useful example for this study because there are two water treatment plants that produce lime sludge within a 20-minute drive of the site (Des Moines and West Des Moines).

In conclusion, limited information showing a potential for the use of lime sludge as a fill material and as a reagent in SO_x removal in coal combustion flue gas has been published, and variations in the composition and moisture content have also been presented. The question that remains is whether the lime sludge produced in Iowa, containing 90% or more $CaCO_3$, will be effective in these and other applications. How will the lime sludge produced in Iowa react with the Class C fly ash (instead of Class F) and Iowa soils? Can the sludge produced in Iowa be substituted for limestone in cement production? Can the Iowa lime sludge be used to neutralize acidic industrial wastewater? Can the sludge produced in Iowa be used to control dust on unpaved gravel roads? These are the questions that will be answered in this research.

Report Organization

Several beneficial solutions for using lime sludge produced in Iowa were initially investigated through a series of feasibility studies. These studies were completed by other graduate students prior to Rob Baker's arrival on the research team, but were not published; the results of their work were passed on to Rob to incorporate into his work. Part I documents the work of these other students in the greatest detail possible. Upon Rob's arrival, one beneficial solution was chosen for more thorough investigation. Detailed descriptions of the materials, methods, and results of laboratory testing are presented and discussed in Part II. Part III presents the in situ tests done on a test embankment constructed from lime sludge stabilized with fly ash and a cost analysis. Finally a set of findings for the entire research period follows in the general conclusions portion.

PART I - FEASIBILITY STUDIES

Introduction

Iowa State University's Department of Civil, Construction, and Environmental Engineering evaluated some applications for the beneficial use of lime sludge. These disposal options included use of the lime sludge to treat SO_x-containing stack gases in coal-burning power plants, to serve as a substitute for limestone in cement production, to stabilize the pH of acidic industrial wastewater, to reduce dust generation on gravel roads, and to serve as fill in road construction projects. The use of stabilized lime sludge in fill materials for road construction was chosen for a more in-depth investigation since it showed promising results in feasibility studies and has the potential for utilizing much of the currently stockpiled lime sludge described in the background section (see also Table 1).

To develop alternative disposal methods, the composition and structure of lime sludge were compared with those of another commonly mined material, limestone. Lime sludge has the same composition as limestone, but is not in rock form: it forms a fine powder when dry. Therefore, applications that used pulverized limestone were identified as possible candidates for the use of lime sludge. Applying this approach, SO_x removal in coal-fired power plants and cement production were chosen as possible alternatives. The construction fill application and dust control options were chosen because they were of interest to the Iowa DOT, a major sponsor of this research.

This part first presents a discussion of the material used and how the presence of moisture content affects its nature. Next, a brief description of methods used in the feasibility tests is offered, and last, a review of the results is presented. Results are presented and discussed in the same section. Since the information in this part was obtained through interim reports to sponsors, the level of detail is not the same as in Part II, but as many of the facts as possible are presented.

Material and Dewatering Properties

None of the applications discussed in this part involve using lime sludge as a solid/liquid slurry (average solids concentration, 3%), the state in which it is withdrawn from the clarifier. The slurry must be dewatered and dried before it can be used in any of the applications discussed herein: drying reduces the bulk volume and mass of the sludge before transportation, and it also improves mechanical properties like shear and compressive strength. Unfortunately, drying is also the most expensive step required to convert the lime sludge to a useful product (assuming transportation costs of dried product to locations within the same greater metropolitan area). Prior to the feasibility studies, some simple drying tests were done to elucidate the physical properties of the lime sludge in water.

It is important to understand how water exists within the solids matrix. The water may either bond to the lime sludge crystals or remain free from attractive forces altogether. If it bonds, the bonding may be through weak hydrogen bonds (attraction energy of about 0.13 kcal) or through chemical covalent bonding. In addition, knowledge of the crystalline structure of the lime sludge can be helpful in designing an optimal drying process.

Summary of Imaging Analysis

An optical microscope and a scanning electron microscope were used to produce the images of the lime sludge from the Ames Water Treatment Plant shown in Figure 6. The micrographics indicate that there is a crystalline structure and that water may be a part of that crystal structure.

Drying Lime Sludge in a Convection Oven

A simple experiment with a convection oven was done to illustrate the drying process. The oven was set at 121^{o}C to simulate rotary kiln drying (process used to dry the Des Moines Water Works sludge). Six samples of Ames lime sludge that began the test at 23% moisture content were dried over 40 minutes, and the weights were recorded at 5-minute intervals. The

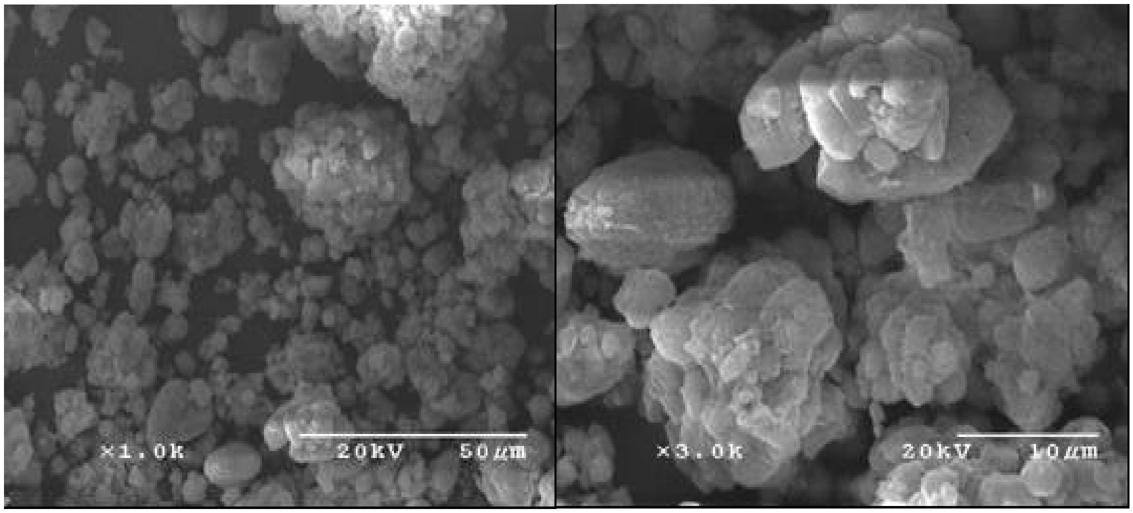

Figure 6: Scanning Electron Micrographics of Lime Sludge

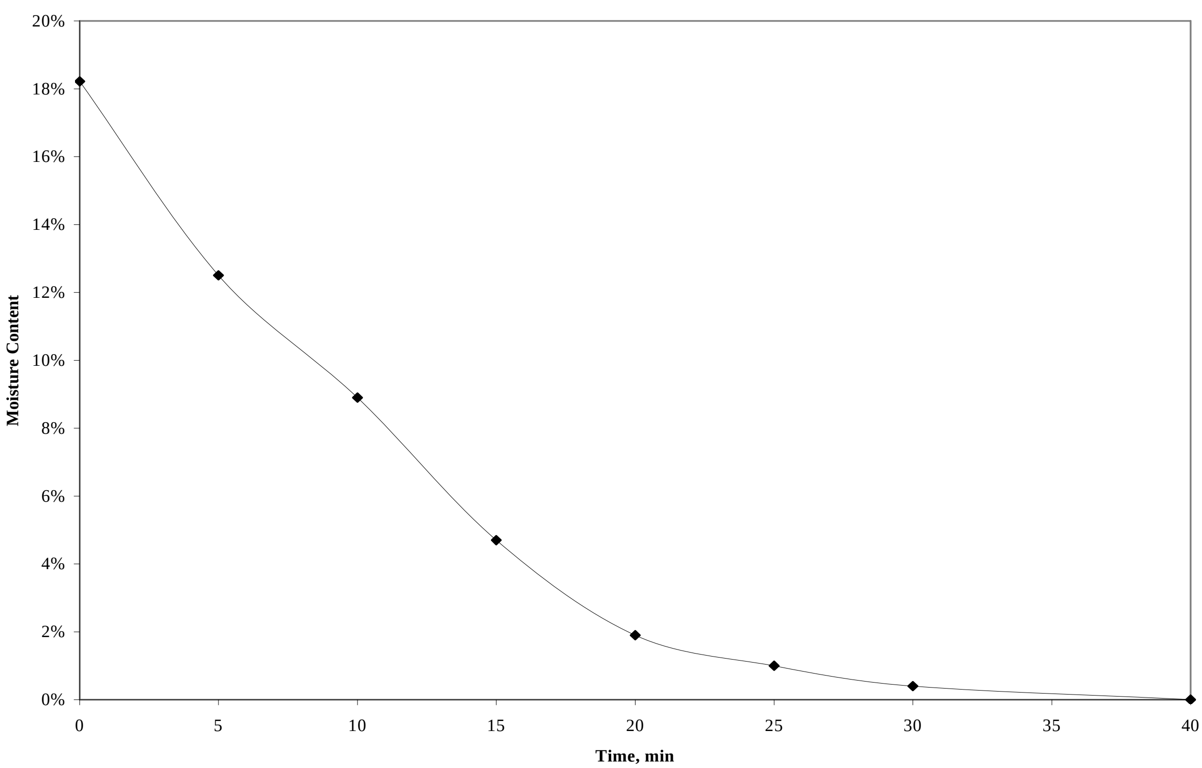

Figure 7: Drying Lime Sludge at 121°C: Moisture Percentage vs. Time

results are shown in Figure 7. Since all but 2% of the known moisture in the lime sludge was driven off at 121°C, most of the water in the sludge is free water, which means that the energy required to remove this moisture would be close to that required to evaporate water.

These results are significant to the application of SO_x removal from flue gases of coal-fired power plants since a moisture content 2% or less is required for pneumatic transport of the lime sludge in the feeding mechanisms of dry scrubbers, according to the management at the Iowa State University Cogeneration Facility (Witt, 2003).

Thermogravimetric Analysis of Lime Sludge

Figures 8 and 9 show a thermogravimetric analysis of the lime sludge from the Ames water treatment plant. The heating was done at a slow rate to 110^{o}C and then at a faster rate up to 1000^{o}C (Figure 9). Most of the moisture was driven off between 20 and 40^{o}C, which may indicate that this portion is free, or unbound, water. Then there was a small loss from 40 to 110^{o}C, which may be due to strongly physically adsorbed water similar to the hydrogen-bound water described in the background section. The loss between 200 and 400^{o}C could be the water associated with magnesium hydroxide, and the loss between 650 and 800^{o}C is due carbon dioxide being driven off as calcium carbonate is decomposed.

Adsorption of Moisture During Cooling

The six samples that were oven dried at 121^{o}C were allowed to passively cool at air temperature (around 20^{o}C) to determine the amount of moisture that the lime sludge would adsorb from the regular laboratory atmosphere. After 1 hour, the samples adsorbed enough water vapor to increase the moisture content to an average of 1.9%. Coincidentally, if lime sludge at 70% moisture content were spread over a plate to a thickness of 10 cm or less, the ambient lab conditions would eventually reduce the moisture content to about 2%. Therefore, drying beyond 2% moisture content is not practical if any subsequent storage of the lime sludge is required prior to use.

In summary, there is no strong bonding between water and the solids in lime sludge, except for the last 2% of moisture. This condition places no limitation on any reuse possibility. A practical limitation on oven drying is that the sludge is reduced to small particles upon

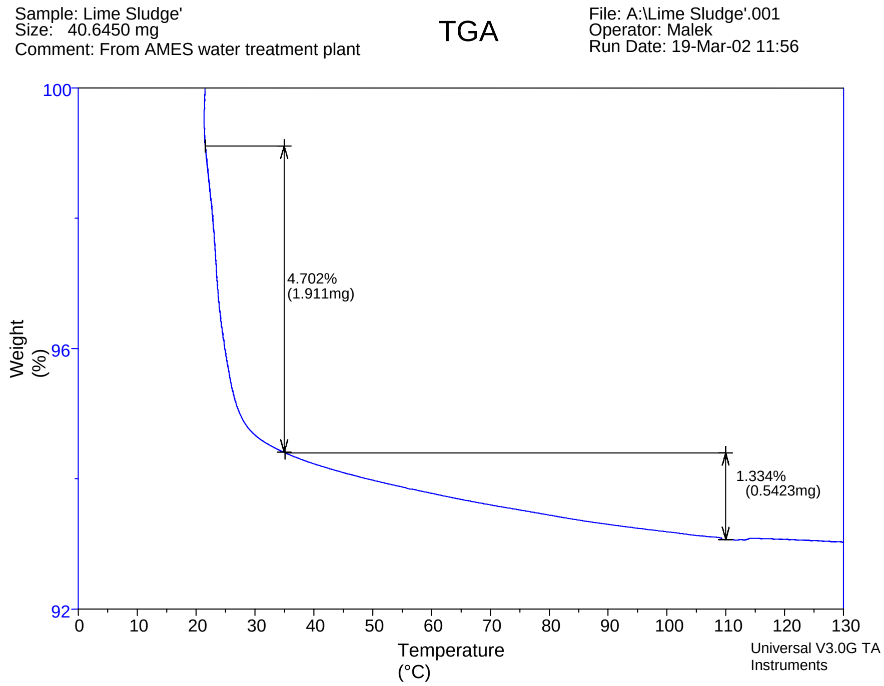

Figure 8: Thermogravimetric Analysis of Lime Sludge (20–130^{o}C)

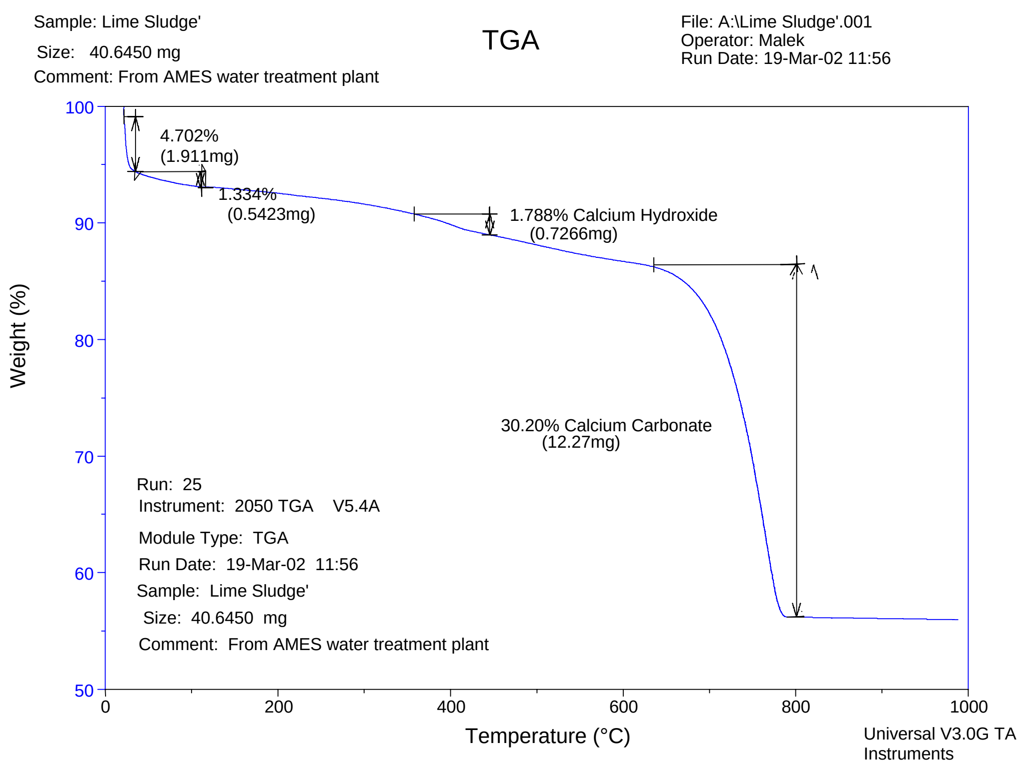

Figure 9: Thermogravimetric Analysis of Lime Sludge (20–1000^{o}C)

drying, which makes subsequent loading and transporting difficult, as the small particles are easily blown away in a cloud of powder. For most applications, a moisture content range of 20% to 35% is the most practical, and this moisture content ensures that the material does not generate dust.

Summary of Methods and Materials

Although the use of lime sludge as a fill material could mostly be evaluated in the laboratory, the applications using lime sludge for SO_x treatment in power plants, as a replacement for limestone in cement kilns, for neutralizing industrial wastewater, and for dust control on rural gravel roads all required full-scale testing to confirm their feasibility. The full-scale feasibility tests were done on a one-time basis, and therefore, the methods could not be further refined and repeated without repeating the entire test. Iowa State University Cogeneration Facility, Lehigh Cement, and Warren Foods all graciously allowed the use of their facilities for lime sludge testing. Since lime sludge used at too high a moisture content clogged their feeding system, the Iowa State University Cogeneration Facility suspended any further tests, and the number of tests done at the Lehigh Cement and Warren Foods facilities had to be limited due to the cost of transporting the sludge to their locations. There was no problem with refining and repeating tests for the application of lime sludge as a fill material for road construction.

Use of Lime Sludge in Dry Scrubbing Power Plants

Iowa State University operates the only power plant in Iowa that uses a dry scrubbing process for SO_x removal and Iowa State’s plant was selected for testing. At this facility, ground limestone is fed into the combustion fluid stream pneumatically. Due to the possibilities of compaction and adhesion resulting from the pipework limitations of this site, the calcium carbonate must be in a very dry state (less than 2% moisture content) or it will clog the feeding mechanism.

Lime sludge was tested for feasibility at the Iowa State University Plant on August 8, 2002. The lime sludge was supplied at a moisture content of 15% instead of the 2% requested. At this moisture content, the material was clumped into a range of 1/4-inch to 3/8-inch diameter balls instead forming a fine powder. This higher moisture content clogged the feeding mechanism and produced sporadic results.

The lime sludge was injected pneumatically through an existing bed injection line using a truck-mounted blower. The lime sludge injection started at 11 am, and the injection system worked fine for approximately 1 hour and 45 minutes, at which point the line plugged at the boiler. After the plugged line was cleared the first time, it continued to plug repeatedly until the test was terminated at 2 pm. After the truck-mounted blower was disconnected, a layer of lime sludge remained caked on the interior surface of the pipe. It is likely that the buildup of material on the piping was caused by the heat of compression from the blower.

Replacing Limestone with Lime Sludge in Cement Kilns

Limestone is one of the raw materials used in cement production. Limited testing was conducted to see if lime sludge would be a suitable ingredient to augment or replace limestone in the production of cement. Twenty tons of solar-dried lime sludge were transported from Ames, Iowa, to Lehigh Cement in Mason City, Iowa. For a one-time test, lime sludge was used in cement production, replacing some of the limestone used as raw material. About 80 tons of cement containing about 15% lime sludge was produced.

Use of Lime Sludge for Wastewater Neutralization

Tests using lime sludge to bring processing wastewater resulting from pasta production to a normal pH value were conducted at Warren Foods in Altoona. This company normally uses sodium hydroxide to neutralize this wastewater, but this material is expensive and adds unwanted salinity to the water. For testing, 2 tons of dry lime sludge, dewatered by filter press and dried in a rotary kiln by Kelderman Lime, were used, and dosing was performed by hand until the water reached a neutral pH.

Use of Lime Sludge for Dust Control on Gravel Roads

To anyone who has driven on a gravel road in Iowa, the dust generation on these roads is obvious. Dr. Ken Bergeson, concluding research at Iowa State University in 1999, found that adding fines to change the overall grading of unsealed road material reduced dust emissions. Dry lime sludge is a fine material that could be applied to unpaved roads to change the material composition towards a more favorable grading.

With the aid of personnel form the Story County Engineer Section, lime sludge was tried on two test sections of gravel road in Story County. The two test sites for a one-time dust control test were Old Bloomington Road and 220th Street in Story County, Iowa; Old Bloomington Road is a gravel road, and 220th Street is a crushed limestone road. On May 29, 2002, a truckload of lime sludge was applied by a dump truck over an approximately 100-foot stretch of road at each site. A road grader made six passes over the 220th Street test section and five passes over the Old Bloomington Road test section to incorporate the lime sludge material into the aggregate. During the grading of the Old Bloomington Road test section, it started to rain. As a consequence, the lime sludge on the Old Bloomington Road test section was not as evenly spread as that on the 220th Street test section. About one month was allowed to elapse before dust deposition rates were measured. During that time, gravel was added to both roads after the lime sludge was applied, but no additional gravel was added to the test sections.

Dust deposition rates were measured with a birdcage dust collector. A mid-sized SUV was driven down the middle of the road a total of 10 times at speeds between 40 and 45 mph. Since the wind was coming from the south during dust monitoring, the monitoring equipment was set up on the north side of the road.

Use of Lime Sludge for Fill Material in Road Construction

The ASTM Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders (ASTM D1633) was used. An exception to the standard methods was the use of molded cylinders 5 cm (2 inches) in diameter by 5 cm (2 inches) high (referred to as 2x2 hereafter). Figure 10 illustrates the compaction device that produces the test cylinders for the unconfined compressive strength tests. In this compaction method, developed at Iowa State University several years ago (O'Flaherty et al., 1963), the materials are screened through a No. 4 sieve (4.75 mm opening) prior to compaction using five blows of a 5 lb. drop hammer on each side of the specimen. This typically yields a maximum dry density similar to that of Standard Proctor compaction. After compaction, the molded specimen is extracted using a hydraulic jack. When a stabilizer such as portland cement or Class C fly ash is used, specimens are protected from moisture loss and cured for the time specified in the results section.

Since finding beneficial uses for municipal by-products was the motivation for this research, fly ash and bottom ash from coal combustion at power plants were incorporated in these tests. Fly ash and bottom ash from the Ottumwa Generating Station in Eddyville, Iowa, were used in the unconfined compressive strength tests. Time of sampling and methods were not documented. However, fly ash can only be drawn from an overhead storage bin in bulk at this facility. A front-end loader bucket (about 1.4 m^3) is used to collect fly ash from the storage bin, and then a supply of fly ash is taken from the bucket. Bottom ash is taken manually from a stockpile large enough to drive dump trucks on.

Unconfined compressive strength test results are the only type of laboratory tests presented in Part I. However, the other graduate students working on this project did complete some moisture-density tests as well. Since all of the moisture-density results were combined and analyzed as one, they are all presented and discussed in Part II. Descriptions of methods and materials used will also be included.

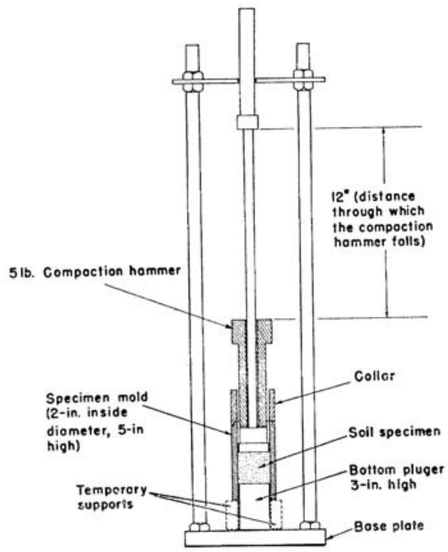

Figure 10: Compaction Apparatus (O'Flaherty et al., 1963)

Results and Discussion

Use of Lime Sludge in Dry Scrubbing Power Plants

The Iowa State Cogeneration Facility measures SO_2 and NO_x in its emissions control program (SO_2 is the major constituent of SO_x gases). Overall, the lime sludge material reacted well with the flue gas stream when it was feeding properly. The sulfur dioxide levels leaving the boiler dropped immediately after injection began. At that point, the normal limestone feed was stopped and the process was run using only the lime sludge. The lime sludge feed rate was manually controlled using valves on the truck, but this method could be greatly improved to achieve a more consistent rate. This inconsistent feed rate may have contributed to the erratic SO_2 and NO_X levels depicted in Figure 11. According to plant personnel, SO_2 levels of 120–125 ppm and NO_X levels of 75–90 ppm were typical for this plant's emissions and within the plant's permit (Witt, 2002).

After the lime sludge feed was started, a few changes in the normal operation of the boiler bed were observed. A small decrease in the boiler bed temperature of about 2–3^{o}C and in increase of about 14^{o}C in the temperature leaving the combustor at the inlet to the cyclone indicated a reduction in the size of the material in the fluidized bed and an increase in the circulation rate of material through the boiler. In addition, a slight, steady decrease in the boiler bed pressure throughout the test period indicated a greater circulation rate, a reduction in bed material sizing, and possibly a reduction of bed inventory. Figure 12 shows a summary of these changes.

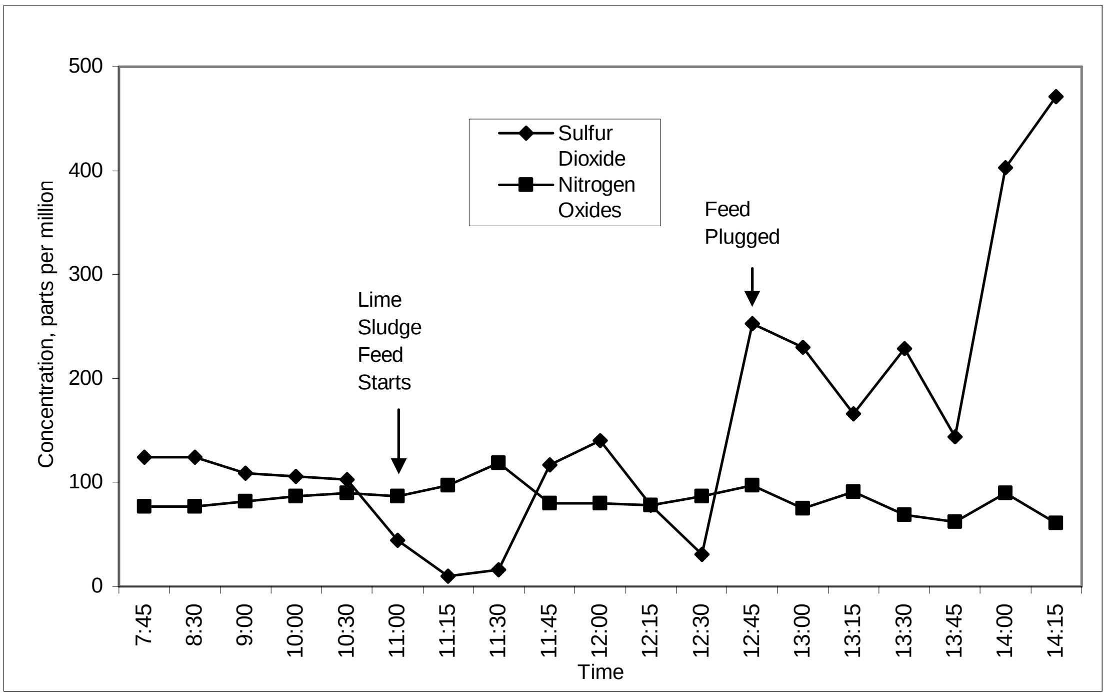

Figure 11: Pollution Control Test, ISU Power Plant, Boiler Emission Levels

The test consumed about 4,500 lb. of lime sludge at a consumption rate of about 1,850 lb./hr. This was a higher consumption rate than that for the limestone normally used. The lime sludge feed problems caused the operators to increase the limestone feed to maintain SO_2 levels. If the lime sludge had been delivered efficiently by the feed mechanism, then a more representative feed rate would have resulted. Wet lime sludge is not necessarily an insurmountable obstacle: power plants have low-grade waste heat that could be used for drying lime sludge. However, special equipment would be required to make use of this opportunity.

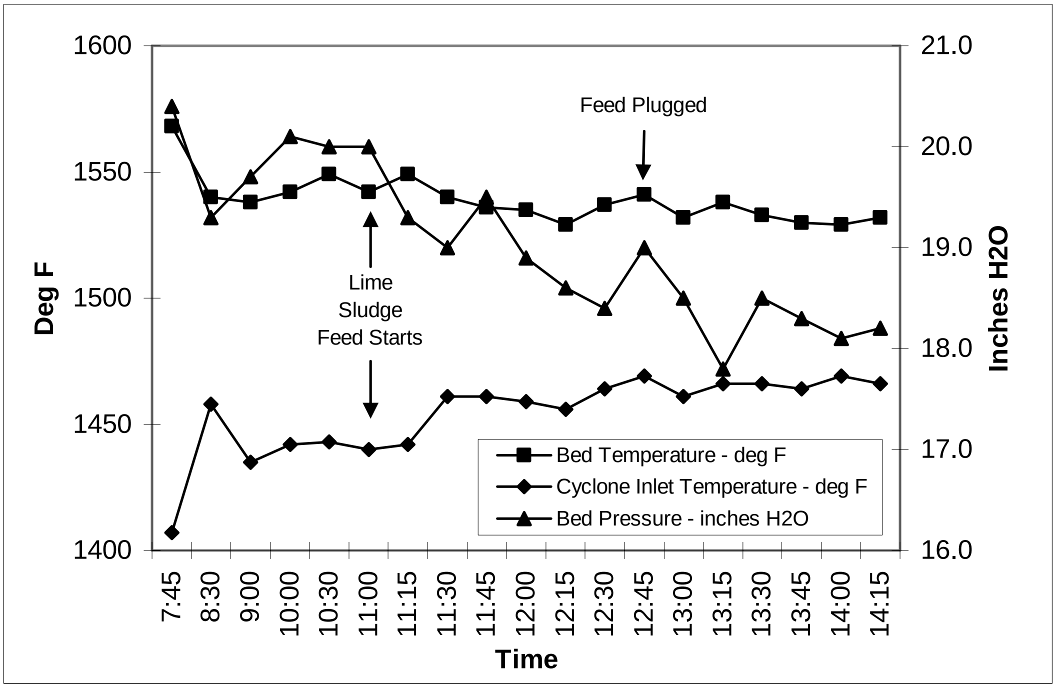

Figure 12: Boiler Bed Trends When Using Lime Sludge for SO_x Control

The lime sludge treatment run did not last long enough to see if problems maintaining adequate bed inventories would develop. If the decrease in bed pressure were to continue along the observed trend, it might present operational problems for the boiler over a longer period. A reduction in the bed sizing can change NO_x emissions, but poor SO_x control makes this observation inconclusive. Subsequent test runs could provide more diverse data and more consistent trends. Longer testing periods are required to be able to ascertain any long-term effects on the boiler. Since this type of testing requires a significant commitment of funds and the use of temporary equipment that was not available at the time, further testing at this facility was suspended indefinitely.

There are plants in Iowa that use a wet scrubbing process for SO_x treatment. To use lime sludge in its wet scrubbing process, the Muscatine power plant would need some changes to its equipment, and operators of that plant have been reluctant to make changes to their system since optimization of the present system was difficult. Generally, a wet scrubber system is more compatible with the use of lime sludge since there is no dryness requirement for accommodating a pneumatic feeding system. However, further testing of lime sludge in SO_x scrubbers at power plants cannot occur unless power plant managers commit to further testing. If such testing is done, the management may discover that using lime sludge instead of limestone can reduce their costs, as was shown in the study done by Shannon et al. (1997) in Kansas.

Replacing Limestone with Lime Sludge in Cement Kilns

According to the Quality Control Manager at Lehigh Cement, Mr. William Ulrich, the quality of the cement manufactured with lime sludge was satisfactory. However, since the plant is located so close to its source of limestone, and its transportation cost is minimal, the cost of limestone at Lehigh Cement amounts to about $1/ton. Therefore, the cost of any alternative to limestone at this cement production plant must be $1/ton or less. Under current conditions, if a water treatment plant wanted to send lime sludge to Lehigh Cement, the cost of dewatering, drying, loading, and transportation would be assumed by the water treatment plant. Transportation to cement plants is therefore not economical.

Use of Lime Sludge for Wastewater Neutralization

The results showed that using lime sludge in neutralization was successful. The following observations were noted:

1. Dosing the acidic wastewater at Warren Foods was successful since it effectively adjusted the pH of the wastewater to the desired level without increasing salinity.
2. The process was easy to control.
3. Lime sludge served as a weighing agent on the sludge flocs, causing them to settle better, which could be a critical factor for this plant's wastewater treatment.
4. The estimated savings for Warren Foods if they used lime sludge, rather than sodium hydroxide, for wastewater neutralization was $5000/year.
5. At the time of the test, Warren Foods produced wastewater at a rate of 140,000 gallons/day.

Use of Lime Sludge for Dust Control on Gravel Roads

To confirm the feasibility of this application, two objectives had to be met:

(1) Lime sludge had to be shown to increase the fines content (defined as the percentage of particles that are 0.075 mm in diameter or smaller) of the particle size distribution of the gravel.

(2) A test needed to show that less dust would be generated on a section of gravel road that had lime sludge mixed into it than on a section that did not.

Figure 13 shows that the test section for 220th Street had a higher fines content (14%) than the control section (7%). However, Figure 14 shows that the control section for Old Bloomington Road had a higher fines content (9%) than the test section (6%), so the first objective was not realized. The dust collection results (Table 5) show that the gross amount of dust collected was greater on the test sections than on the control sections, however the two samples are quite similar. A simple t-statistic was calculated for each location's dust measurements and a null hypothesis, that there was no difference in the population means of dust amounts collected, was tested. The t-statistic for the Bloomington Road was -0.4809 and the 220th Street was -0.1820. The t-statistic for alpha divided by 2 was 2.447; since the absolute value of each t-statistic for the roads was less than the t-statistic for alpha divided by 2, the null hypothesis was not rejected. Within a 95% confidence interval, there was no statistical difference between the population means of the two samples. Therefore the results do not support that second objective of reducing dust generation by applying lime sludge to the gravel road.

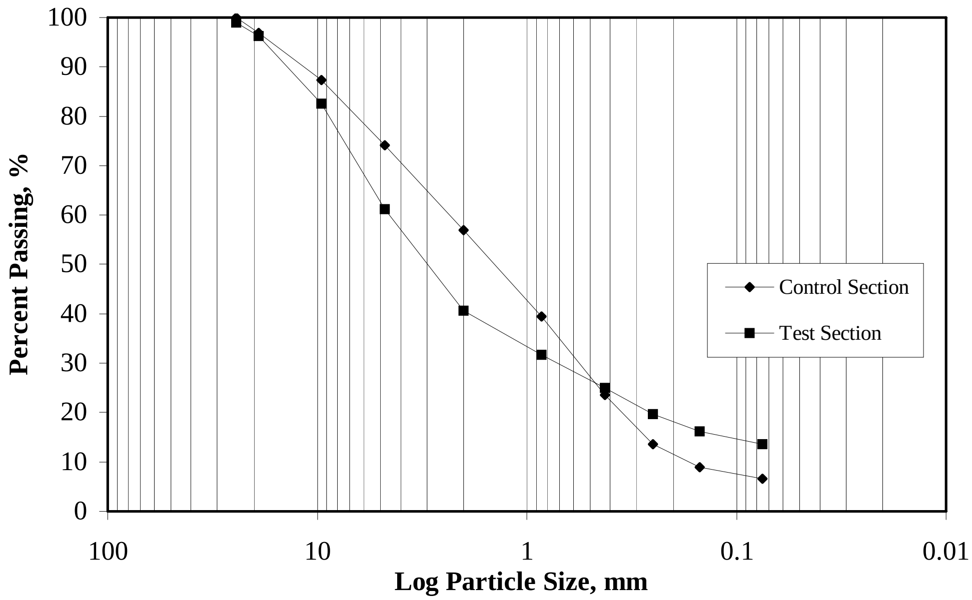

Figure 13: 220th Street Particle Size Distribution (Wet Sieved)

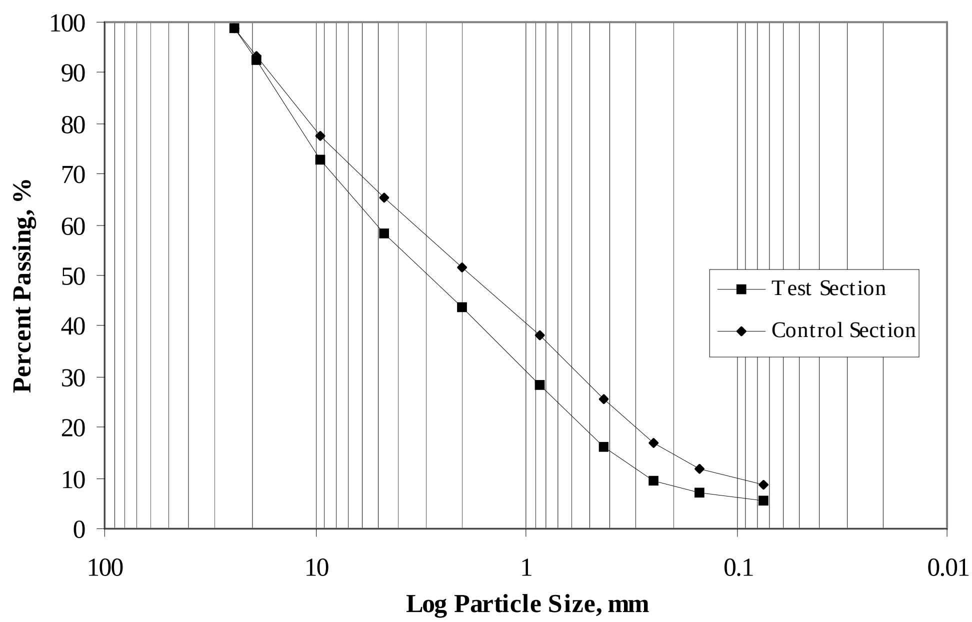

Figure 14: Old Bloomington Road Particle Size Distribution (Wet Sieved)

Table 5: Results for Dust Collection Tests

Location/Type	6/24/02 Weight of Dust (g)	7/4/02 Weight of Dust (g)	7/24/02 Weight of Dust (g)	8/7/02 Weight of Dust (g)
Bloomington/Control	0.1324	0.3104	0.2204	0.051
Bloomington/Test	0.1503	0.4267	0.2745	0.0522
220th/Control	0.1599	0.2658	0.2904	0.3459
220th/Test	0.1434	0.4254	0.1756	0.3763

Use of Lime Sludge for Fill Materials in Road Construction

Unconfined compressive strength (UCS) is one method to judge the strength of a fill material. The benchmark used to evaluate whether the lime sludge had sufficient UCS was 345 kPa (50 psi). This was the minimum value recommended by Ferguson and Leverson (1999) to significantly reduce the potential for settlement in deep fills. Lime sludge was first added to a silty soil, as an admixture would be, and then compared to cement in UCS tests. The purpose of this test was to evaluate whether or not lime sludge added strength to a known weak soil (Western Iowa loess, a silt).

Figure 15 shows how a common additive, portland cement, increases the unconfined compressive strength (UCS) of the loess soil. When lime sludge is added in a similar manner, no strength advantages are realized. Table 6 shows the data used to generate Figure 15. From these tests, it was concluded that lime sludge, by itself, does not add UCS to a soil. It is noted that lime sludge has no binding properties like those of portland cement.

In general, stabilizers like portland cement and fly ash bond soil particles together. When the mixtures are allowed to cure, they gain strength. The next set of tests considered cure time as a variable in strength gain. Figure 16 and Table 7 show that for lime sludge alone, no strength

Table 6: Mixing Cement and Lime Sludge with Loess Soil and Testing UCS

Cement (%)	Lime Sludge (%)[b]	Moisture Content, Soil (%)[b]	Moisture Content, Mix (%)[b]	Dry Density (g/cm^3)	Cure Time (days)	Load (kN)	Stress (kPa)	Error from Average[a] (kPa)
0	0	17.3	17.3	4.85	1	0.58	289	5.53
0	0	17.3	17.3	4.84	1	0.59	293	1.38
0	0	17.3	17.3	4.86	1	0.61	301	6.91
5.9	0	17	17	4.70	28	5.18	2559	128.52
5.9	0	17	17	4.71	28	5.25	2591	96.35
5.9	0	17	17	4.81	28	5.57	2748	60.28
5.9	0	17	17	4.74	28	5.43	2679	7.95
5.9	0	17	17	4.75	28	5.79	2860	172.53
11.7	0	17	17	4.70	34	8.38	4138	43.10
11.7	0	17	17	4.75	34	7.99	3945	236.18
11.7	0	17	17	4.70	34	8.35	4123	58.84
11.7	0	17	17	4.69	34	8.73	4307	125.90
11.7	0	17	17	4.70	34	8.90	4394	212.21
17.6	0	17	17	4.65	34	10.96	5410	10.96
17.6	0	17	17	4.66	34	10.83	5344	54.75
17.6	0	17	17	4.70	34	10.85	5355	43.15
17.6	0	17	17	4.71	34	10.60	5232	166.99
17.6	0	17	17	4.66	34	11.45	5653	253.92
23.4	0	17	17	4.71	34	13.05	6441	108.14
23.4	0	17	17	4.65	34	12.06	5952	380.62
23.4	0	17	17	4.70	34	12.07	5960	372.95
23.4	0	17	17	4.70	34	13.60	6714	381.49
23.4	0	17	17	4.69	34	13.37	6597	263.94
0	4.4	17.4	15.3	4.65	31	0.66	326	9.11
0	4.4	17.4	15.3	4.69	31	0.66	326	9.11
0	4.4	17.4	15.3	4.68	31	0.67	330	4.97
0	4.4	17.4	15.3	4.71	31	0.69	343	7.46
0	4.4	17.4	15.3	4.72	31	0.71	351	15.74
0	8.7	16.7	14.7	4.57	31	0.74	367	4.97
0	8.7	16.7	14.7	4.57	31	0.73	359	3.31
0	8.7	16.7	14.7	4.57	31	0.74	367	4.97
0	8.7	16.7	14.7	4.61	31	0.72	355	7.45
0	8.7	16.7	14.7	4.62	31	0.74	363	0.83
0	14.9	17.1	14.2	4.53	31	0.76	376	2.48
0	14.9	17.1	14.2	4.45	31	0.76	376	2.48
0	14.9	17.1	14.2	4.48	31	0.79	392	14.07
0	14.9	17.1	14.2	4.49	31	0.79	388	9.93
0	14.9	17.1	14.2	4.43	31	0.73	359	19.04

Table 6: Mixing Cement and Lime Sludge with Loess Soil and Testing UCS

Cement (%)	Lime Sludge (%)[b]	Moisture Content, Soil (%)[b]	Moisture Content, Mix (%)[b]	Dry Density (g/cm^3)	Cure Time (days)	Load (kN)	Stress (kPa)	Error from Average[a] (kPa)
0	17.1	16.9	14.3	4.57	28	0.72	322	35.61
0	17.1	16.9	14.3	4.57	28	0.71	355	2.48
0	17.1	16.9	14.3	4.52	28	0.74	351	6.62
0	17.1	16.9	14.3	4.49	28	0.79	367	9.94
0	17.1	16.9	14.3	4.49	28	2.37	392	34.78
2.5	2.5	17.4	16.0	4.91	28	2.47	1171	90.26
2.5	2.5	17.4	16.0	4.74	28	2.09	1220	139.41
2.5	2.5	17.4	16.0	4.79	28	1.92	1031	49.18
2.5	2.5	17.4	16.0	4.79	28	2.09	949	131.31
2.5	2.5	17.4	16.0	4.75	28	4.31	1031	49.18
5	5	17.5	15.2	4.70	28	4.35	2127	42.93
5	5	17.5	15.2	4.69	28	4.11	2148	63.16
5	5	17.5	15.2	4.65	28	4.35	2030	54.23
5	5	17.5	15.2	4.69	28	3.99	2148	63.16
5	5	17.5	15.2	4.65	28	5.01	1969	115.02
7.5	7.5	17.4	14.5	4.62	28	5.14	2470	5.66
7.5	7.5	17.4	14.5	4.67	28	4.81	2535	70.06
7.5	7.5	17.4	14.5	4.63	28	4.92	2374	91.05
7.5	7.5	17.4	14.5	4.66	28	5.09	2430	34.62
7.5	7.5	17.4	14.5	4.62	28	5.31	2515	49.94
10	10	17.5	13.4	4.67	28	5.33	2623	39.35
10	10	17.5	13.4	4.54	28	5.27	2631	31.31
10	10	17.5	13.4	4.54	28	5.44	2599	63.46
10	10	17.5	13.4	4.58	28	5.62	2684	20.91
10	10	17.5	13.4	4.53	28	0.00	2776	113.20

Notes:

a. The error was calculated by taking the absolute value of the stress determined minus the average value of the stresses in the given set. A set is defined as the specimens having the same mix design.

b. Percentages based on total dry weight of solids

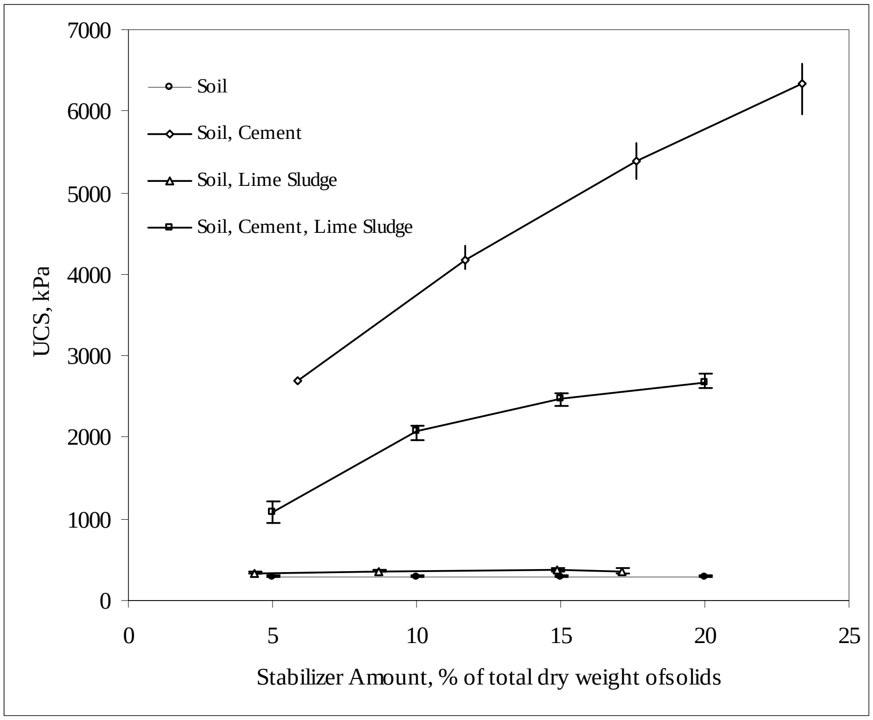

Figure 15: Effects of Mixing Cement and Lime Sludge with Loess Soil on the UCS

gain occurs with additional curing time. However, Figures 16 and 17 demonstrate that strength gain was associated with cure when either portland cement or fly ash was present—especially in the first 28 days. In Figure 16, the specimens containing low stabilizer amounts (10% or less) lost strength between 28 and 56 days of cure time. The reasons for this strength loss could not be determined because not all of the data from these tests were available. Figure 17 and Table 8 show that the strength achieved with bottom ash compared fairly well with that achieved with another coarse material, concrete sand.

Table 7: Effect of Curing Time on UCS of Chemically Stabilized Lime Sludge Mixtures

Cure (days)	Lime Sludge (%)	OGS FA (%)	Portland Cement (%)	Moisture Content (%)	Average Dry Density (g/cm^3)	Average UCS (kPa)	Upper Error Bar (kPa)	Lower Error Bar (kPa)
1	100	0	0	51	1.06	99.8	0	0
28	100	0	0			109.8	0	0
56	100	0	0			117.2	0	0
1	95	0	5	51	1.08	149.6	7.1	5.6
28	95	0	5			193.6	12.7	10.7
56	95	0	5			172.8	14.1	10
1	90	0	10	40	1.18	386.9	9.6	18.5
28	90	0	10			496.1	0.9	0.4
56	90	0	10			434.2	46.7	32.4
1	95	5	0	47	1.11	130.6	5.4	6
28	95	5	0			180.6	15.6	9.2
56	95	5	0			165.0	9.8	8.9
1	70	30	0	40	1.21	340.7	12.3	19.2
28	70	30	0			496.8	12.9	21.9
56	70	30	0			535.8	4	4
1	50	50	0	36	1.26	277.1	21.7	38.6
28	50	50	0			443.8	2.9	1.8
56	50	50	0			444.3	21.9	12.9

Note: Percentages based on total dry weight of solids.

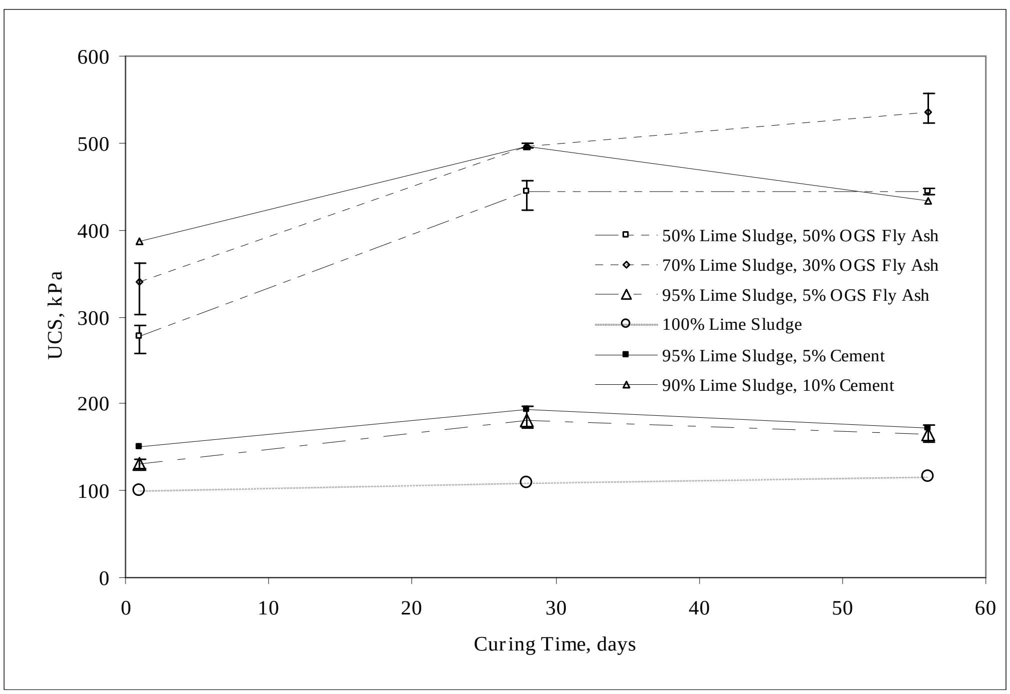

Figure 16: Effect of Curing Time on Lime Sludge and Cement/Fly Ash Mixtures

Table 8: Effects of Curing Time on the UCS of Chemically Stabilized Lime Sludge Specimens Mixed with Bottom Ash and Concrete Sand

Cure (days)	Lime Sludge (%)	Ames FA (%)	Bottom Ash (%)	Concrete Sand (%)	Moisture Content before Cure (%)	Moisture Content after Cure (%)	Average UCS (kPa)	Upper Error Bar (kPa)	Lower Error Bar (kPa)
7	82.5	17.5	0	0	25	24.0	603.1	107.9	69.3
28	82.5	17.5	0	0	25	24.0	879.4	75.2	86.2
56	82.5	17.5	0	0	25	24.0	918.9	38.4	60.2
7	65	17.5	0	17.5	21	20	735.4	79.8	165
28	65	17.5	0	17.5	21	20	947.4	62.3	66
56	65	17.5	0	17.5	21	19.0	1104.9	82.1	77.9
7	65	17.5	17.5	0	22	21.0	824.0	52.6	40.5
28	65	17.5	17.5	0	22	20.0	934.0	93	160.1
56	65	17.5	17.5	0	22	21.0	1054.6	54.5	72.4

Note: Percentages are based on total dry weight of solids.

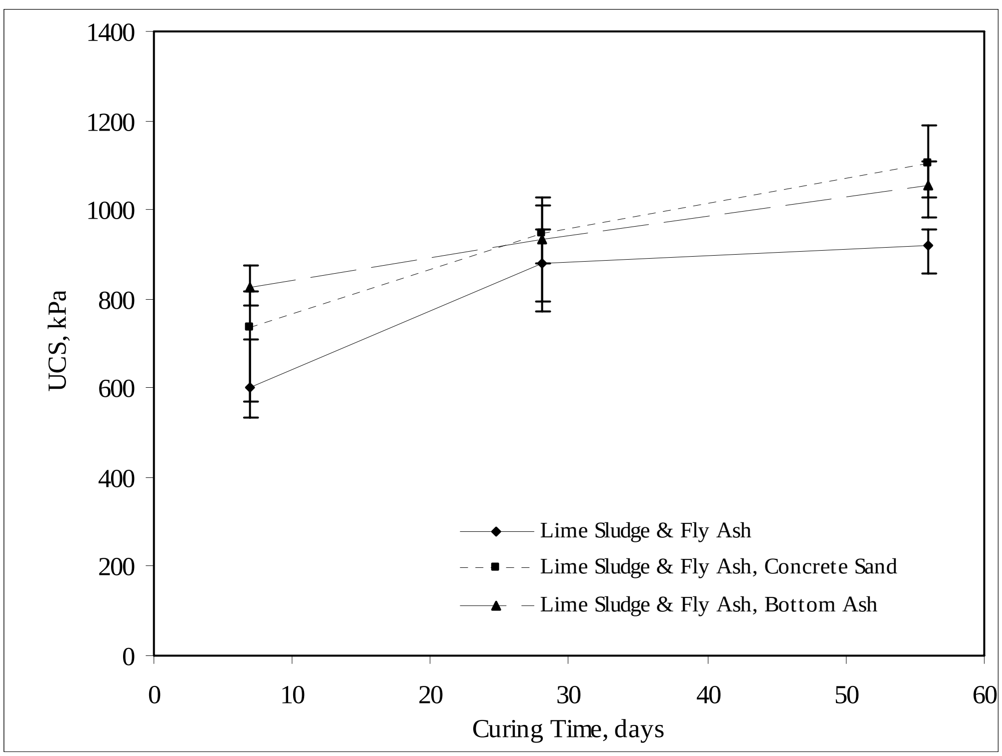

Figure 17: Effects of Curing Time on Mixes Containing Fly Ash and Bottom Ash

Conclusions and Recommendations

In all of the feasibility studies, two problems were common concerns: the cost of dewatering and the cost of transportation. Considering the low value of the product in most reuse applications, these costs should play a crucial role in any further feasibility studies.

Use of Lime Sludge in Dry Scrubbing Power Plants

In summary, lime sludge showed positive signs of reducing the amount of sulfur dioxide at the Iowa State University Cogeneration Facility. The observed impacts on boiler bed temperatures and bed pressures were not as dramatic as the operators expected, but there was concern over the long-term impact that feed problems may have on the boiler beds. Furthermore, the impact of lime sludge use on NO_X emissions and consumption rate was inconclusive due the feed problems. These problems can be addressed with an effective mechanism for controlling the feeding rate of the lime sludge, by delivering the lime sludge at the prescribed moisture content, and by conducting more test runs over longer periods.

The full evaluation of the potential of lime sludge for dry scrubbing would require equipment that is not available to this particular research program. To accomplish the evaluation, future research needs to be able to dry 40 tons of lime sludge to about 2% moisture. This was not possible with the time, funds, and facilities available to this project and staff. This work would directly benefit the City of Ames and the Iowa State University Cogeneration Facility, as producer and consumer of the product, but the two parties were not willing to invest in a sludge drying facility at the time of this research. If developed, the facility not only would contribute to maintaining protection of the environment from SO_x and NO_x gas by-products of power generation, but also could pay for itself through a reduction in the cost of lime sludge disposal and savings in the purchase of calcium carbonate reagent.

Power plants generally have low grade waste heat available that could be used for lime sludge drying. It would require a dryer specifically designed to dry lime sludge, however. In the case of Ames, the lime sludge production and the dry scrubber reagent needs of the Iowa State Cogeneration Facility are almost a perfect match and the distance is only three miles.

Replacing Limestone with Lime Sludge in Cement Kilns

The current conditions mandate that any water treatment plant that sends lime sludge to Lehigh Cement for use in cement production must absorb most of the cost of dewatering, drying, loading, and transportation. These costs far exceed the cost of the other alternative disposal options. Use of lime sludge in cement production would only be feasible if a water treatment plant were closer to the cement plant than the source of supply for limestone. Such an opportunity was not known to be available in Iowa during the duration of this research project.

Use of Lime Sludge for Wastewater Neutralization

Further research effort with this reuse application was stopped only because it did not fall within the scope of this research project, which seeks to present applications that will empty stockpiles by consuming large amounts of lime sludge. Nevertheless, lime sludge should definitely be considered for neutralization of acidic wastewaters wherever applicable, although the dosing method would need to be refined. A major advantage of this application is that dosing can handle significant errors without detrimental effects to the resulting effluent. Since the lime sludge buffers the water being treated (instead of being a strong base), the operator can overdose the water and still not reach pH levels that are greater than normal.

Use of Lime Sludge for Dust Control on Gravel Roads

The results of the dust control experiment did not show that incorporating lime sludge in the gravel resulted in a reduction of dust generated. The research team brainstormed different methods of incorporating the lime sludge into the gravel surface layer, considered more testing over a longer period, and looked at using a different method for measuring dust generation. However, it was decided not to continue work on this application because the tests performed did not show enough potential for success, and changes to the test methods were not expected to make enough of a difference to justify further effort and expenditure of resources.

Use of Lime Sludge for Fill Materials in Road Construction

Three significant findings resulted from the feasibility tests for using lime sludge as a fill material for road construction. (1) Lime sludge is not a stabilizer; that is, it does not add strength to a soil as cement and fly ash do. (2) While lime sludge, by itself, did not achieve the benchmark for UCS, when it was stabilized with cement or fly ash, significant increases in UCS resulted and far surpassed the UCS benchmark. (3) Gains in UCS resulted after 28 days of cure time. Between 28 and 56 days of cure time, increases in UCS were inconsistent. In mixes with at least 17.5% (of total dry weight of solids) fly ash in them, there were UCS gains between the 28- and 56-day cure times. In mixes containing 5% and 10% of fly ash or cement, there was not a strength gain between the 28- and 56-day cure times.

UCS is not the only parameter of interest in evaluating the potential of a material for fill. Further testing regarding classification, density, shear strength, durability, penetration resistance, and hydraulic conductivity were of interest following these feasibility tests. Since the UCS results were positive and the application has a great potential to consume all of the lime sludge stockpiles, using lime sludge in construction fill was chosen as the application on which to focus the research effort.

PART II - CHARACTERIZATION OF CHEMICALLY STABILIZED LIME SLUDGE FOR USE IN STRUCTURAL FILLS

Introduction

Construction fill is a common application for the disposal of excess solid waste products in Iowa. The state government has given universal approval for the use of items such as foundry sand, glass, lime kiln dust, concrete rubble, brick rubble, asphalt pavement rubble, sandblasting abrasive, wastewater filter sand, wood ash, so long as they are in compliance with section 108.6(1) of the code (Iowa Administrative Code, 2005). Settlement, durability, strength, and leaching could present problems with some wastes. Section 108.6(1) is primarily concerned with the environmental effects of placing the fill—especially leaching. The owners of the property to which the fill is applied are interested in any potential for settlement or degradation (erosion) of the fill volume. Stability and volume change potential are important engineering parameters that must be evaluated to ensure sound foundations for buildings and roads. Since the density of roads and road construction are greatest around cities, the ability to use lime sludge as a fill material could be a good match, as water treatment plants are also close to or within cities. In addition, the amount of roadway fill materials used in the State of Iowa far exceeds the amount of lime sludge stockpiled and produced. Therefore, the use of dried lime sludge, modified with stabilizers or mixed with soil and other solid materials, was investigated further.

When considering a material for use as a construction fill, several engineering properties should be investigated. These include particle size distribution, shear strength, hydraulic conductivity, and durability in wet/dry and freeze/thaw conditions. Once these properties are quantified through lab and site testing, engineers can incorporate this information into the design of embankment fill applications. The information presented in this part will describe the laboratory testing performed.

Organization of this Part

The work in this Part was organized as follows: (1) Selected index properties were investigated. (2) Mixtures of lime sludge, a silty soil (loess), portland cement, bottom ash, and fly ash were tested. (3) Amounts of stabilizer and moisture were varied within the mixes. (4) Laboratory tests including unconfined compressive strength, direct shear, CBR, and hydraulic conductivity were performed and presented in this part.

Materials

Lime Sludge

The lime sludge used for testing came from the water treatment plant located in Ames, Iowa. As described earlier, this sludge was dewatered in a lagoon and then dried on a pavement pad. Once the sludge is dried, the sludge-processing contractor, BMG Biosolids, stores it temporarily under a canopy. The floor of the storage canopy is paved. After visiting the site more than a 10 times of the past year and during each season, I’ve never seen the sludge drying area flooded with standing water. There were periods in the spring and summer of 2003 that resulted in flooding in Story County, but not to the extent that Ames was classified as a disaster area by the Governor of Iowa. Around the edges of the canopy pavement is a cinder block wall that is about 4 feet tall. The sides of the canopy are open, and the roof is a semi-ellipse, so rain precipitation can be diverted away from the stockpile, even though there are no gutters or water directional devices coming from the roof. One sample of lime sludge was taken in August 2003 and was used for the entire laboratory testing in Part II.

The Ames stockpile is emptied and restocked by BMG on a regular basis each summer, as they dry and sell lime sludge for agricultural purposes, but the frequency of the turnover was not documented. Sampling in August 2003 was done by hand shovel, and material on the top 6 inches was discarded. It was thought that the material on the surface of the stockpile would not be at the same moisture content as the rest of the pile due to some surface evaporation. About one 44-gallon container (about 0.16 m^3) was taken in the August 2003 sampling. The moisture content of the sample was about 43%. The sample was stored in a closed container.

Periodically, the moisture content was verified, but it remained at 43% throughout the course of this study. Estimating the size visually, the particle sizes of the lime sludge taken in the August 2003 sampling varied from large, agglomerated boulders (256 mm or more) to a fine powder (0.04 mm or less). All sizes can be easily reduced to the powder form with a mortar and pestle.

Fly Ash

Two types of fly ash were used for the testing. One was from the Ames Power Plant and the other from the Ottumwa Generating Station (OGS). One sampling of fly ash was taken from each location for laboratory work. Each sample of fly ash was obtained directly from each power plant's overhead fly ash storage bin in August 2003.

When coal is burned in power generation facilities, two types of solids remain in the furnace. Bottom ash is a sandy, gritty solid that remains at the bottom of the furnace after combustion. Fly ash consists of the solids that are carried up the flue with the gases created from combustion. Fly ash is collected from the gas stream in an electrostatic precipitator and transported to an overhead storage bin (which large trucks can drive underneath to load). Due to the high temperatures in the flue, the ash is dry and easily forms an aerosol with air because of its small particle size (silt and clay sizes). Alternatively, due to the spherical particle shape, the solids will pour and flow like water if not dispersed into the air. Care must therefore be taken when handling, pouring, and mixing fly ash.

The lightweight, clay and silt-sized particles in fly ash contain various compounds, including minerals formed from varying amounts of calcium, aluminum, silicon, quartz, calcium oxide (lime), calcium sulfate (anhydrite), and a few heavy metals. Fly ash from both sources (Ames and OGS) was analyzed for their mineral composition by the Materials Analysis Research Laboratory (MARL) at Iowa State University. Figure 18 shows the mineral composition of the Ames and OGS fly ash sampled in August 2003.
The analytical elemental composition of fly ash is quite variable. Table 9 shows this variability in each of fly ashes used by showing the analytical elemental composition of ash

taken from the same plant, but at different times, between 2001 and 2005. The XRF tests in Table 9 were not done on the fly ash used to produce the data in this thesis. Table 5 shows that it is very likely that the ash used to produce the data in this thesis did not have the same analytical elemental composition.

In order to determine how the UCS of fly ash varies with the moisture content, a simple experiment was performed. Fly ash and varying amounts of water were mixed and poured into 5 cm by 5 cm cube molds. The specimens were sealed in plastic wrap and in ziplock bags and cured for 1 week at 100^{o}F. Following cure, the specimens were tested to the maximum unconfined compressive strength at a strain rate of 0.127 cm/min. Mixtures were not tested in triplicate as these experiments were only preliminary. Figure 19 shows a comparison of the strengths of the two fly ashes used in this study. Each fly ash has a distinct moisture content that results in a maximum UCS: 24 % for the Ames fly ash and 32% for the OGS fly ash. These values were taken into account in the mixture design used for engineering property evaluation.

Table 9: X-Ray Fluorescence Test on Fly Ash Produced on Different Dates.

Constituent	OGS Sample 1	OGS Sample 2	Ames Sample 1	Ames Sample 2
Na_2O	3.28	3.27	2.29	2.42
MgO	4.29	4.27	5.74	5.93
Al_2O_3	21.55	21.47	16.73	17.59
SiO_2	37.23	37.10	35.37	33.55
P_2O_5	1.45	1.44	1.20	1.09
Fe_2O_3	5.73	5.71	6.44	5.92
SO_3	2.20	2.19	2.95	3.48
K_2O	0.53	0.52	0.38	0.52
CaO	22.60	22.51	26.89	26.76
TiO_2	1.54	1.53	1.62	1.65
SrO	0.42	0.42	0.33	0.30
Mn_2O_3	0.03	*	0.02	0.03
BaO	0.76	0.75	0.78	0.73
Total	101.59	101.18	100.74	99.96

*Indicates no data.

Note: If the total is not exactly 100%, then there was most likely an error in weighing the initial sample or the default value of the specimen weight was entered.

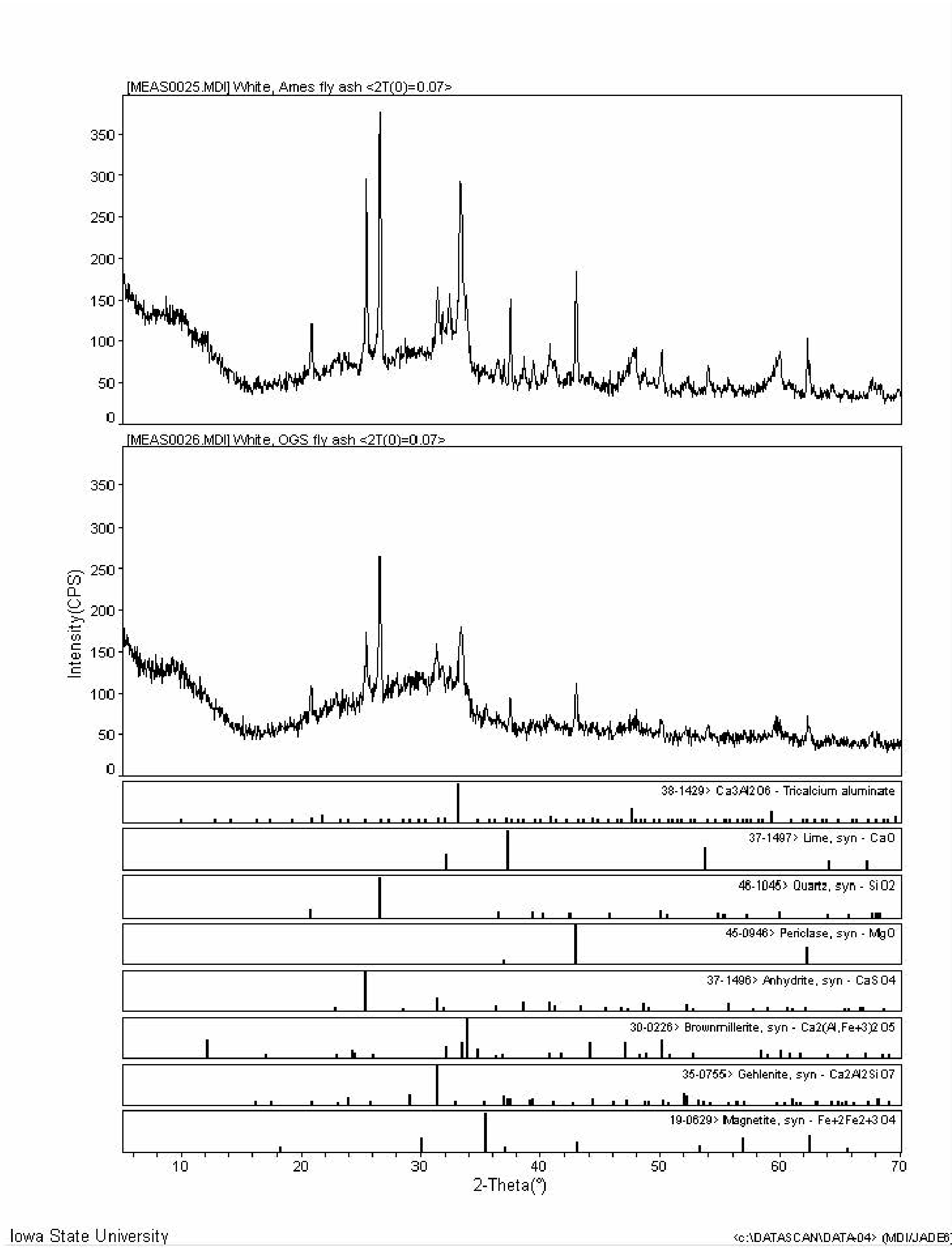

Figure 18: XRD Analysis of Ames and OGS Fly Ash

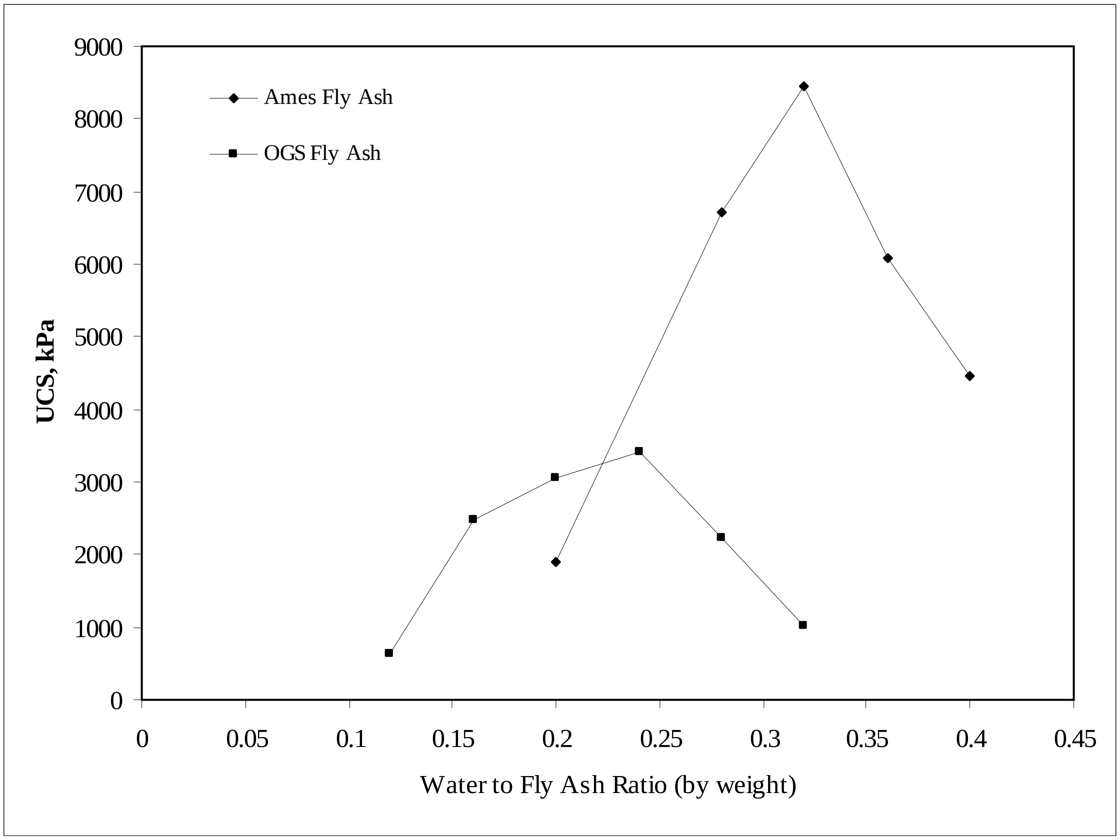

Figure 19: Fly Ash Strength vs. Moisture Content

Fly ashes vary not only in strength, but also in how fast they react with water to form cementitious products. A simple experiment quantifies this reaction. A circular steel pan about ¾-inch deep and 4 inches in diameter was filled with freshly mixed fly ash and water. The moisture content used was the optimum chosen from the strength curves. Next, the surface of the fly ash and water mixture was leveled off even with the top of the circular steel pan with a straightedge, and measurements of penetration resistance, taken with a pocket penetrometer, were recorded at set time intervals. Measurements were taken until the fly ash hardened and the penetration resistance was maximized. No replications of the test were done, as this preliminary test was performed to obtain an idea of how fast a given fly ash sets. Figure 20 shows the results: the Ames fly ash set in about 12 minutes, but the OGS fly ash took 65 minutes.

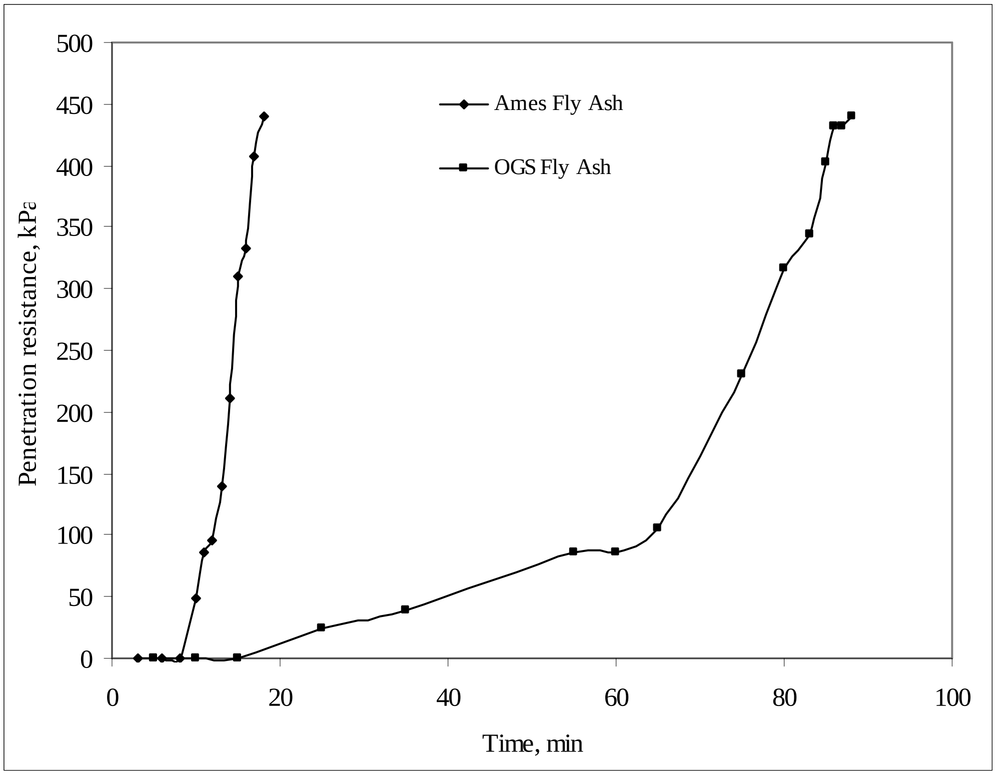

Figure 20: Fly Ash Set Times for Ames and OGS Fly Ashes

Fly ashes vary in performance due to differences in the type of coal burned, how the coal is burned, and what it is burned with. For example, the fly ash from the Ames Power Plant is burned with up to 10% solid refuse (municipal paper and plastic waste), while the coal at OGS is periodically burned with switch grass. Specific reasons for the difference in the UCS of the two fly ashes were not investigated. The purpose of the preliminary UCS and penetration resistance tests was to determine the optimum moisture for maximizing the UCS of fly ash alone and to roughly quantify how fast each fly ash sets.

Portland Cement

Type I portland cement was purchased from the Central Stores at Iowa State University, so during the various stages of testing, there was no uncertainty about the consistency and quality of this material. It was used in this phase of the research studies as an admixture or stabilizer for the lime sludge to contribute additional strength and durability to the mixture. It was also used as a comparison for the other stabilizer, fly ash. The qualities of portland cement are well documented by institutions, such as the Portland Cement Institute, all across the country. Therefore, several mixtures were prepared with portland cement instead of fly ash for comparison purposes.

As with fly ash, the unconfined compressive strength of portland cement varies with moisture content. Portland cement and varying amounts of water were mixed and poured into 5 cm by 5 cm cube molds. The specimens were sealed in plastic wrap and in ziplock bags and cured for 1 week at about 38^{o}C. Following cure, the specimens were tested to the maximum unconfined compressive strength at a strain rate of 0.127 cm/min. Mixtures were not tested in triplicate as these experiments were only preliminary. The results for the portland cement used in this study are shown in Figure 21. The portland cement has a distinct moisture content (32%) that results in a maximum strength. This value was taken into account in the mixture design for the fill material tests.

Bottom Ash

Bottom ash was obtained from the Ottumwa Generating Station in August 2003. It was sampled manually with a shovel from a large outdoor stockpile. About 22 gallons (0.083 m^3) was collected. It is a black, nonvolatile, sandy, and gritty mixture of hard solids that fell to the bottom of the combustion chamber. The purpose of incorporating this material in the mixtures was to use another stockpiled waste material in the fill. Incorporating this material for these tests was encouraged for this research program since it involves emptying stockpiles of another municipal waste.

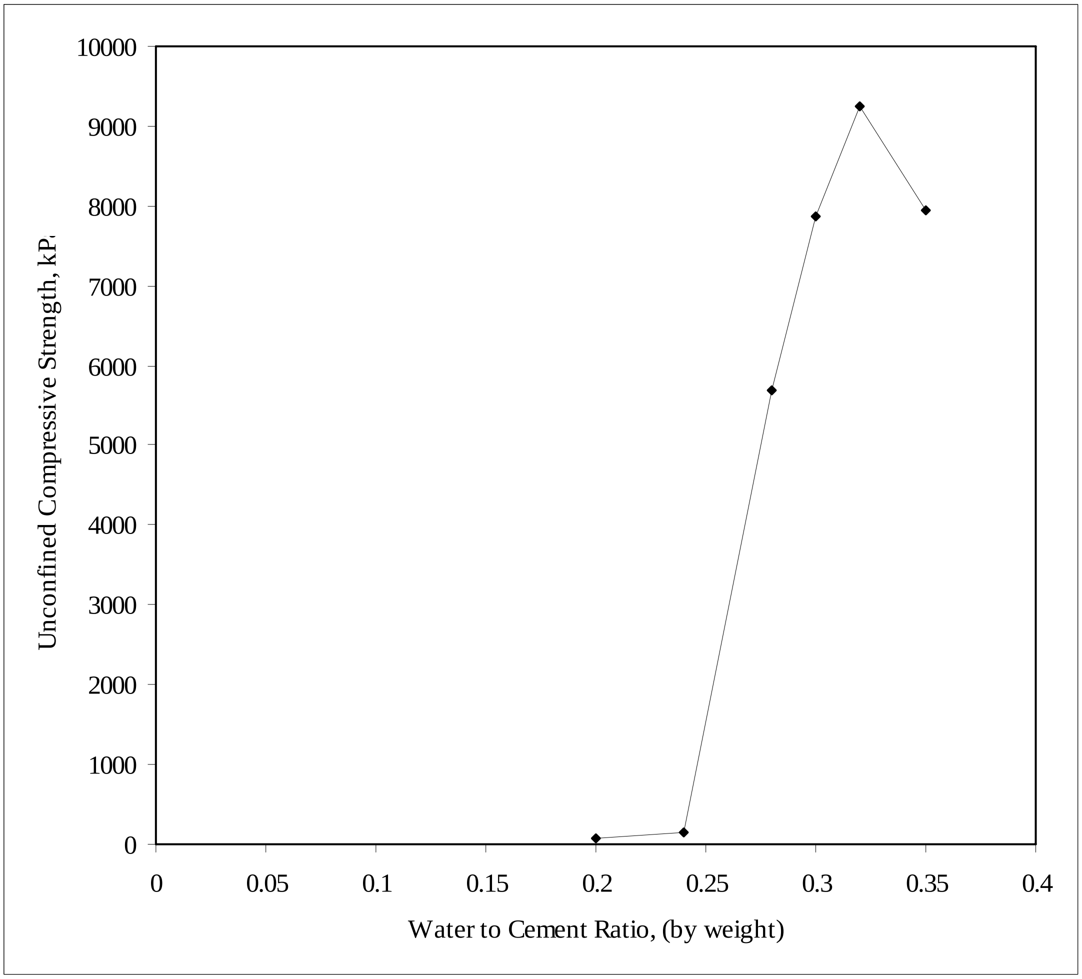

Figure 21: Portland Cement Strength vs. Moisture

Methods

The purpose of the tests was to define the engineering properties of the lime sludge mixtures. The tests chosen were as follows: particle size analysis and soil classification, Atterburg limits (liquid and plastic limits and plasticity index), moisture density relationship, unconfined compressive strength, direct shear, California bearing ratio, and flexible wall permeameter.

Particle Size Distribution and Atterberg Limits

For the particle size distribution, the Standard Test Method for Particle Size Analysis of Soils (ASTM D422) was used. The lime sludge was air dried in the laboratory to a moisture content of about 2% and then thoroughly pulverized until the particles could not be broken down further (as specified by ASTM D422). The sample retained on the Standard No. 10 sieve was washed (Standard Practice for Dry Preparation of Soil Samples for Particle Size Analysis, ASTM D421) and the wash water retained and dried for use in fines analysis. The multipoint liquid limit method of the Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils (ASTM D4318) was used on pulverized, air-dried lime sludge. All lime sludge used for this test passed the Standard No. 40 sieve for these tests.

Moisture-Density Relationship

In defining the moisture density relationship, ASTM D698, The Standard Test Method for Moisture Density Relations, was used except for the type of compaction apparatus. The same apparatus that was used to prepare 2x2 specimens for the UCS test in Part I was used for moisture-density tests in this Part. In this test, all specimens were compacted with the same compaction effort, but at different moisture contents. The goal of the test was to find the moisture content that resulted in the highest density. The materials are screened through a No. 4 sieve (4.75 mm opening) prior to compaction using five blows of a 5 lb. drop hammer on each side of the specimen. This typically yields a maximum dry density similar to that for Standard Proctor compaction. After compaction, the molded specimen is extracted using a hydraulic jack, and the weight and dimensions are measured. The moisture content is determined by oven-drying.

Unconfined Compressive Strength

The Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders (ASTM D1633) was used. Instead of the Standard Proctor size specimens prescribed by the standard method, UCS tests were performed on 2x2 cylindrical specimens to save time and material. In a few cases, the mix designs were not tested in triplicate. The reason for single-specimen testing was to deduce a trend in mix design, not to establish a formal strength value. In this thesis, the UCS results that have error bars show those tests tested in triplicate. Those without error bars were single-specimen results.

When a stabilizer such as portland cement or Class C fly ash was used, specimens were wrapped in thin plastic wrap, wrapped again in aluminum foil, and then sealed in a ziplock freezer bag before curing. Curing either occurred for 7 days in an oven set at 38^{o}C, or in a moisture room at about 20^{o}C for the prescribed amount of time. Curing time was varied for a few of the mixes to determine any changes in strength. The moisture content was measured after the materials were mixed together and on the same day that the specimens were molded. The moisture content was also taken after strength testing for the specimens for which results appear in Table 15. The moisture content after strength testing should be less than the moisture content taken directly after mixing since the fly ash hydrates during cure and binds water in chemical bonding.

Particle sizes were reduced to below the Standard No. 4 sieve size for tests with the 2x2 specimens. Given the small size of the lime sludge and fly ash particles, this only required breaking up clumps of material into its original form. However, since the bottom ash had many larger particles, those particles retained on the Standard No. 4 sieve were discarded.

Direct Shear

The Standard Test Method for Direct Shear Test of Soils Under Consolidated Shear Conditions (ASTM D3080) was performed to characterize the shear strength parameters of stabilized lime sludge. For each set of tests, three individual specimens were tested at the normal stresses of 34.49 kPa (5 psi), 68.97 kPa (10 psi), or 103.5 kPa (15 psi), respectively. The first set of specimens were composed of lime sludge without the fly ash additive and were tested immediately after compaction. The second set of specimens consisted of one part fly ash mixed with two parts lime sludge (by dry weight) and was tested after 28 days of cure. The third set of specimens consisted of one part fly ash mixed with one part lime sludge (by dry weight) and was tested after 28 days of cure. The fourth and fifth sets of specimens had the same composition as the second and third sets, but were tested after 56 days of cure time.

For silt-sized materials, ASTM D3080 requires the freshly mixed soil and water to stand for about 18 hours prior to compaction to allow full hydration. However, during specimen preparation, the lime sludge and fly ash mix was not allowed to stand prior to compaction. From the results of the preliminary penetration tests on the fly ashes being used, it was known that if the mixtures were allowed to stand for 18 hours prior to compaction, the compaction hammer could break the bonds formed by the hydrating stabilizer, and thus the reason for using the stabilizer would be lost. Therefore, the mixes were compacted immediately after fly ash addition. After curing, all specimens were submerged in a pool of water and allowed to soak overnight prior to the start of consolidation. The direct shear box was submerged in the pool of water, and the consolidation and shearing parts of the test were done submerged as well.

The apparatus used for the tests was the Direct Shear Machine, Model number 26-2112, by ELE International. The weights that provide the normal stress are manually applied to the specimen, but the machine applies the shear at a preset rate of horizontal displacement. The machine is fitted with automatic transducers that relay horizontal and vertical displacements back to a computer, where they are automatically recorded. Shear force was measured via a proving ring. Displacements of that ring were communicated back to the computer via a third automatic transducer. The program for the test converted the proving ring displacements to shearing forces so they could be recorded as well.

California Bearing Ratio

The Standard Test Method for California Bearing Ratio (CBR) of Laboratory Compacted Soils (ASTM D1883) was used to quantify the strength and stiffness of the lime sludge mixes. A control set of lime sludge specimens and two mix ratios of lime sludge and Ames fly ash were prepared. The lime sludge and fly ash were mixed together at a moisture content of 30%, based on the combined dry weight of the solids. The lime sludge control sample was compacted at 42% moisture content.

The bearing ratio was determined by varying the compaction energy. Each set of three specimens had specimens corresponding, respectively, to 12, 25, and 56 blows per layer using a 5.5 lb rammer and a 12-inch drop as specified in the Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (ASTM D698). The first set of specimens compacted was the lime sludge only. The second and third sets were specimens of containing fly ash mixed at the 1:2 and 1:1 fly ash to lime sludge mix ratios. The second set was tested after 28 days of cure time and the third set after 56 days of cure time. Specimens were soaked for at least 16 hours prior to testing. A surcharge of about 4.54 kg was applied to the specimen during the soaking and testing period.

The apparatus used for CBR tests is a manually operated machine manufactured by ELE International, Soil Test Model CN-472 with a 26.7 kN (6000 lbf) proving ring. The machine moves the specimen upward into the penetration piston. A proving ring is situated directly above the penetration piston to measure the force applied to the piston via displacement of the proving ring. The displacement of the penetration piston and the displacement of the proving ring are measured by dial meters that measured to the nearest 0.254 mm (0.01-inch) and 0.0254 mm (0.001-inch), respectively. Readings are manually recorded. Displacement rate was measured by counting the displacement travel on the dial meter for a given time period. A timer was placed in clear view of the machine operator to maintain a consistent rate of displacement.

All of the material used in the mold passed the 3/4-inch sieve. Specimens were wrapped in plastic bags and then placed in covered plastic containers with a few inches of water at the bottom to prevent moisture loss during curing. Once the required cure time had elapsed, the specimens were removed from the plastic tub and soaked. Specimens were soaked for 16 hours prior to testing.

Durability

The weather cycles in Iowa's temperate climate can create durability problems for some fill materials. Lab tests that simulate alternating cycles of freezing and thawing and flooding and drought were performed. Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures (ASTM D559) and for Freezing and Thawing Compacted Soil-Cement Mixtures (ASTM D560) were followed using 2x2 cylinders. These tests also included an abrasion component. For each of these tests, the ingredients were mixed at optimum moisture with varied additive rates, compacted, and finally cured under a controlled moisture and temperature environment prior to durability testing.

The first set of wet/dry and freeze/thaw durability tests involved five different amounts of stabilizer and only measured mass loss of brushed specimens. Volume change measurements were not taken in the first set. Freezing and thawing was the most aggressive test for these mixes. No specimen survived a full 12 cycles of brushing regardless of additive amount. A second set of freeze/thaw durability tests was performed with two mix ratios to determine volume changes and mass losses of specimens that were not brushed.

The wetting and drying test involved placing two sets of specimens in a bucket of water for 6 hours and then drying them in a warm oven (about 37.8^{o}C) for about 42 hours. Weight measurements were taken between each cycle, and cycles continued until the specimen either failed or reached 12 cycles. Since the wetting and drying test was not the most aggressive test, it was not repeated for volume change measurements for these mixes. Using the standard procedure, specimens were brushed with a steel brush at a consistent pressure (about 3 lbf) after the drying part of the cycle. This is the simulated abrasion or erosion component of the test.

The freezing and thawing test involved placing two sets of specimens in a freezer at -12.2^{o}C for 24 hours and then thawing them in a moisture room (100% humidity at room temperature or 20^{o}C) for 24 hours. Weight and volume measurements were taken after each cycle. Volume was measured by measuring the diameter and height of the cylinder. If the specimen's shape had degraded so much that it no longer had cylindrical dimensions that could be measured, it was discarded and a 100% loss was recorded. After thawing, one of the two specimens was brushed. The specimen that was not brushed was only measured for volume and mass change.

<u>Hydraulic Conductivity</u>

The Standard Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter (ASTM D5084) was followed to determine the hydraulic conductivity. The specimens tested included lime sludge without fly ash, a 1:1 lime sludge to Ames fly ash mixture (on a dry weight basis), and a 2:1 lime sludge to Ames fly ash mixture (on a dry weight basis). Specimens containing Ames fly ash and lime sludge were cured in the test cell under no pressure for 1 week prior to commencement of saturation and consolidation. Deaerated water was used as a permeant.

Saturation was achieved through application of the "B-value" test. That is, for a given pressure increment, if the value of the increase in pore pressure divided by the increase in cell pressure was 0.95 or higher, the specimen was considered to be saturated. Although beginning and final specimen height measurements were taken and recorded for calculations, no height measurements were taken while the specimen was in the test cell. Since lime sludge has a low plasticity, it was assumed that test specimens would have minimal volume change during saturation.

For permeation, a constant head difference was applied to the specimen. The volume of water flowing through the specimen was measured and the time required to make this flow was recorded. This reflects the constant head, constant rate of flow, or Method D of ASTM D5084. The head difference was based on the gradients recommended by ASTM D5084 for materials with a hydraulic conductivity of 10^{-6} cm/sec. For each trial, the permeation was performed under two gradients. Whenever possible, the hydraulic conductivity value chosen for calculations and for reporting was the value using the lower gradient since it reflected volumes transmitted over a longer period of time. The hydraulic conductivity was calculated using the equation listed in 10.1.1 of the ASTM D5084.

The apparatus used for this test is the ELE International, Soil Test Tri-Flex 2, Model 25-0697. This apparatus uses water pressure to apply cell pressure and back pressure to the specimen. It has the capability to produce and store de-aired water in a separate cylinder for use as a permeant. It was also capable of applying vacuum to the tube, annulus, and specimen caps that transport the permeant to the specimen.

Results and Discussion

Index Properties of Lime Sludge

In the feasibility tests described in Part I, the lime sludge appeared to be a very fine and lightweight material without cohesive properties (when air-dried). The low UCS values of lime sludge only specimens supported this observation, but don't fully characterize it. The following data will demonstrate the particle size and plasticity of dried lime sludge and reveal how its density changes with moisture changes.

The particle size distribution of the lime sludge from the Ames Water Treatment Plant is shown in Table 10 and Figure 22. Since no mass was retained on the Standard No. 80 sieve, the percent fines for the Standard No. 60 and 80 sieves are the same. Liquid limit test results on the same sludge are shown in Table 11 and Figure 23. A linear regression of the moisture content versus the log of the number of drops was performed, and the equation is shown on Figure 23. Using this relation, the corresponding moisture content for 25 drops is 41%, which is the liquid limit. The moisture contents corresponding to the plastic limit specimens were 37%, 38%, and 37%. The plastic limit was accepted at 37%, resulting in a Plasticity Index of 4%.

From these results, lime sludge is classified as an inorganic silt, or ML, under the Unified Soil Classification and as an A-5 soil material under the classification used by the American Association of State Highway Transportation Officials (AASHTO). A material with over 90% fines and a low plasticity index is generally considered by AASHTO as "fair to poor" for highway subgrade construction.

Moisture-Density Relationship

The next set of tests quantified the effects of a standard compaction effort on samples of lime sludge. The density of a soil material has strong influences on strength, stiffness, and permeability. Various graduate students prior to Rob Baker's involvement in the projects started these tests; and these results were combined with all the results under one data set.

Table 10: Particle Size Distribution Data

Type	Sieve No.	Diameter, mm	% finer
Gravel	3/8 in.	9.525	100
	4	4.75	100
Sand	10	2	100
	20	0.85	99
	40	0.425	98
	60	0.25	96
	80	0.18	96
	100	0.15	93
	200	0.075	90
Silt (0.075–0.002)		0.0359	80
		0.0229	65
		0.0133	15
		0.0094	6
		0.0067	5
		0.0033	0
Clay (0.002–0.001)		0.0014	0

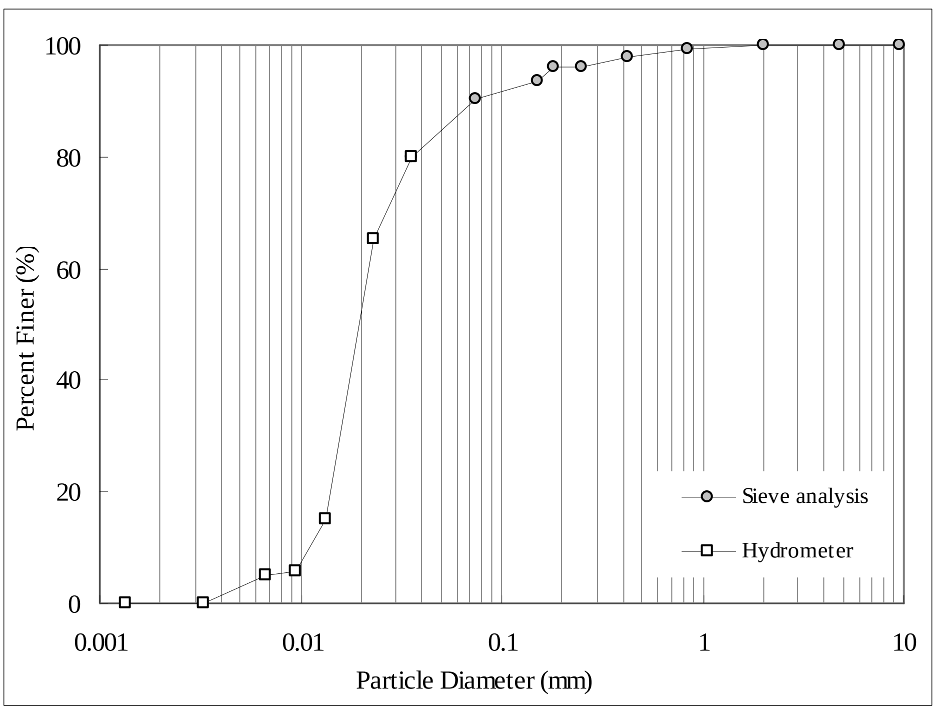

Figure 22: Particle Size Distribution for Lime Sludge

Table 11: Liquid Limit Data for Lime Sludge (Multipoint Method).

Sample Number	Moisture Content, %	No. of Drops	Log No. Drops
1	44	18	1.26
2	45	14	1.15
3	42	19	1.28
4	42	26	1.41
5	39	28	1.45
6	41	20	1.30
7	41	22	1.34

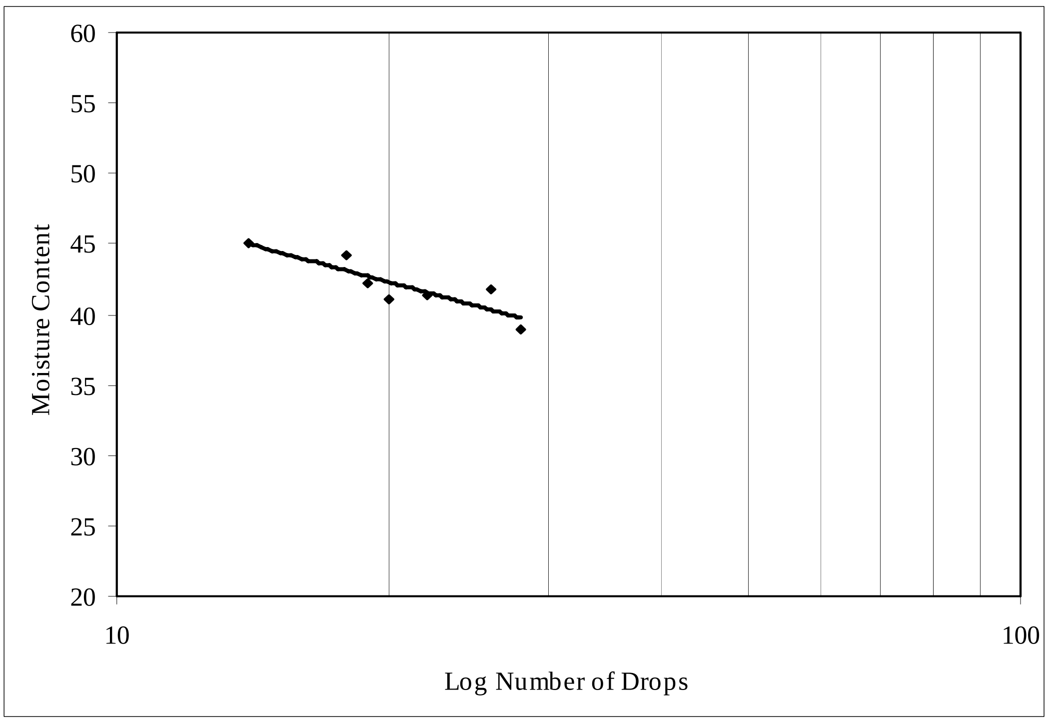

Figure 23: Liquid Limit Data for Lime Sludge

The same procedure was performed for comparison purposes, on a soil of similar particle size commonly found in Iowa—loess. The moisture density relationship for loess is also provided in Figure 24. Tables 12 and 13 contain the data used to construct the moisture density curves.

The zero air void curve for each type of material was drawn using this equation:

$\gamma_{ZAV} = \gamma_w / (w + 1/G_s)$

where γ_{ZAV} is the unit weight if the voids are completely filled with water, γ_w is the unit weight of water (= 1 g/cm^3), w is the moisture content expressed as a decimal, and G_s is the specific gravity of the material. The specific gravity for lime sludge was determined as 2.62 and was determined before Rob Baker joined the project.

Most soil materials have one maximum in the plot of their moisture-density data. This indicates the optimum moisture content correlating to maximum density. Figure 24 shows that the Western Iowa loess has an optimum moisture content at about 17% and a dry density at that moisture content of about 1.7 g/cm^3. Unfortunately, lime sludge does not seem to have an obvious maximum. This is consistent with published results by Wang et al. (1991), who could find no distinct maximums in the moisture density plots for two of the three sludges tested. Raghu et al. (1987) found a maximum dry density of 0.8 g/cm^3 for lime sludge, but at a moisture content of 68%. The tests with the Ames lime sludge reached a practical limit at about 45%. Specimens were not compacted at moisture contents greater than 45% because the compacted specimens were sticking to the mold, compaction hammer, and extrusion device. In addition, specimens compacted at moisture contents greater than 45% were plastic and easily deformed while extruding from the mold. From a handling perspective, the best moisture content range for working with the lime sludge was 40% or less. The dry unit weight corresponding to a moisture content of 35%, about 1.1 g/cm^3, was chosen for future mixture design.

It appears that the trend line for the lime sludge would pass through the zero air voids curve for the lime sludge if it were continued to 60% moisture content. The trend line is approximate, but since the material at the estimated point of intersection is no longer a solid, but a more of a non-Newtonian fluid consisting mostly of water and very little solid ($W_w >> W_s$), the relationship for zero air voids is beyond the point of usefulness. For example, if we were to compact a specimen that was mostly water, say with a moisture content of 500%, the equation for zero air voids would yield a result of 0.18 g/cm^3. However, the specimen would still weigh more than the weight of water without any solids in it for the same volume.

Table 12: Moisture-Density Data for Lime Sludge.

Moisture (%)	Dry Unit Weight (pcf)	Dry Density (g/cm^3)
5	67.6	1.08
5	66.4	1.06
10	65.9	1.06
11	69.2	1.11
15	67.6	1.08
15	68.9	1.10
20	70.0	1.12
22	69.3	1.11
25	69.4	1.11
25	68.5	1.10
30	70.5	1.13
31	68.1	1.09
31	66.5	1.07
33	66.6	1.07
34	71.1	1.14
35	68.9	1.10
38	67.6	1.08
40	71.1	1.14
41	67.2	1.08
43	71.1	1.14
46	68.8	1.10
48	67.8	1.09

Table 13: Moisture-Density Data for Western Iowa Loess.

Moisture (%)	Dry Unit Weight (pcf)	Dry Density (g/cm^3)
10	103.2	1.65
13	99.5	1.59
15	104.3	1.67
15	103.5	1.66
19	104.3	1.67
17	100.1	1.60
19	102.2	1.64
19	105.3	1.69
22	100.3	1.61
21	103.2	1.65
23	100.6	1.61
13	99.4	1.59
15	100.1	1.60
18	103.9	1.67
17	100.9	1.62
19	104.5	1.67
18	104.6	1.68
22	99.2	1.59
13	106.1	1.70
13	106.6	1.71
16	107.6	1.72
17	106.2	1.70
20	101.8	1.63
19	103.1	1.65
21	100.6	1.61
22	100.0	1.60
24	94.9	1.52
13	100.7	1.61
15	103.8	1.66
15	105.5	1.69
17	104.7	1.68
17	104.4	1.67
20	103.9	1.67
19	104.6	1.68
22	102.2	1.64
17	105.7	1.69
24	98.8	1.58

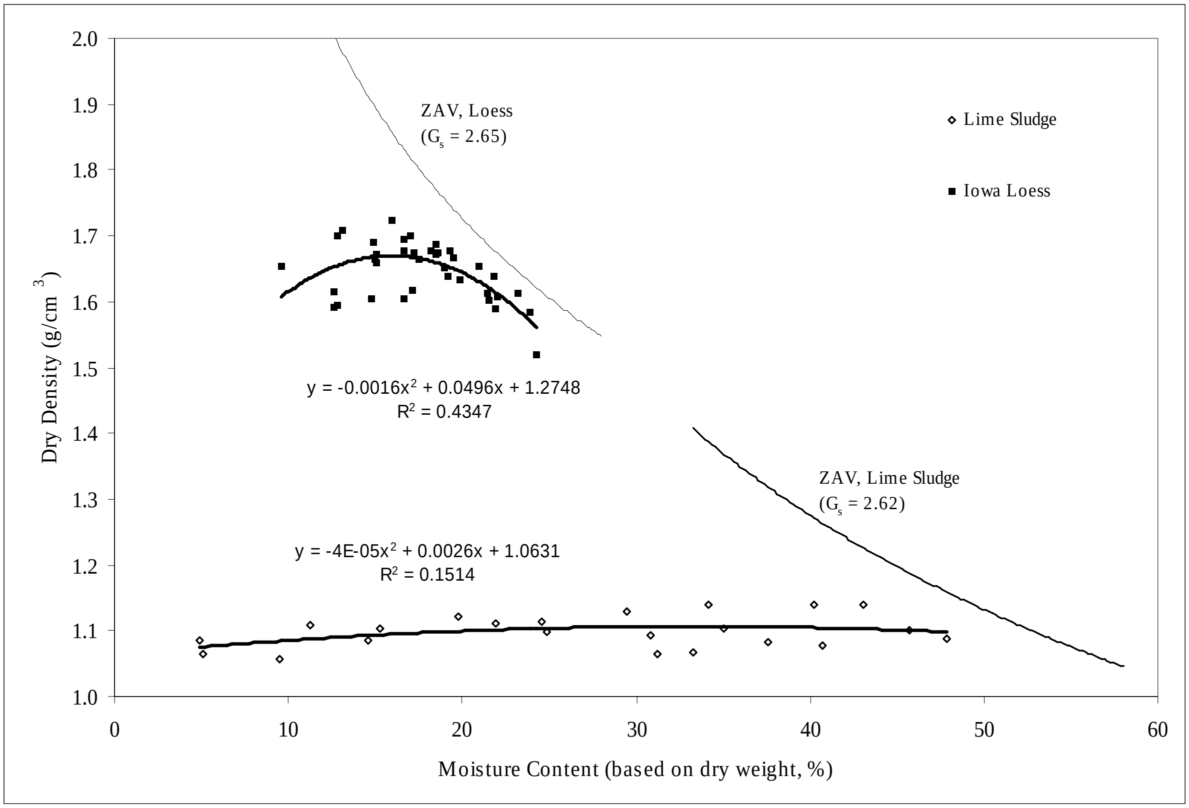

Figure 24: Moisture-Density Relationship.

Unconfined Compressive Strength Tests

The two major parameters of concern involved with chemical stabilization are moisture content and the amount of additive added. Part I demonstrated that increasing the amount of portland cement and/or fly ash increases the UCS. In the preliminary UCS tests done on each stabilizer, it was shown that the amount of moisture affects UCS. The next step was to investigate how moisture affects a chemically stabilized lime sludge specimen and what the best moisture content is for achieving maximum strength.

Table 14 and Figure 25 show a set of tests completed to discover the best mix moisture content for each type of stabilizer. The existence of an optimum moisture for all stabilizer content levels was not assumed; instead, two stabilizer content levels were chosen for evaluation. One stabilizer content was relatively high, about 33% fly ash or 17% cement, and the other low, about 9% fly ash or 5% cement (percentages based on the total weight of dry solids). The amounts of portland cement used in the mixtures are about half those of fly ash, by percentage, since the UCS results in Part I showed that the percentage of added cement required to reach a given UCS is half the percentage of added fly ash required to reach the same UCS.

For each set of specimens and given mixture ratio of stabilizer to lime sludge, the moisture was varied to see if there would be a peak in UCS. To estimate the moisture range tested, the weight of water required to hydrate each stabilizer to its highest UCS was found using the data in Figures 19 and 21. To that weight, the weight of water for the other portion of the mix, lime sludge, was added. The ratio of the weight of water to the weight of the lime sludge (dry weight basis) was varied from 0.1 to 0.5. The weight of water added to the mix for the fly ash and that added for the lime sludge were determined separately as a means of determining how to vary the mix moisture. All values of moisture content reported in Table 14 are based on the mixture of fly ash and lime sludge after thorough stirring.

The peak moisture contents for the lime sludge specimens chemically stabilized with OGS fly ash were 27% and 29%, and those stabilized with portland cement peaked at moisture contents of 40% and 39% (Figure 25). However, the two sets of lime sludge specimens chemically stabilized with Ames fly ash did not peak at similar moisture contents: their strength peaks occurred at 39% and 24% (Figure 25). These results were taken into account in the next set of UCS experiments, in which the moisture content was maintained at a constant level, and the amount of stabilizer in the mix was varied.

In the UCS tests in which the stabilizer amount was varied, the specimens chemically stabilized with Ames fly ash used the range of moisture contents from Figure 25 (24–39%); the mixture with OGS fly ash used 28%; and those with portland cement used 40%. Table 15 and Figure 26 show the results. The points represent an average UCS of three specimens, and there are error bars to represent the data ranges in kPa. Figure 26 clearly shows that mixing in higher percentages of stabilizer produces higher strength. In addition, since bottom ash does not significantly lower the UCS values for chemically stabilized lime sludge specimens, incorporating it in the mixture does not have a detrimental effect to UCS.

Table 14: Effects of Moisture on the Strength of Chemically Stabilized Lime Sludge

Type	Stabilizer[a]	Lime Sludge[a]	Moisture Content	Dry Density	Cure Time[b]	Load	Stress
	(%)	(%)	(%)	(g/cm^3)	(days)	(kN)	(kPa)
Ames FA	9	91	8	0.00	7	0.62	305
	9	91	12	1.08	7	0.72	356
	9	91	21	1.15	7	0.89	441
	9	91	30	1.15	7	1.23	608
	9	91	39	1.16	7	1.35	668
	9	91	41	1.41	7	0.78	384
	9	91	44	1.35	7	1.05	518
	33	67	15	1.37	7	2.86	1410
	33	67	17	1.33	7	2.74	1355
	33	67	24	1.22	7	3.34	1647
	33	67	31	1.15	7	3.18	1568
	33	67	37	1.15	7	0.73	360
OGS FA	9	91	7	1.18	7	0.64	316
	9	91	11	1.16	7	0.77	378
	9	91	20	1.16	7	1.15	567
	9	91	29	1.18	7	1.31	646
	9	91	38	1.18	7	1.07	529
	33	67	11	1.32	7	1.93	953
	33	67	14	1.34	7	2.24	1107
	33	67	20	1.33	7	2.61	1287
	33	67	27	1.30	7	2.90	1430
	33	67	34	1.28	7	2.44	1203
Cement	5	95	6	1.06	7	0	0
	5	95	11	1.12	7	0.75	369
	5	95	21	1.11	7	1.10	545
	5	95	30	1.13	7	1.01	498
	5	95	40	1.14	7	1.36	672
	5	95	42	1.05	7	1.10	545
	5	95	44	1.18	7	1.20	593
	17	83	10	1.24	7	0.57	281
	17	83	14	1.17	7	1.82	898
	17	83	22	1.16	7	2.08	1028
	17	83	30	*	7	2.21	1089
	17	83	39	*	7	2.43	1199
	17	83	40	*	7	1.36	672
	17	83	43	*	7	1.10	545

*Data not available.

Notes:

a. Percentages based on total dry weight of solids.

b. Specimens cured for 7 days in a 100^{o}F oven to simulate a 28-day cure.

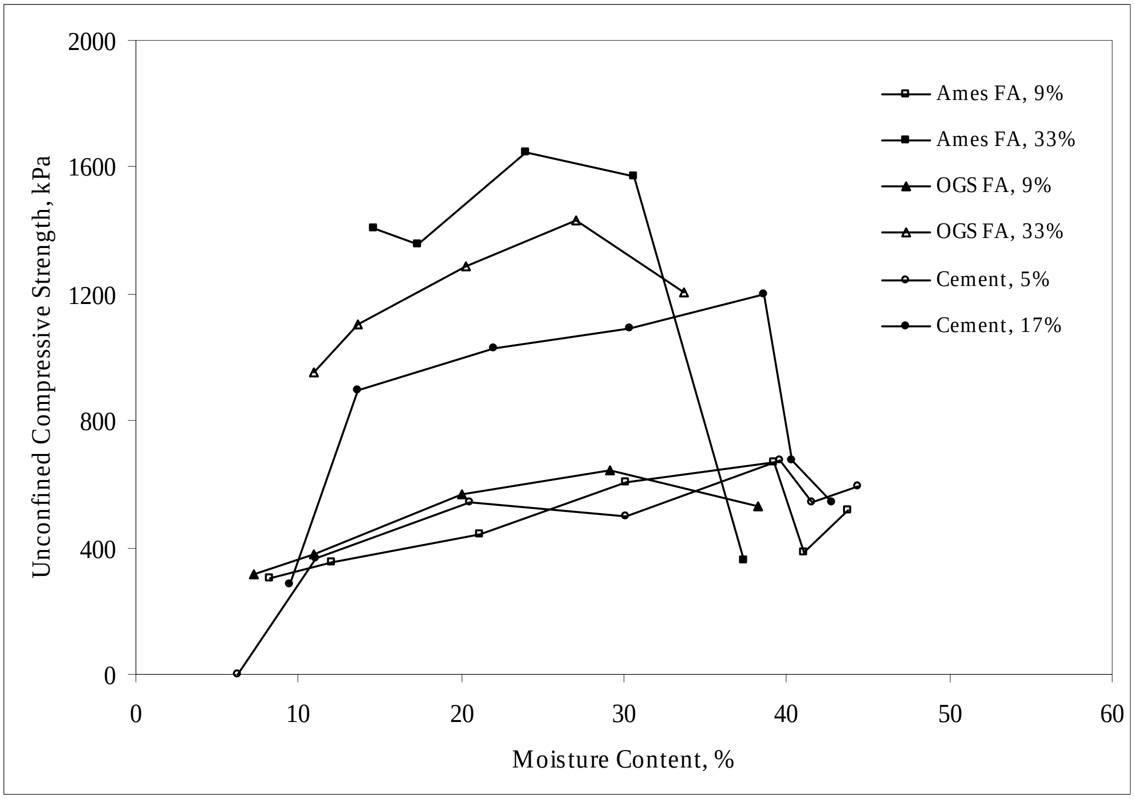

Figure 25: Effects of Moisture on the Strength of Chemically Stabilized Lime Sludge

Figure 26 could be used as a predictive tool for using the mixes as fill. For example, for a target UCS of 700 kPa, using OGS fly ash as the stabilizer, reference to Table 15 and/or Figure 26 yields a rough estimate of 13% OGS fly ash needed at about 28% moisture content.

The difference in the moisture contents measured before cure and after the UCS test shown in Table 15 represents the moisture that has not yet reacted with the fly ash, but will react by the time of the UCS test. The hydration products tie up the water present in the mix in chemical bonds, and this water will not vaporize in a drying oven set to 110^{o}C. In a few cases, the moisture content after the UCS test may be greater than the moisture content prior to cure. This is likely a result of human error.

Table 15: Effects of Stabilizer Amount on the UCS of Chemically Stabilized Lime Sludge

Stabilizer Type	Stabilizer Amount[1] (%)	Bottom Ash Amoun[1] (%)	Lime Sludge [1] (%)	Moisture Content, Before Cure (%)	Moisture Content, After UCS Test (%)	Averag e Dry Density (g/cm^3)	Averag e Stress (kPa)	Upper Error Bar (kPa)	Lowe r Error Bar (kPa)
Ames FA	0	0	100	39.0	*	*	110	0	0
	9	0	91	37.0	*	1.17	596	21.2	20.5
	18	0	82	[2]	*	*	577	46.8	58.6
	27	0	73	30.3	29.96	1.50	990	50.5	87.8
	36	0	64	46.5	25.68	1.12	1007	9.5	19.0
	45	0	55	24.7	25.87	1.31	1277	57.8	60.8
OGS FA	0	0	100	39.0	*	*	110	0	0
	9	0	91	27.9	*	*	571	57.1	35.1
	18	0	82	21.9	*	1.31	927	30.0	33.7
	27	0	73	22.0	*	1.34	980	87.1	62.2
	36	0	64	22.4	*	1.38	1207	66.6	58.6
	45	0	55	21.2	*	1.43	1446	49.0	49.0
	0	0	100	39.0	*	*	110	0	0
	9	9	82	30.31	28.03	1.17	492	32.9	32.9
	18	18	64	28.11	32.03	1.29	766	27.1	27.8
	27	27	46	27.84	24.82	1.23	784	72.5	39.5
	36	36	28	27.02	24.69	1.28	874	68.1	52.7
	45	45	10	26.20	24.52	1.30	958	34.4	40.3
Cement	0	0	100	39	*	*	110	0	0
	5	0	95	39.3	36.89	1.14	567	10.2	18.3
	9	0	91	36.5	37.02	1.17	900	48.3	57.1
	13	0	87	37.9	35.41	1.19	1243	43.9	59.3
	17	0	83	36.0	34.08	1.21	1512	24.9	36.6
	20	0	80	35.1	33.18	1.50	1638	24.2	30.7
	0	0	100	39	*	*	110	0	0
	5	5	90	35.8	36.54	1.18	608	46.1	30.7
	8	9	83	35.7	34.96	1.19	993	41.0	22.7
	12	14	74	33.5	32.80	1.23	1254	54.9	41.7
	14	18	68	32.3	29.75	1.28	1777	117.9	106.1
	17	17	66	32.6	28.63	1.28	1978	262.1	265.0

*Data not available.

Note 1: Percentages based on total dry weights.

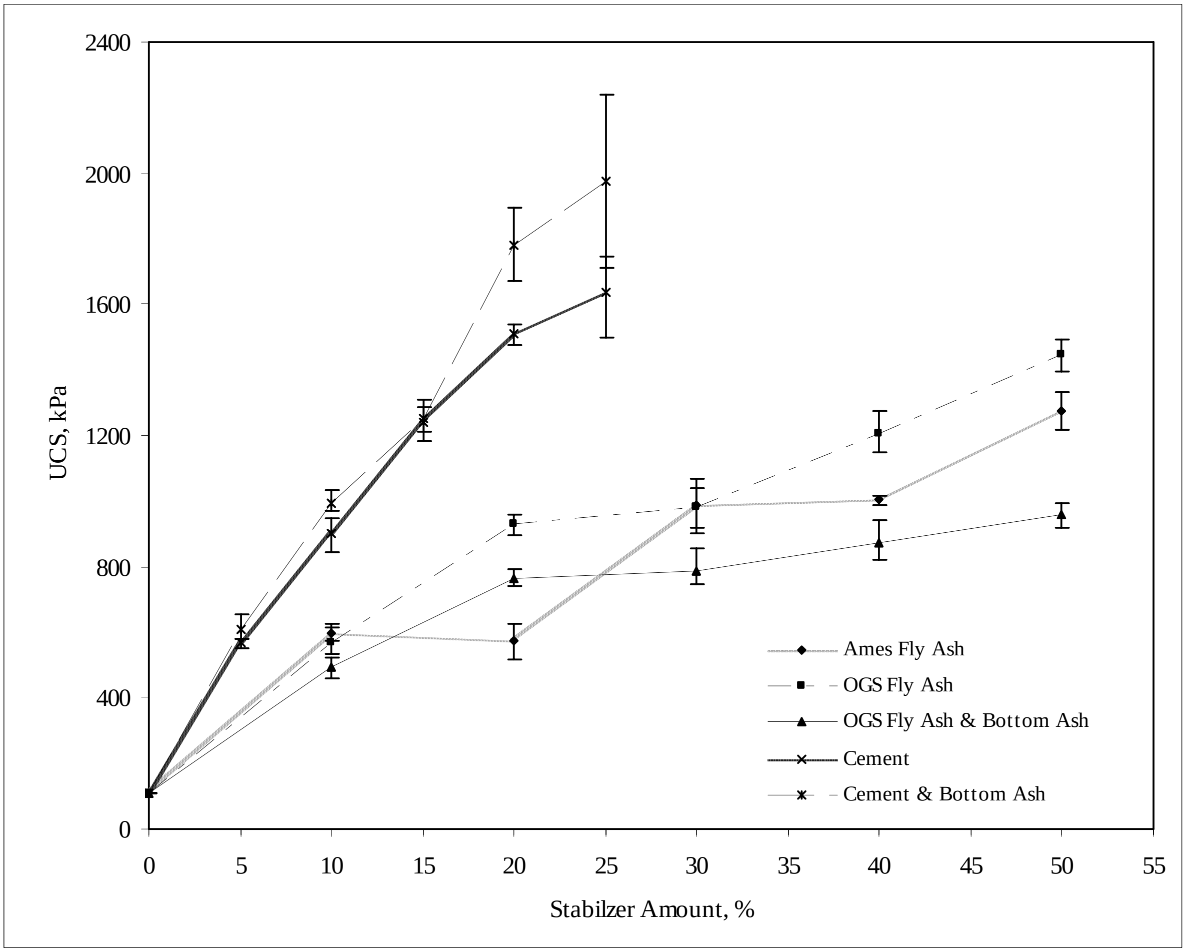

Figure 26: Effects of Stabilizer Amount on the UCS of Chemically Stabilized Lime Sludge

Direct Shear Strength Tests

Table 16 is a summary of the results for the friction angle and range of cohesion from direct shear tests. Due to significant variability in the data, the friction angle and cohesion range found for the chemically stabilized lime sludge specimens cured for 56 days do not meet the requirements of the standard used. ASTM D3080 requires that the data from at least three different normal stresses be used to define the friction angle and cohesion. Since there was not enough time to perform more tests for the required minimum amount of data points for friction angle, the values reported on Table 16 were approximated from the two normal stresses that were consistent.

Typical values of drained friction angles for sands with angular grains range from 30 to 45 degrees and those for silts range from 26 to 35 degrees (Das, 2002). Laguros and Davidson (1963) found a friction angle of 37 degrees for a cured specimen composed of an Iowa silt stabilized with 12% Portland cement (on a dry weight basis). The value of cohesion they determined was 20 psi (140 kPa).

Since the friction angle values for the stabilized lime sludge are relatively high compared to natural soils, values for other wastes and by-products were consulted. As shown in the background and literature review, Wang et al. (1992) reported friction angles of water treatment sludges that fell in the UCS classification of CH, using the triaxial compression test (consolidated-undrained); these friction angles ranged from 42 to 44 degrees for three different sludges. Based on total stress, Wang et al. (1992) reported friction angles ranging from 17 to 19 degrees for the same sludges. According to results from Charlie (1977), paper-mill sludges had effective friction angles as high as 76 degrees.

Table 16: Summary of Direct Shear Tests.

Mix Type	Friction Angle (degrees)	Cohesion Range (kPa)		Cure Time (days)
Lime sludge only	39	5	13	0
Lime sludge and Ames fly ash 2:1	35	52	181	28
Lime sludge and Ames fly ash 2:1	33*	24*	189*	56
Lime sludge and Ames fly ash 1:1	42	27	168	28
Lime sludge and Ames fly ash 1:1	35*	47*	112*	56

*Indicates value based on data of two specimens, not three.

There was a cementation effect with the fly ash stabilized mixes. An example of this effect can be seen in the spike of the shear stress versus horizontal displacement plot in Figure 29. This spike is due to the rupture of the chemical bonding resulting from fly ash hydration. The range of cohesion values shown on the shear stress versus normal stress plots is a characterization of the cementation effect.

Direct Shear Tests, Lime Sludge Only

The shear stress versus horizontal plot is shown in Figure 27. The specimen tested at 69 kPa normal stress was not consistent with the specimens tested at the other two normal stresses at horizontal displacements greater than 2.0 mm. The shear stresses corresponding to horizontal displacements greater than 2.0 mm for the 69 kPa specimen were omitted from the slope calculations for friction angle.

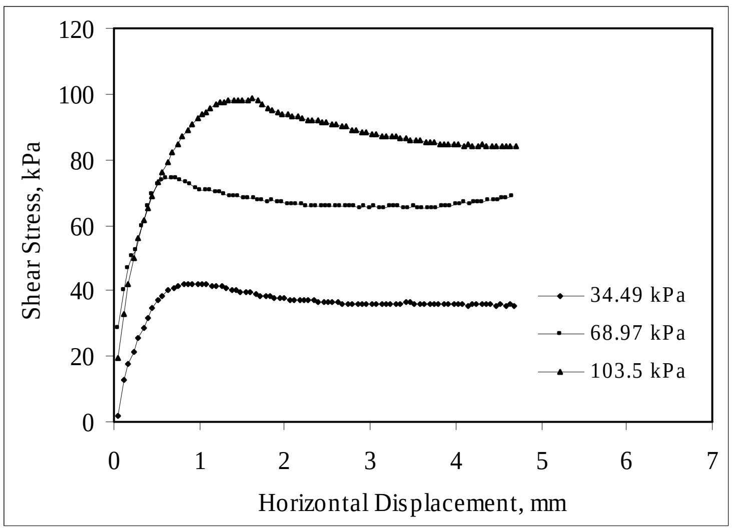

Figure 27: Shear Stress vs. Horizontal Displacement, Lime Sludge Only

Figure 28 shows the plot of vertical displacement versus horizontal displacement. When this plot has a positive slope, the specimen is "dilating." When the slope is negative, the specimen is "contracting." For a consistent set of specimens, the specimens should dilate and contract at the same time. In Figure 28, the specimens tested at the 35 kPa and 103 kPa followed similar paths, but the specimen tested at the 69 kPa did not.

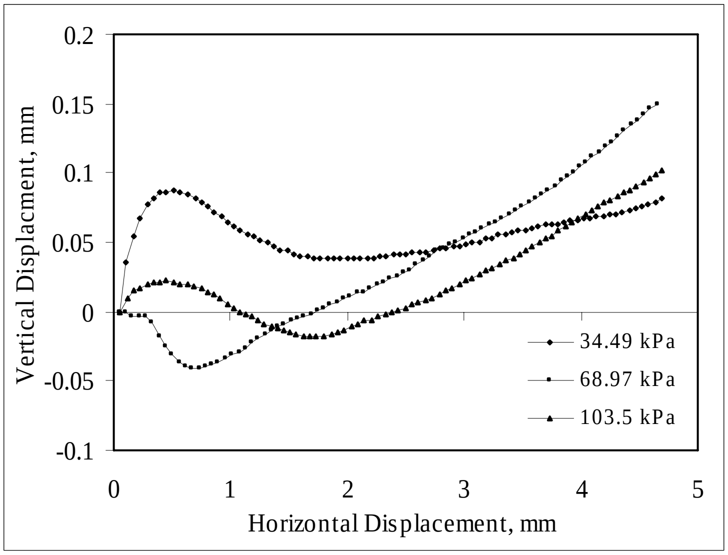

Figure 28: Vertical Displacement vs. Horizontal Displacement, Lime Sludge Only

Figure 29 shows a plot of the shear stress versus the normal stress for the lime sludge only specimens. The two lines plotted are the ranges of the maximum and minimum cohesion values; each line is drawn at a slope equal to the tangent of the friction angle, which was found by selecting the shear stresses at the horizontal displacement of 2.5 mm. According to Figure 28, all three specimens are fairly consistent in what they are doing (dilating), and according to Figure 27, all three specimens are in the residual strength phase of the shear test, with little or no cohesion left.

Once the points for residual shear stress are determined, a linear regression is done on the three points. In this case, the points were (35 kPa, 36 kPa), (69 kPa, 66 kPa), and (103 kPa, 91 kPa), and the linear regression resulted in a slope of 0.822. The arctangent of this slope is taken, and the resulting friction angle is 39 degrees. Once the cohesion in the specimen has broken down, any three points can define the friction angle, but Figures 27 and 28 should consulted first to see if there will be variability in the three points chosen.

For the upper boundary of the cohesion range, the three maximum shear stress points were chosen from Figure 27. A line with the slope of the tangent of 39 degrees was fitted onto these data points to define the upper boundary of the cohesion range. Since the specimen at a normal stress of 69 kPa was dilating and contracting opposite to the two specimens at the other normal stresses (in Figure 28) at any given horizontal displacement, it was not taken into consideration when fitting the line for the upper limit. The y-intercept for the upper boundary of cohesion was 13 kPa. The points taken to define the lower boundary of cohesion were (35 kPa, 35.5kPa), (69 kPa, 65.6 kPa), and (103 kPa, 83.8 kPa). A line with the slope of the tangent of 39 degrees was fitted onto these data points to define the lower boundary of the cohesion range, a linear regression was completed on the points defining this fitted line, and the y-intercept, 5 kPa, was found.

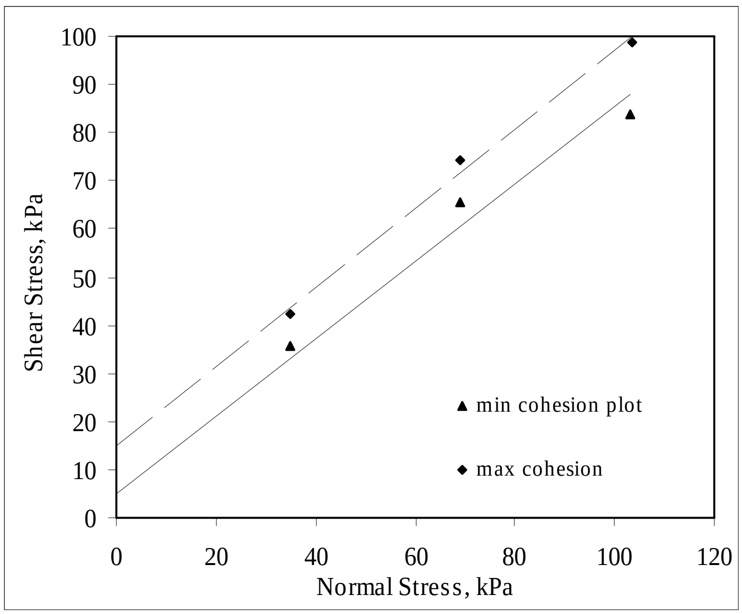

Figure 29: Shear Stress vs. Normal Stress, Lime Sludge Only

Table 17: Summary of Direct Shear Specimens, Lime Sludge Only

Normal Stress (kPa)	Initial Moisture (%)	Initial Dry Unit Wgt (g/cm^3)	Diameter: Thickness Ratio	Final Moisture (%)	Cohesion Range (kPa)	Friction Angle (degrees)
34.49	40	1.35	2	60	5 to 13	39
68.97	39	1.36	2.5	60		
103.5	37	1.43	2.5	60		

Direct Shear, Lime Sludge to Fly Ash Ratio 2:1

The shear stress versus horizontal displacement plot for the specimens containing a mixture of two parts lime sludge to one part fly ash (dry weight basis), with a cure time of 28 days, is shown in Figure 30. There are sharp peaks in shear stress for the specimens sheared at a normal stresses of 69 kPa and 103 kPa. The specimen sheared at a normal stress of 35 kPa had a prolonged peak in shear, then a significant drop, followed by a consistent residual. Since the specimen sheared at a normal stress of 103 kPa had the highest cohesion value (defined as the difference between the maximum shear stress and the shear stress at the minimum level of residual stress), it was chosen to define the upper boundary of the cohesion range.

Figure 31 shows that specimens at all three normal stresses dilate a little initially, then contract. After the specimen sheared at a normal stress of 35 kPa passed peak shear, its rate of contraction was higher than that of the other two specimens. Otherwise, these three specimens were consistent with each other in Figure 31. Once residual shear has been reached, the friction angle should be the about same regardless of where the points are chosen, which is illustrated with this data set. According to Figures 30 and 31, after 2.0 mm of horizontal displacement, cohesion is gone, and residual stress remains in all three specimens. The data points for the horizontal displacements of 2.0 mm were (35 kPa, 97 kPa), (69 kPa, 141 kPa), and (103 kPa, 143 kPa); linear regression of these points results in a slope of 0.677, and arctangent of this slope (or friction angle) is 34 degrees . The data points for the horizontal displacement of 2.3 mm were (35 kPa, 92 kPa), (69 kPa, 139 kPa), and (103 kPa, 139 kPa); linear regression of these points yields a slope of 0.691, and the friction angle is 35 degrees. The data points for the horizontal displacement of 3.0 mm were (35 kPa, 89 kPa), (69 kPa, 132 kPa), and (103 kPa, 139 kPa); linear regression of these points results in a slope of 0.735, and the friction angle is 36 degrees. Therefore, the average friction angle was taken as 35 degrees.

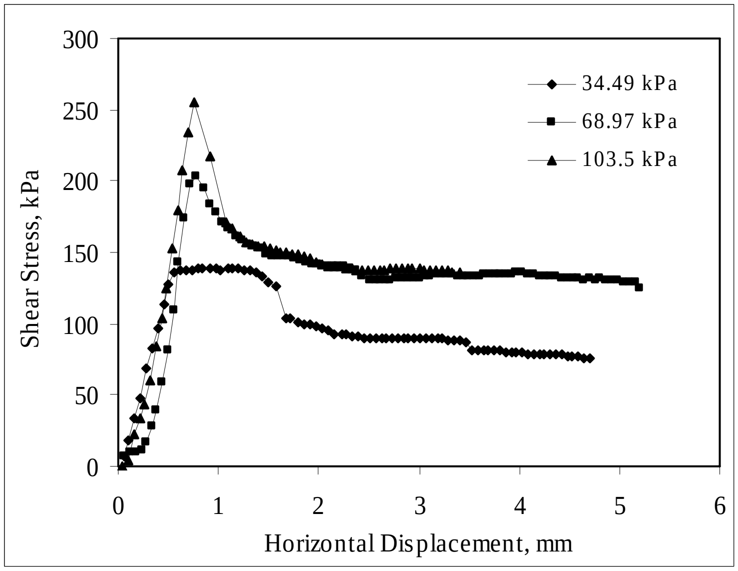

Figure 30: Shear Stress vs. Horizontal Displacement, Lime Sludge to Fly Ash Ratio 2:1, 28 Days

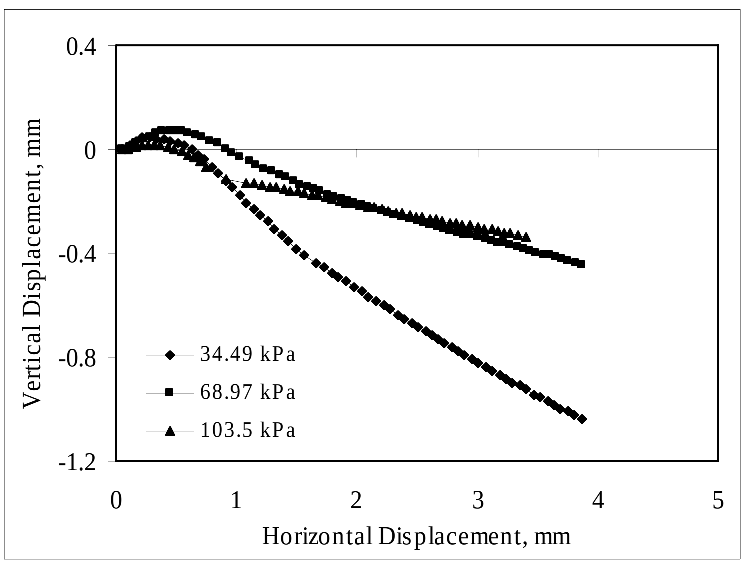

Figure 31: Vertical Displacement vs. Horizontal Displacement, Lime Sludge to Fly Ash Ratio 2:1, 28 days

The shear stress versus normal stress plot, Figure 32, shows a plot of the maximum shear values. These specimens had varying levels of cohesion since they do not plot to a friction angle of 35 degrees. Therefore, for the upper boundary of cohesion, a line with a slope of 0.7 (equals the tangent of 35 degrees) was extended from the maximum shear point for the normal stress at 103 kPa back to the y-axis. The y-intercept, 181 kPa, is the upper boundary of cohesion. The lower boundary was determined in a similar manner, except that it was based on the lowest residual shear value, which was (35 kPa, 77 kPa). A line was drawn at a slope of 0.7 (tangent of 35 degrees), and a linear regression was done on the points defining this line; the resulting y-intercept was 52 kPa.

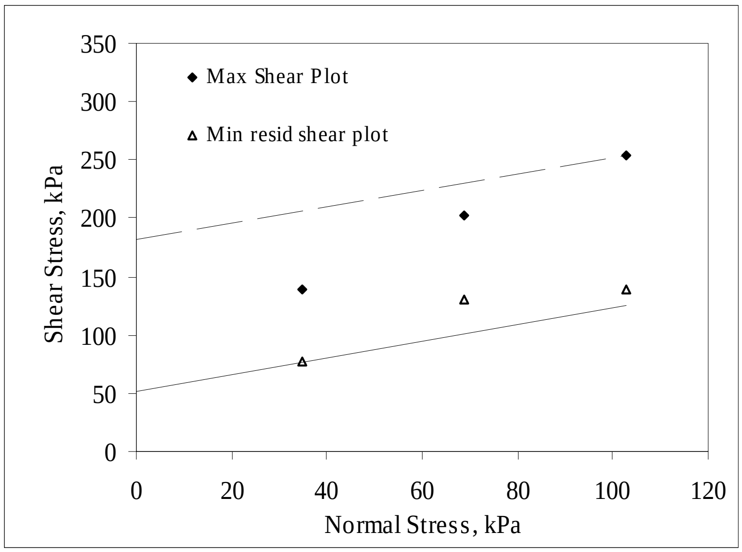

Figure 32: Shear Stress vs. Normal Stress,
Lime Sludge to Fly Ash Ratio 2:1, 28 days

Figure 33 shows the shear stress versus horizontal displacement plot for the lime sludge specimens chemically stabilized with fly ash at a lime sludge to fly ash mix ratio of 2:1 and cured for 56 days. Here, the specimen sheared at a normal stress of 35 kPa had the most cohesion. The specimen sheared at 103 kPa had the least cohesion, and it has an unusual shear stress versus horizontal displacement plot. It almost appears as if there is no cohesion in the specimen and that it takes a slow path up to its residual shear strength. In addition, this specimen continued to dilate when the others contracted in the vertical displacement versus horizontal displacement plot (Figure 34). The specimen sheared at a normal stress of 69 kPa has a small effect from cohesion and then settles into a residual shear higher than that of the specimen sheared at a normal stress of 103 kPa. This specimen did not dilate at all in the beginning of the shearing test, as the specimen sheared at a normal stress of 35 kPa did. Based on the inconsistent nature of the data for the specimen sheared at the normal stress of

103 kPa, the friction angle was calculated from the specimens sheared at normal stresses of 35 kPa and 69 kPa.

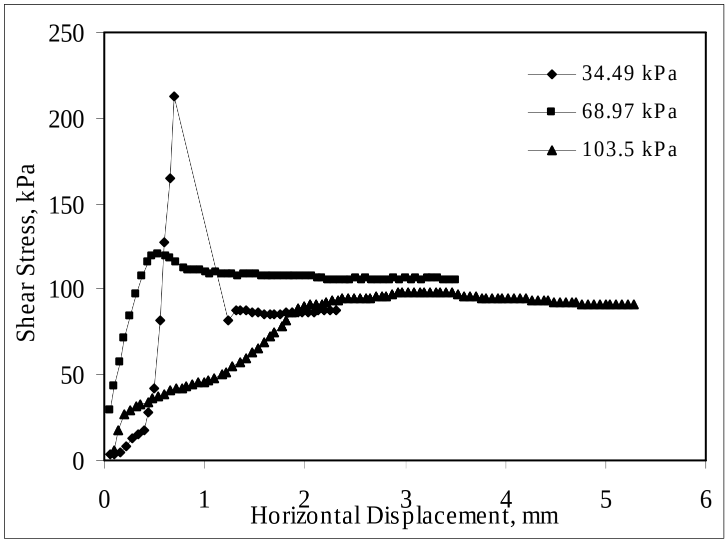

Figure 33: Shear Stress vs. Horizontal Displacement, Lime Sludge to Fly Ash Ratio 2:1, 56 Days

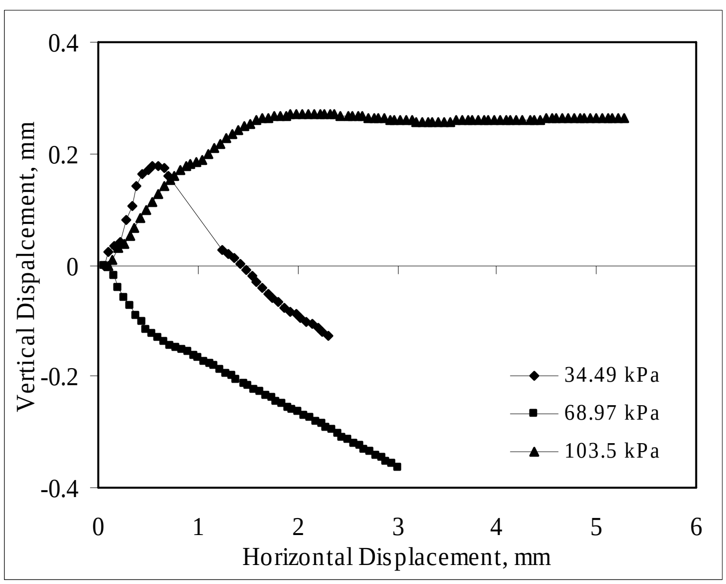

Figure 34: Vertical Displacement vs. Horizontal Displacement, Lime Sludge to Fly Ash Ratio 2:1, 56 days

According to Figure 33, at a horizontal displacement of 1.5 mm or greater, cohesion is gone and residual stress remains in the two selected specimens (normal stresses of 35 and 69 kPa).

The data points for the horizontal displacement of 1.5 mm were (35 kPa, 86 kPa) and (69 kPa, 108 kPa); linear regression of these points results in a slope of 0.647, and the arctangent of this slope (or friction angle) is 33 degrees. The data points for the horizontal displacement of 1.75 mm were (35 kPa, 85 kPa) and (69 kPa, 107 kPa); linear regression of these points yields a slope of 0.647, with an arctangent of 33 degrees. The data points for the horizontal displacement of 2 mm were (35 kPa, 86 kPa) and (69 kPa, 107 kPa); and linear regression of these points results in a slope of 0.618, and the friction angle is 32 degrees. Therefore the average friction angle was taken as 33 degrees and reported as such in Table 16.

To define the upper boundary of cohesion, the maximum shear stresses corresponding to each normal stress were plotted. These points did not result in a line with a tangent of 0.649 (friction angle of 33 degrees), so the specimen with the greatest cohesion was used. The specimen sheared at a normal stress of 35 kPa had the greatest cohesion in Figure 33. A line with the slope of 0.649 was fitted through this point, and the y-intercept was found through linear regression. The upper boundary of cohesion was 189 kPa.

The lower range of cohesion was found in a similar manner. Since the minimum residual shear values for all three normal stresses did not result in a line with the slope of 0.649, the specimen with the lowest residual shear was chosen. Residual shear was evaluated from Figure 33 by locating the lowest residual shear amongst the three specimens. The specimen sheared at a 103.5 kPa normal stress was chosen, and a line with the slope of 0.649 was fitted to this point. The y-intercept, 24 kPa, was found by linear regression on the points defining this line. A summary table of the specimens mixed at a ratio of two parts lime sludge to one part fly ash is shown in Table 18.

Direct Shear, Lime Sludge to Fly Ash Ratio 1:1

The direct shear tests for the specimens containing a mixture of one part fly ash to one part lime sludge (dry weight basis), cured to 28 days, are shown in Figures 36 to 38. Figure 36 shows that the specimen sheared at a normal stress of 35 kPa has much more cohesion than the other two specimens. From Figure 37, it can be seen that all three specimens dilated at first, then gradually contracted at similar rates. The specimen sheared at 35 kPa normal stress showed a sharp drop in vertical displacement in Figure 37, whereas the other two specimens did not. In calculations for finding the friction angle, the data from this specimen also produced variability.

The minimum residual shear value for each specimen was used to calculate the friction angle. These points were (35 kPa, 59 kPa), (69 kPa, 91.2 kPa), and (103 kPa, 121.4 kPa), and the linear regression of these points results in a slope of 0.911. The arctangent of this slope is 42

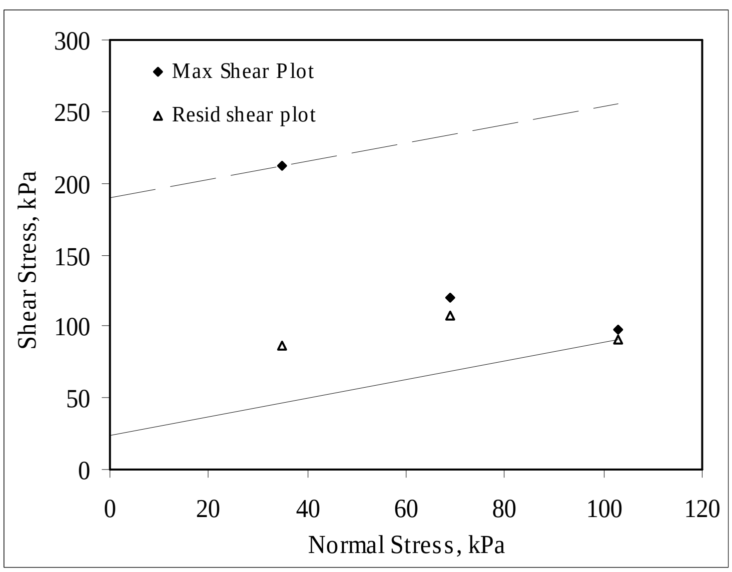

Figure 35: Shear Stress vs. Normal Stress,
Lime Sludge to Fly Ash Ratio 2:1, 56 days

Table 18: Summary of Direct Shear Tests, Lime Sludge to Fly Ash Ratio 2:1.

Cure (days)	Normal Stress (kPa)	Initial Moisture (%)	Initial Dry Unit Weight (g/cm^3)	Diameter: Thickness Ratio	Final Moisture (%)	Cohesion Intercept (kPa)	Friction Angle (degrees)
28	34.49	15	1.96	2	42	52 to 181	35
28	68.97	22	1.79	2	39		
28	103.5	21	1.82	2	41		
56	34.49	16	1.98	2	38	24 to 189	33
56	68.97	20	1.81	2.5	42		
56	103.5	14	1.9	2.5	43		

degrees (friction angle). The method of averaging three points after the maximum cohesion is gone (on the shear stress versus horizontal displacement plot) was used, but the resulting values for the friction angle were inconsistent and uncharacteristically high (47 degrees and higher). Therefore, the friction angle of 42 degrees angle was accepted as the best value for this data set.

To define the upper boundary of the cohesion, the maximum shear stresses corresponding to each normal stress were plotted. These points did not result in a line with a tangent of 0.911 (friction angle, 42 degrees), so the specimen with the most cohesion was used. The specimen sheared at a normal stress of 35 kPa had the greatest cohesion in Figure 36. A line with the slope of 0.911 was fitted through this point and the y-intercept was found through linear regression. The upper boundary of cohesion was 168 kPa. The plot of minimum residual shear values is based on the friction angle for all three specimens, and these shear values were used to define the lower boundary of cohesion. A linear regression was computed on these points, and the resulting y-intercept was 27 kPa.

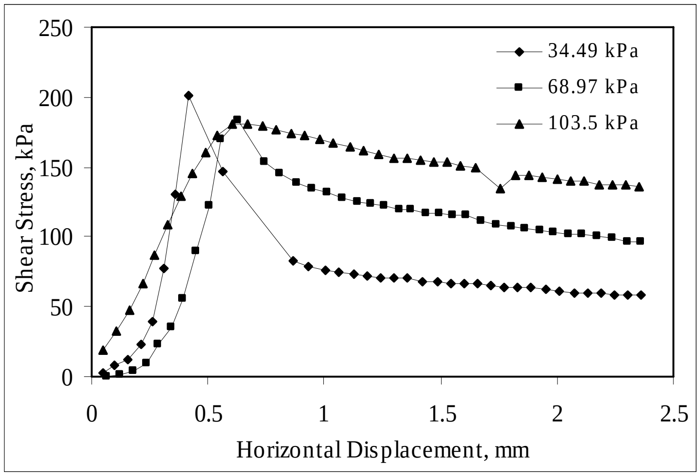

Figure 36: Shear Stress vs. Horizontal Displacement,

Lime Sludge to Fly Ash Ratio 1:1, 28 Days

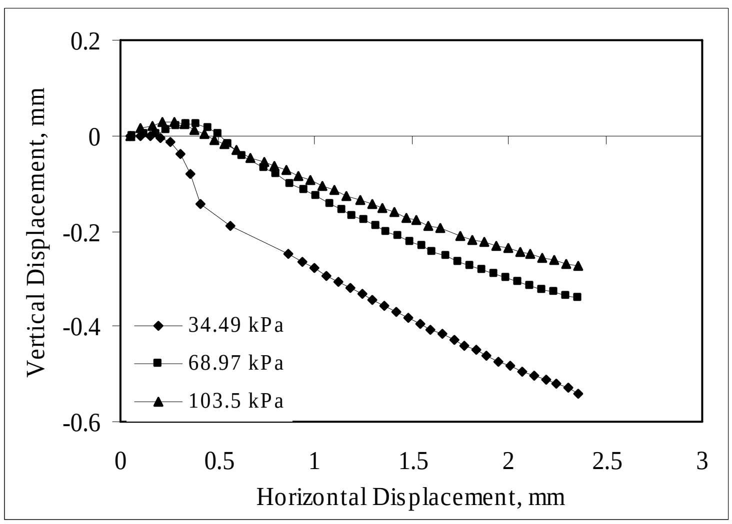

Figure 37: Vertical Displacement vs. Horizontal Displacement,

Lime Sludge to Fly Ash Ratio 1:1, 28 days

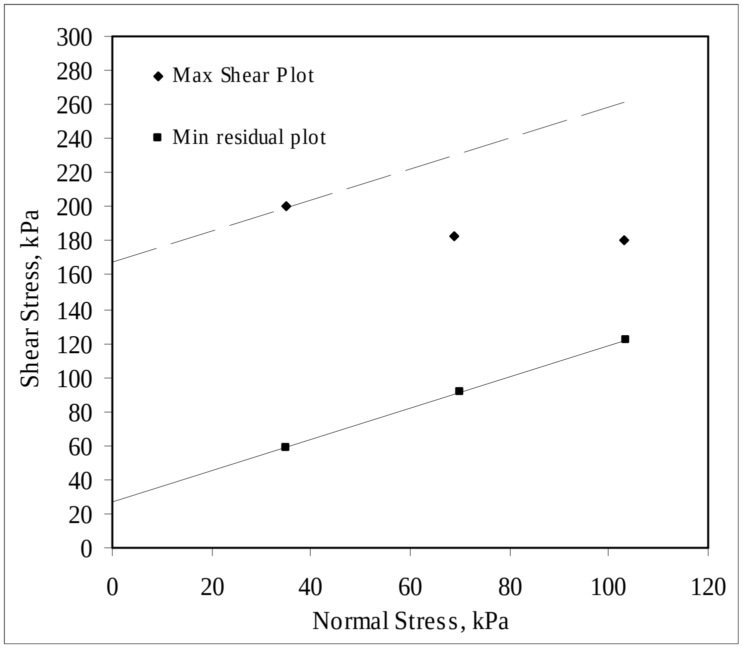

Figure 38: Shear Stress vs. Normal Stress,
Lime Sludge to Fly Ash Ratio 1:1, 28 days.

In Figure 39, the specimen sheared at a normal stress of 105 kPa appears to have the greatest cohesion. The path shown for the specimen sheared at a normal stress of 69 kPa (Figure 39) was an unusual one; however, like the other 56-day cure specimen (for the 2:1 mix ratio), the 69 kPa specimen does not have a maximum shear or discernable cohesion. Furthermore, the data for the 69 kPa specimen does not produce consistent results for either the friction angle or the range of cohesion and will therefore be neglected. Figure 40 does show all three specimens mostly contracting through the test, but not at consistent rates, which indicates some variability in the data.

According to Figure 39, at horizontal displacements of 2.0 mm or greater, most of the cohesion is gone and residual stress remains in the specimens. The data points for the horizontal displacement of 2.0 mm were (35 kPa, 76 kPa) and (103 kPa, 128 kPa); linear regression of these points results in a slope of 0.765, and the arctangent of this slope is 37 degrees (friction angle). The data points for the horizontal displacement of 2.5 mm were (35 kPa, 75 kPa) and (103 kPa, 123 kPa); linear regression of these points results in a slope of

0.713, and the friction angle is 35 degrees. The data points for the horizontal displacement of 3.0 mm were (35 kPa, 72 kPa) and (103 kPa, 121 kPa); the linear regression of these points results in a slope of 0.713, and the friction angle is 35 degrees. Therefore, the average friction angle was taken as 35 degrees.

To define the upper boundary of the cohesion, the maximum shear stresses corresponding to each normal stress were plotted. These points did not result in a line with a tangent of 0.7 (friction angle of 35 degrees), so the specimen with the greatest cohesion was used. From Figure 39, the specimen sheared at a normal stress of 103 kPa had the greatest cohesion. A line with the slope of 0.7 was fitted through this point, and the y-intercept was found through linear regression. The upper boundary of cohesion was 112 kPa. The plot of minimum residual shear values for the specimens sheared at normal stresses of 35 kPa and 103 kPa did not result in a line with a slope of 0.7, so a line with the slope of 0.7 was constructed through the point (35 kPa, 72 kPa), representing the specimen that exhibited the lowest cohesion. A linear regression was computed on the points defining this line, and the resulting y-intercept was 47 kPa. A summary table of the specimens mixed at a ratio of one part lime sludge to one part fly ash is shown in Table 19.

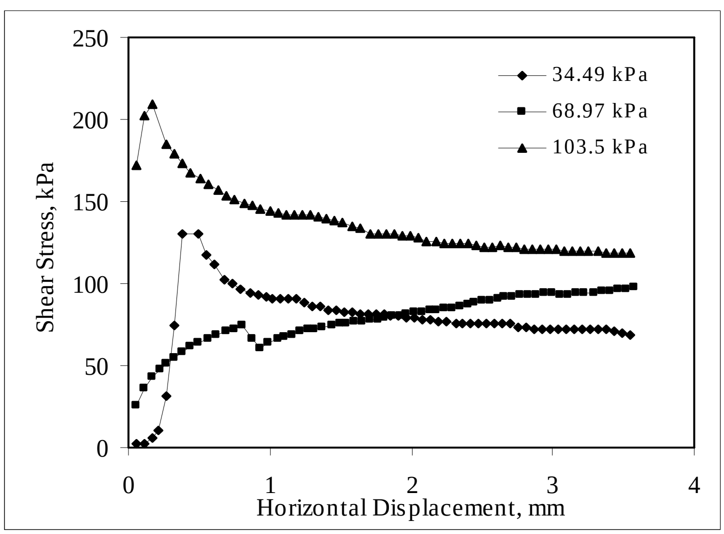

Figure 39: Shear Stress vs. Horizontal Displacement, Lime Sludge to Fly Ash Ratio 1:1, 56 Days

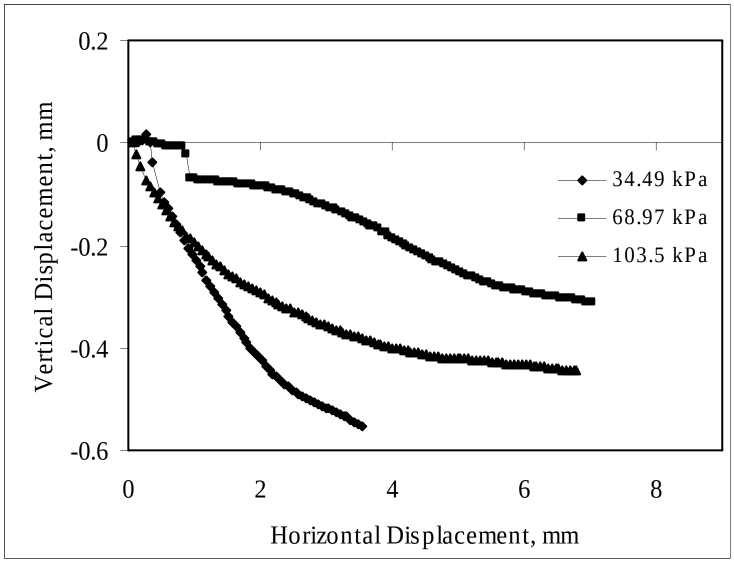

Figure 40: Vertical Displacement vs. Horizontal Displacement,

Lime Sludge to Fly Ash Ratio 1:1, 56 days

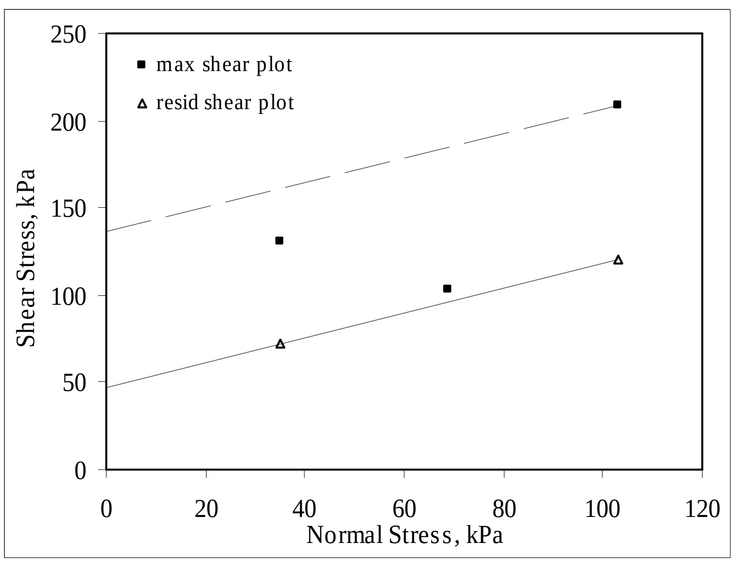

Figure 41: Shear Stress vs. Normal Stress,

Lime Sludge to Fly Ash Ratio 1:1, 56 days

Table 19: Summary of Direct Shear Tests, Lime Sludge to Fly Ash Ratio 1:1

Cure (days)	Normal Stress (kPa)	Initial Moisture (%)	Initial Dry Unit Weight (g/cm^3)	Diameter: Thickness Ratio	Final Moisture (%)	Cohesion Intercept (kPa)	Friction Angle (degrees)
28	34.49	18	1.91	2.5	40	16 to 162	47
28	68.97	18	1.95	2.5	39		
28	103.5	20	1.87	2.5	40		
56	34.49	17	1.84	2	41	47 to 112	35
56	68.97	18	1.84	2	50		
56	103.5	18	1.89	2.5	40		

California Bearing Ratio (CBR) Tests

CBR is a comparison of strength between a potential subgrade soil and an ideal base course material for pavement in road construction. The CBR for the soil being considered is the ratio of the penetration stress required to force a steel piston to penetrate 0.254 cm (0.100 inch) divided by 1000 psi. The 1000 psi stress is the stress required to push the same steel piston through crushed rock for the same penetration distance.

The CBR test results for lime sludge (with and without stabilization) are found in Table 20. Overall, the CBR values are relatively high when compared with other soils in the same classification. The required tests were repeated, as indicated on Table 20, and all three repeated test confirmed that the CBR calculate for the 5.08 mm (0.200 inch) penetration reading should be reported as the CBR for that mix and cure time. Table 20 reflects these values. According to Rollings and Rollings (1996), CBR ranges from 20 to 40% for silty sands, 10 to 20% for clayey sands, and 5 to 15% for silts and sandy silts.

Table 20: Summary of CBR Results for Chemically Stabilized Lime Sludge (Ames Fly Ash)

Mix Ratio[a]	Cure Time (days)	Bearing Ratio, 12 blows (%)	Bearing Ratio, 25 blows (%)	Bearing Ratio 56 blows (%)	Repeat Test? (5 mm > 2.5in.)
LS only	0	1	2	5	No
2 to 1	28	21[b]	21	27	12 blows
2 to 1	56	36[b]	42[b]	57	12, 25 blows
1 to 1	28	14	22	26	No
1 to 1	56	11	26	45	No

Note a: mix ratios are expressed as dry weight of lime sludge to dry weight of fly ash
Note b: CBR's calculated based on 5.08 mm penetration. Results confirmed by repeat test.

Tables 21 and 22 and Figure 42 show the CBR test on a specimen of lime sludge only. A correction for the 2.54 mm (0.1-inch) penetration was not needed, as the curves drawn on Figure 43 were concave downward. In addition, all three values for the CBR in Table 22 were acceptable since the CBR calculated for the 5.08 mm (0.2-inch) penetration was less that for the 2.54 mm penetration.

Table 21: Data Table for Penetration vs. Stress, CBR Test on Lime Sludge Only

Penetration (mm)	Stress (kPa)		
	12 Blows	25 Blows	56 Blows
0	0	0	0
0.635	52	69	147
1.27	69	104	217
1.905	78	113	277
2.54	87	139	321
3.175	95	147	364
3.81	104	173	390
4.445	104	191	434
5.08	113	208	460
7.62	130	251	572
10.16	139	303	685
12.7	156	347	798

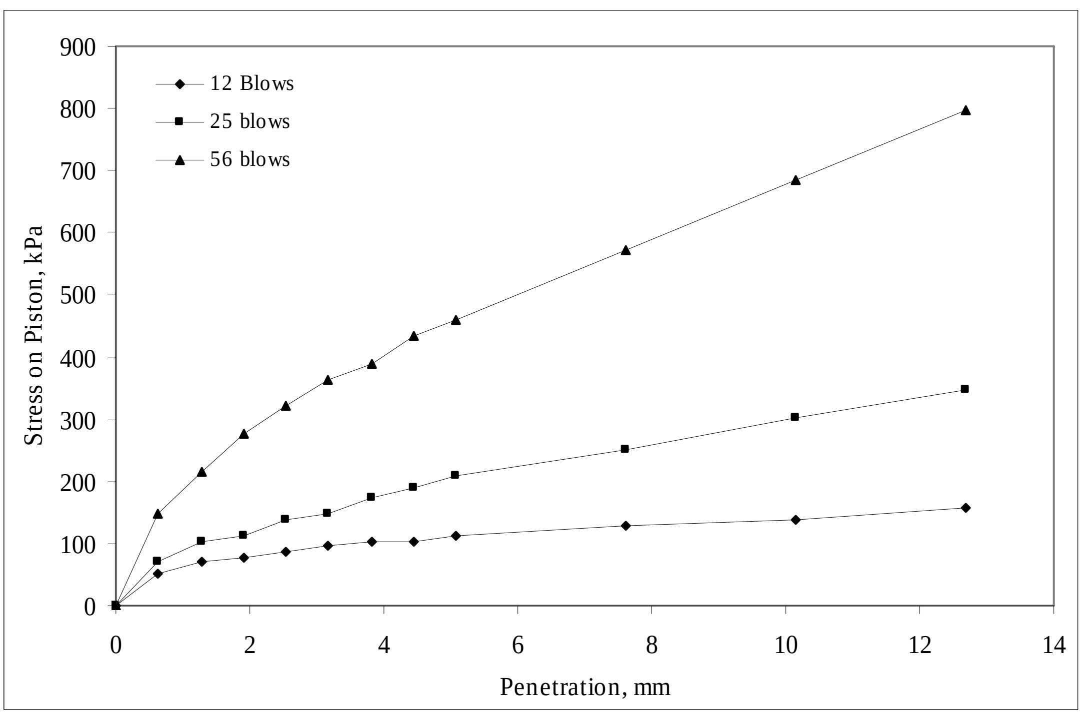

Figure 42: Penetration vs. Stress, CBR Test on Lime Sludge Only

Table 22: Characteristics of CBR Specimens, Lime Sludge Only

Characteristic	12 Blows	25 Blows	56 Blows
Moisture content after compaction, %	43	43	43
Moisture content top 2.54 mm (1 inch) after soak	74	71	69
Dry density before soak, kN/m^3	11.7	12.0	15.1
Dry density after soak, kN/m^3	14.6	14.1	17.0
Height before soak, mm	116.43	116.43	116.43
Height after soak, mm	114.33	116.43	114.83
Swell, % (negative indicates settlement)	-1.8	0	-1.3
Bearing ratio, 0.100 penetration, %	1.26	2.01	4.65
Bearing ratio, 0.200 penetration,%	1.08	2.01	4.44

Tables 23 and 24 and Figure 43 show results of the CBR test on the specimen containing the lime sludge to fly ash ratio of 2:1, with the 28-day cure. A correction for the 2.54 mm (0.1 inch) penetration was needed for the 56-blow curve only since it had a concave upwards shape at its beginning (Figure 43). The correction was obtained graphically (per ASTM

Table 23: Data Table for Penetration vs. Stress, CBR Test, 2:1 Mix Ratio, 28 Days

Penetration (mm)	Stress (kPa)		
	12 Blows	25 Blows	56 Blows
0	0	0	0
0.635	416	720	101
1.27	763	1024	1223
1.905	1050	1223	1518
2.54	1318	1414	1752
3.175	1561	1587	1952
3.81	1787	1718	2221
4.445	2004	1856	2412
5.08	2169	1960	2602
7.62	2776	2299	3175
10.16	3262	2169	3756
12.7	3635	2646	4199

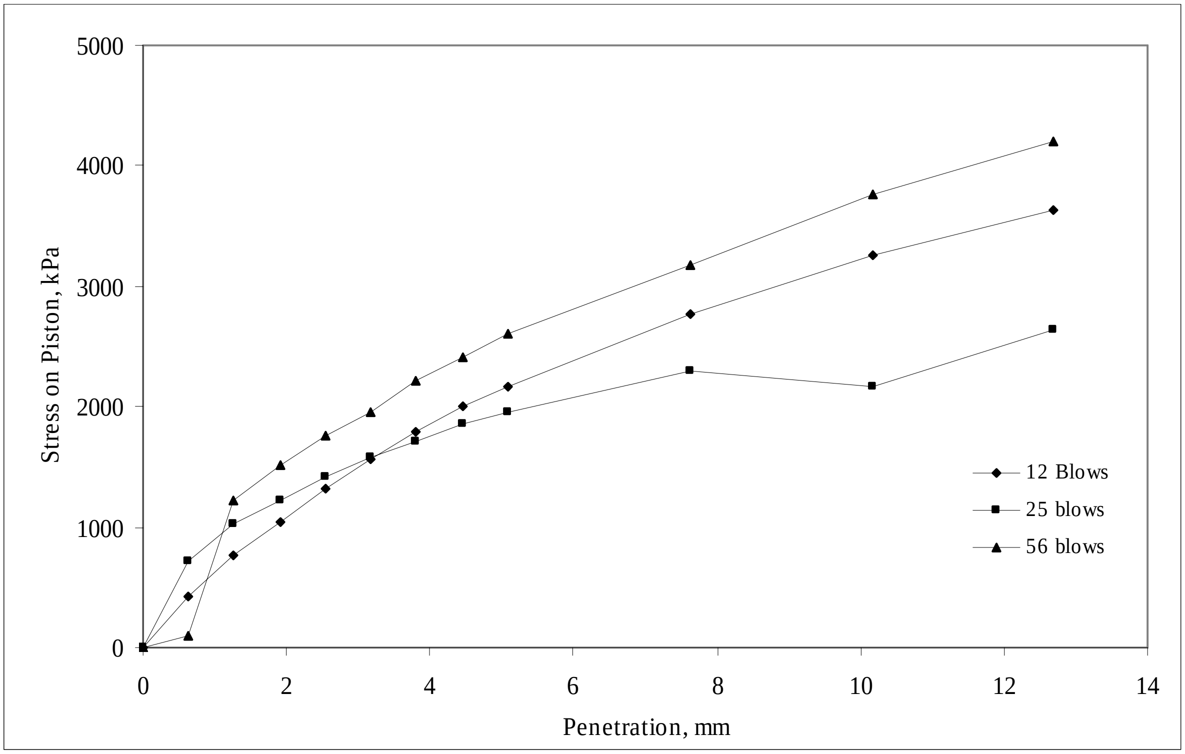

Figure 43: Penetration vs. Stress, CBR Test, 2:1 Mix Ratio, 28 Days

D1883), and the stresses corresponding to the 2.54 mm and 5.08 mm penetrations were 1,881 kPa and 2,728 kPa, respectively. In addition, the standard method requires the CBR test to be repeated for the 12-blow specimen since the CBR corresponding to the 5.08 mm penetration is larger than the value for the 2.54 mm penetration. The other two CBR values in Table 24 were acceptable since the CBR calculated for the 5.08 mm (0.2-inch) penetration was less that for the 2.54 mm penetration.

Table 24: Characteristics of CBR Specimens, 2:1 Mix Ratio, 28 days

Characteristic	12 Blows	25 Blows	56 Blows
Moisture content after compaction, %	26	28	28
Moisture content top 2.54mm (1 inch) after soak	44	47	43
Dry density before soak, kN/m^3	11.8	12.7	16.3
Dry density after soak, kN/m^3	13.4	15.8	19.2
Height before soak, mm	116.43	116.43	116.43
Height after soak, mm	116.43	116.31	116.38
Swell, % (negative indicates settlement)	0	-0.11	-0.04
Bearing ratio, 2.54 mm penetration, %	19.12	20.5	27.27
Bearing ratio, 5.08 mm penetration, %	20.96	18.95	26.37

Tables 25 and 26 and Figure 44 show the repeated CBR test results for the specimens containing the lime sludge to fly ash ratio of 2:1, with the 28-day cure. A correction for the 2.54 mm (0.1-inch) penetration was not required, as the curves drawn on Figure 44 were concave downward. The CBR values were greater for the 5.08 mm penetrations than for the 2.54 mm penetrations in the 12- and the 25-blow specimens. The CBR values corresponding to the 25- and 56-blow specimens were not repeated, so the previous results are combined here with the values for the repeated tests. Table 26 shows significantly lower moisture content after compaction than for the previous tests for this mix design and cure period. An error was made in measuring moisture content for the lime sludge prior to compaction, which resulted in a lower mixture moisture before soaking.

Table 25: Data Table for Penetration vs. Stress, CBR Test, 2:1 Mix Ratio, 28 Days (Repeated Test)

Penetration (mm)	Stress (kPa)		
	12 Blows	25 Blows	56 Blows
0	0	0	0
0.635	113	720	101
1.27	173	1024	1223
1.905	243	1223	1518
2.54	321	1414	1752
3.175	382	1587	1952
3.81	468	1718	2221
4.445	520	1856	2412
5.08	581	1960	2602
7.62	798	2299	3175
10.16	867	2169	3756
12.7	954	2646	4199

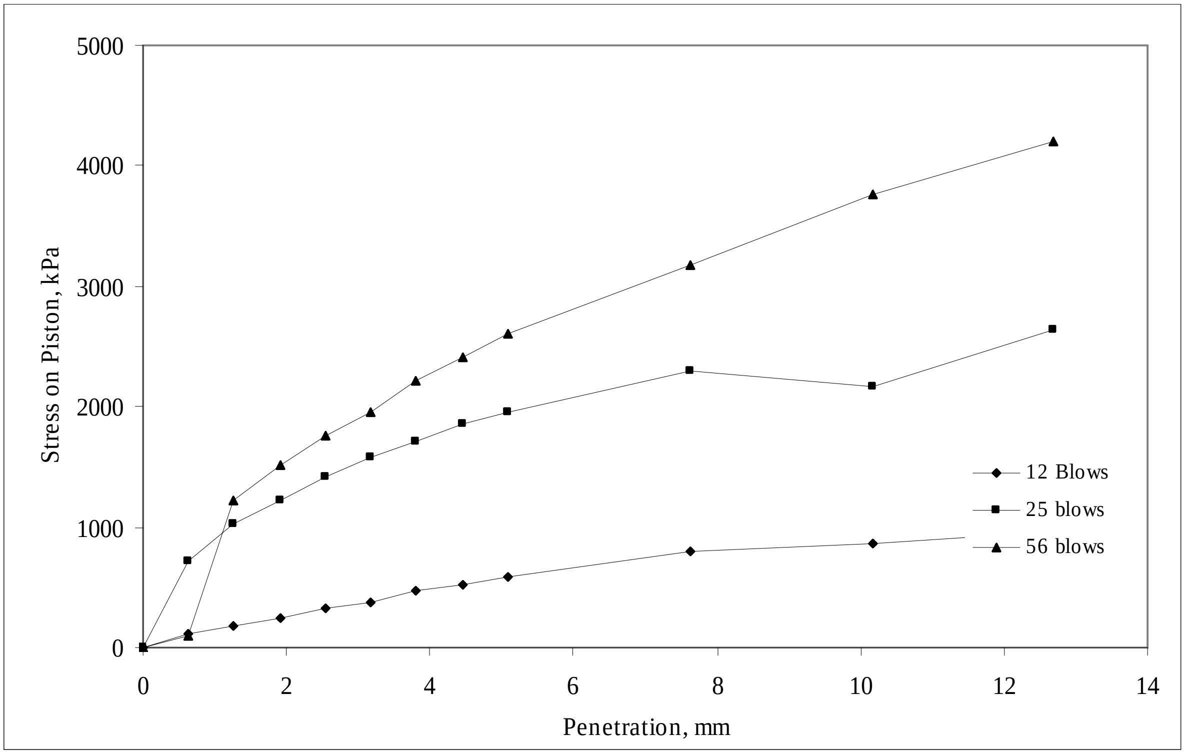

Figure 44: Penetration vs. Stress, CBR Test, 2:1 Mix Ratio, 28 Days (Repeated Test)

Table 26: Characteristics of CBR Specimens, 2:1 Mix Ratio, 28 days (Repeated Test)

Characteristic	12 blows	25 Blows	56 Blows
Moisture content after compaction, %	16	28	28
Moisture content top 2.54mm (1 inch) after soak	66	47	43
Dry density before soak, kN/m3	16.2	12.7	16.3
Dry density after soak, kN/m3	16.2	15.8	19.2
Height before soak, mm	116.43	116.43	116.43
Height after soak, mm	116.43	116.31	116.38
Swell, % (negative indicates settlement)	0	-0.11	-0.04
Bearing ratio, 2.54 mm penetration, %	4.7	20.5	27.27
Bearing ratio, 5.08 mm penetration, %	5.6	18.95	26.37

Tables 27 and 28 and Figure 45 show the CBR test results on the specimens containing the lime sludge to fly ash ratio of 2:1, with the 56-day cure. A correction for the 2.54 mm (0.1-inch) penetration was not needed, as the curves in Figure 45 were concave downward. In addition, the standard method requires the CBR test to be repeated for the 12- and 25-blow specimens since the CBR corresponding to the 5.08 mm penetrations is larger than the value for the 2.54 mm penetrations. The CBR value corresponding to the 56-blow specimen was acceptable since the CBR calculated for the 5.08 mm (0.2-inch) penetration was less that for the 2.54 mm penetration.

Table 27: Data Table for Penetration vs. Stress, CBR Test, 2:1 Mix Ratio, 56 Days

Penetration (mm)	Stress (kPa)		
	12 Blows	25 Blows	56 Blows
0	0	0	0
0.635	1136	1301	1345
1.27	1613	1952	2160
1.905	1917	2420	3366
2.54	2186	2819	3938
3.175	2386	3201	4207
3.81	2550	3609	4763
4.445	2689	4034	4997
5.08	3713	4329	5404
7.62	4190	5448	6428
10.16	4589	6619	7764
12.7	5005	7495	8527

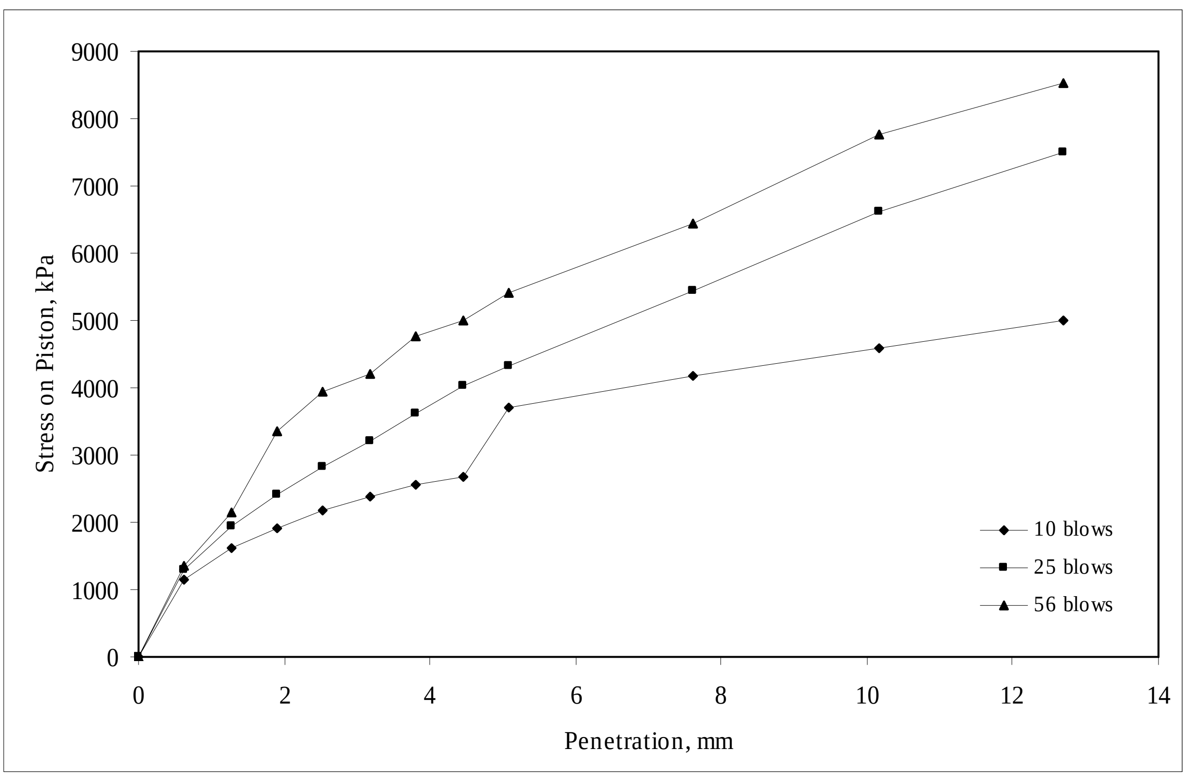

Figure 45: Penetration vs. Stress, CBR Test, 2:1 Mix Ratio, 56 Days

Table 28: Characteristics of CBR Specimens, 2:1 Mix Ratio, 56 days

Characteristic	12 Blows	25 Blows	56 Blows
Moisture content after compaction, %	26	28	28
Moisture content top 2.54mm (1 inch) after soak	42	31	33
Dry density before soak, kN/m^3	14.4	15.7	16.7
Dry density after soak, kN/m^3	16.1	17.0	17.4
Height before soak, mm	116.43	116.43	116.43
Height after soak, mm	116.43	116.46	116.31
Swell, % (negative indicates settlement)	0	0.02	-0.11
Bearing ratio, 2.54 mm penetration, %	31.7	40.9	57.1
Bearing ratio, 5.08 mm penetration, %	35.9	41.8	52.2

Tables 29 and 30 and Figure 46 show the repeated CBR test results on the specimens containing the lime sludge to fly ash ratio of 2:1, with the 56-day cure. A correction for the 2.54 mm (0.1-inch) penetration was not needed, as the curves shown in Figure 46 were concave downward. The CBR values were greater for the 5.08 mm penetrations than for the 2.54 mm penetrations in the 12- and the 25-blow specimens. The CBR value corresponding to the 56-blow specimen was not repeated, so the previous results are combined here with the values for the repeated tests. Table 30 shows significantly lower moisture content after compaction than was shown in the previous tests for this mix design and cure period. An error was made in measuring moisture content for the lime sludge prior to compaction, resulting in a lower mixture moisture before soaking.

Table 29: Data Table for Penetration vs. Stress, CBR Test, 2:1 Mix Ratio, 56 Days (Repeated Test)

Penetration	Stress (kPa)		
(mm)	12 Blows	25 Blows	56 Blows
0	0	0	0
0.635	113	217	1345
1.27	173	408	2160
1.905	260	624	3366
2.54	330	815	3938
3.175	416	1024	4207
3.81	486	1214	4763
4.445	564	1405	4997
5.08	624	1561	5404
7.62	859	1969	6428
10.16	1058	2307	7764
12.7	1136	2654	8527

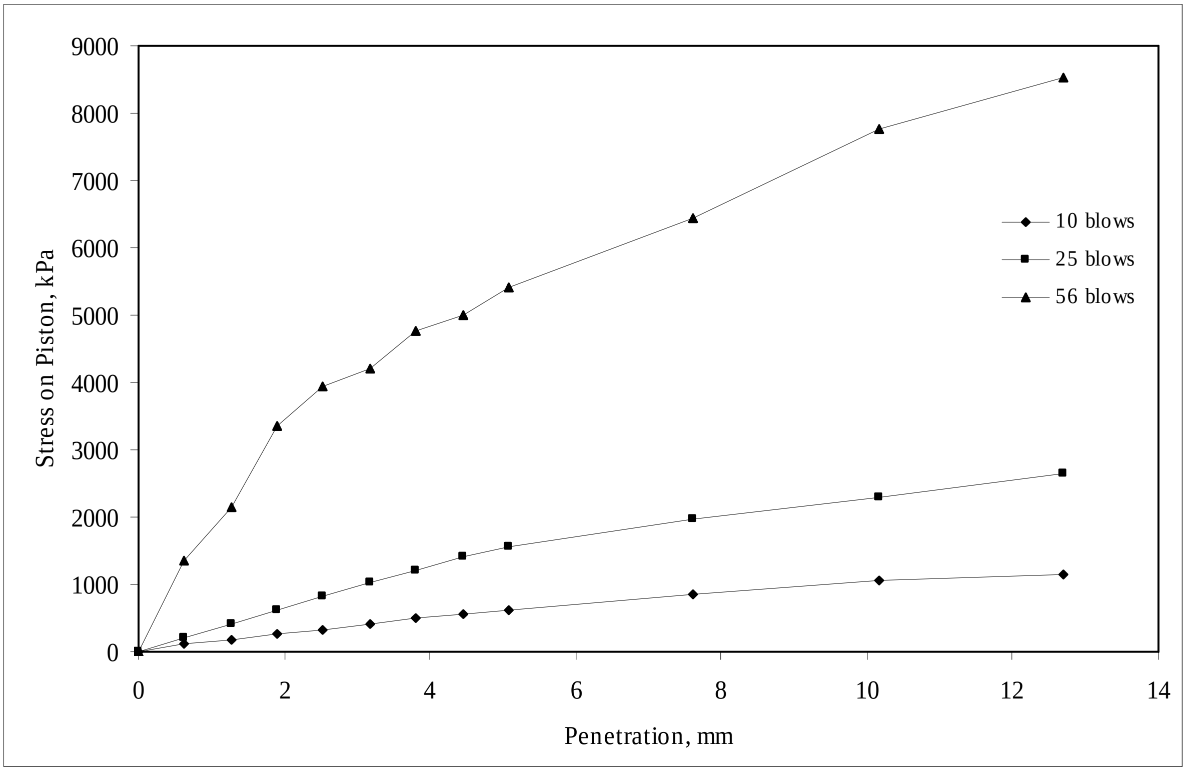

Figure 46: Penetration vs. Stress, CBR Test, 2:1 Mix Ratio, 56 Days (Repeated Test)

Table 30: Characteristics of CBR Specimens, 2:1 Mix Ratio, 56 days (Repeated Test)

Characteristic	12 blows	25 Blows	56 Blows
Moisture Content after Compaction, %	16	17	28
Moisture Content top 1" after Soak	16	17	28
Dry Density Before Soak, kN/m^3	16.0	16.5	16.7
Dry Density After Soak, kN/m^3	16.0	16.5	17.4
Height before soak, inches	116.43	116.43	116.43
Height After Soak, inches	116.43	116.43	116.31
Swell, % (negative indicates settlement)	0	0	-0.11
Bearing Ratio, 0.100 penetration, %	4.8	11.8	57.1
Bearing Ratio, 0.200 penetration, %	6	15.1	52.2

Tables 31 and 32 and Figure 47 show the CBR test results on the specimens containing the lime sludge to fly ash ratio of 1:1, with the 28-day cure. A correction for the 2.54 mm (0.1-inch) penetration was not needed, as the curves shown in Figure 47 were concave downward. In addition, all three values for the CBR in Table 32 were acceptable since the CBR calculated for the 5.08 mm (0.2-inch) penetration was less that for the 2.54 mm penetration.

Table 31: Data Table for Penetration vs. Stress, CBR Test, 1:1 Mix Ratio, 28 Days

Penetration (mm)	Stress (kPa)		
	12 Blows	25 Blows	56 Blows
0	0	0	0
0.635	451	642	633
1.27	642	1032	1414
1.905	815	1266	1657
2.54	963	1501	1770
3.175	1093	1709	1787
3.81	1223	1891	1882
4.445	1327	2073	1995
5.08	1440	2177	2082
7.62	1752	2698	2203
10.16	1978	3149	2229
12.7	2151	3548	2333

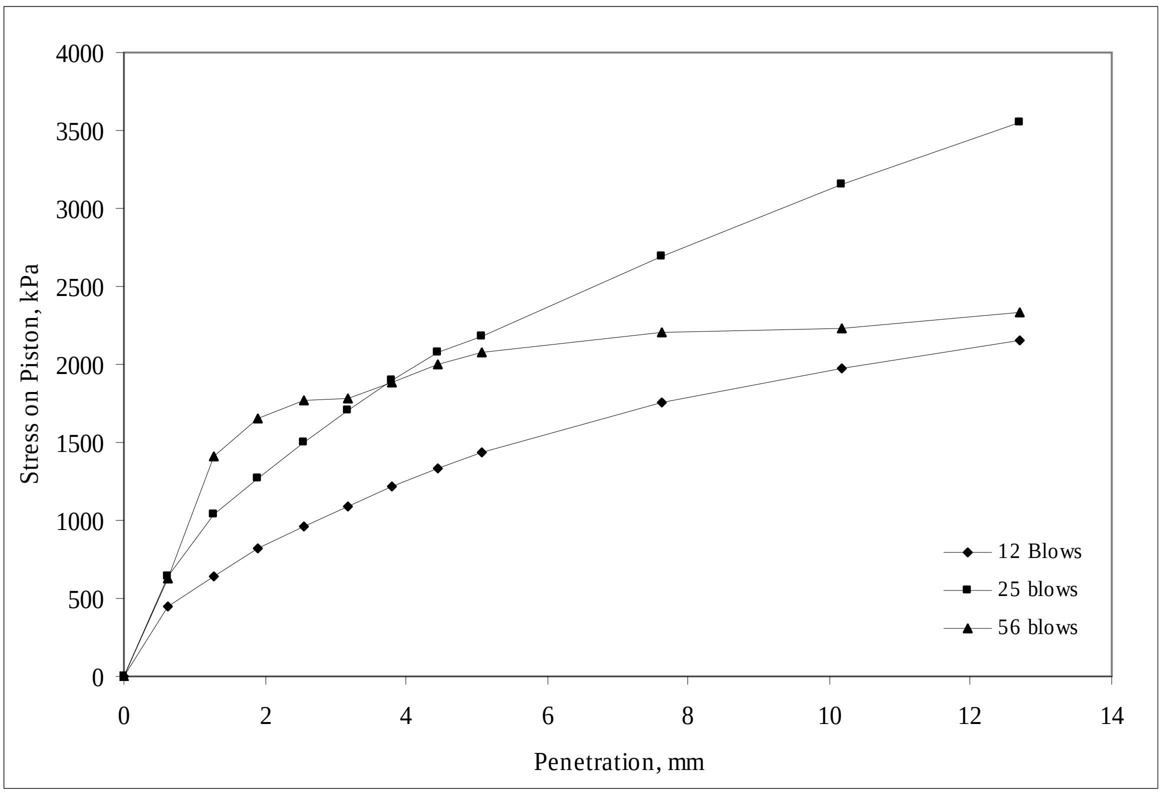

Figure 47: Penetration vs. Stress, CBR Test, 1:1 Mix Ratio, 28 Days

Table 32: Characteristics of CBR Specimens, 1:1 Mix Ratio, 28 days

Characteristic	12 blows	25 Blows	56 Blows
Moisture content after compaction, %	22	17	19
Moisture content top 2.54 mm (1 inch) after soak	40	47	43
Dry density before soak, kN/m^3	12.6	14.2	15.1
Dry density after soak, kN/m^3	16.4	17.0	17.4
Height before soak, mm	116.43	116.43	116.43
Height after soak, mm	116.15	116.31	116.43
Swell, % (negative indicates settlement)	-0.24	-0.11	0
Bearing ratio, 2.54 mm penetration, %	14	21.8	25.7
Bearing ratio, 5.08 mm penetration, %	13.9	21.5	20.3

Tables 33 and 34 and Figure 48 show the CBR test results for the specimens containing the lime sludge to fly ash ratio of 1:1, with the 56-day cure. A correction for the 2.54 mm (0.1-inch) penetration was not required as the curves drawn on Figure 48 were concave downward. In addition, all three values for the CBR in Table 34 were acceptable since the CBR calculated for the 5.08 mm (0.2-inch) penetration was less that for the 2.54 mm penetration.

Table 33: Data Table for Penetration vs. Stress, CBR Test, 1:1 Mix Ratio, 56 Days

Penetration (mm)	Stress (kPa)		
	12 Blows	25 Blows	56 Blows
0	0	0	0
0.635	416	833	260
1.27	607	1379	1926
1.905	703	1570	2464
2.54	755	1761	2819
3.175	798	1917	3123
3.81	893	2073	3374
4.445	971	2203	3635
5.08	1015	2290	3730
7.62	1284	2715	4554
10.16	1561	3080	5118
12.7	1778	3409	5604

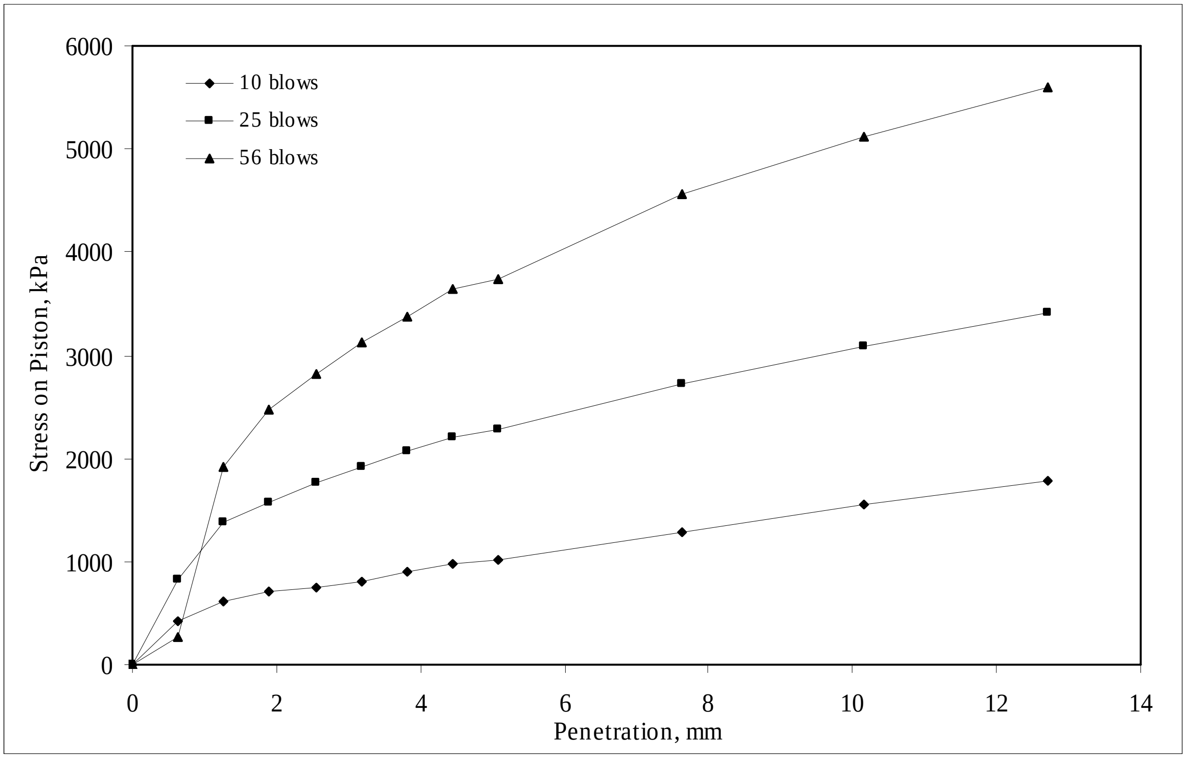

Figure 48: Penetration vs. Stress, CBR Test, 1:1 Mix Ratio, 56 Days

Table 34: Characteristics of CBR Specimens, 1:1 Mix Ratio, 56 days

Characteristic	12 blows	25 Blows	56 Blows
Moisture content after compaction, %	22	22	19
Moisture content top 2.54 mm (1 inch) after soak	49	n/a	38
Dry density before soak, kN/m^3	14.4	15.7	16.7
Dry density after soak, kN/m^3	15.9	17.0	17.4
Height before soak, mm	116.43	116.43	116.43
Height after soak, mm	116.46	116.31	116.43
Swell, % (negative indicates settlement)	0.02	-0.11	0
Bearing ratio, 2.54 mm penetration, %	10.9	25.5	45
Bearing ratio, 5.08 mm penetration, %	9.8	22.1	38

According to Figure 49, increased amount of stabilizer in the mix does not increase the CBR in a dry density range of 12 and 17 kN/m^3. Above a mixture dry density of about 17 kN/m^3, the CBR increased with high amounts of stabilizer. Figures 50 and 51 show that as the cure time increases, so does the CBR. Figures 49 and 50 are plotted with the original set of results and not the CBR values from the repeated tests.

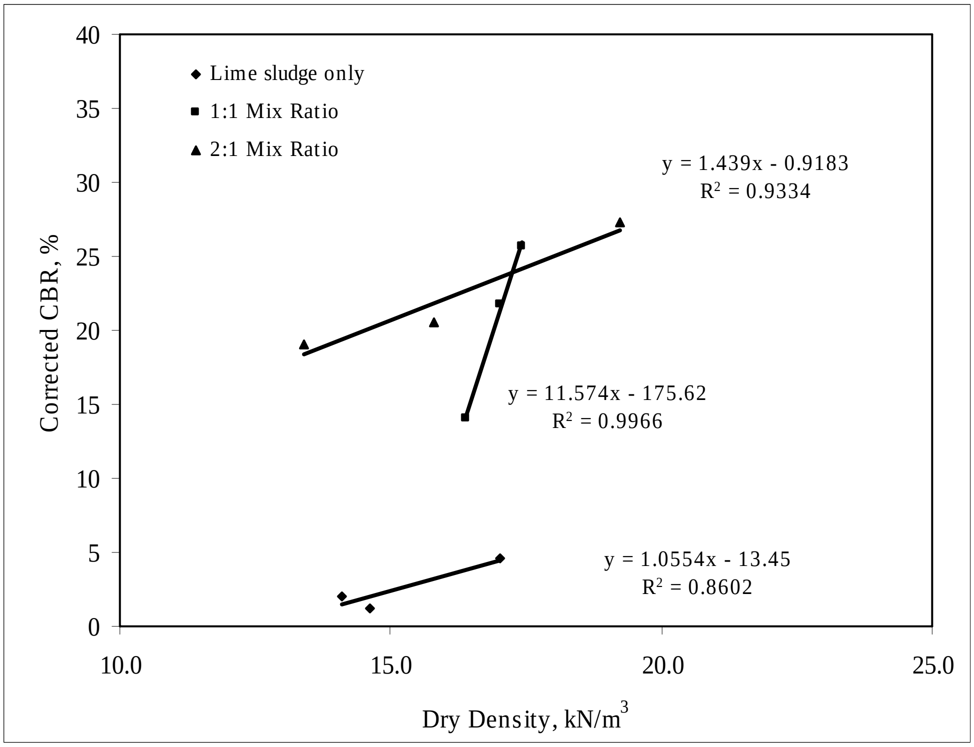

Figure 49: Effect of Additive amount in CBR Tests

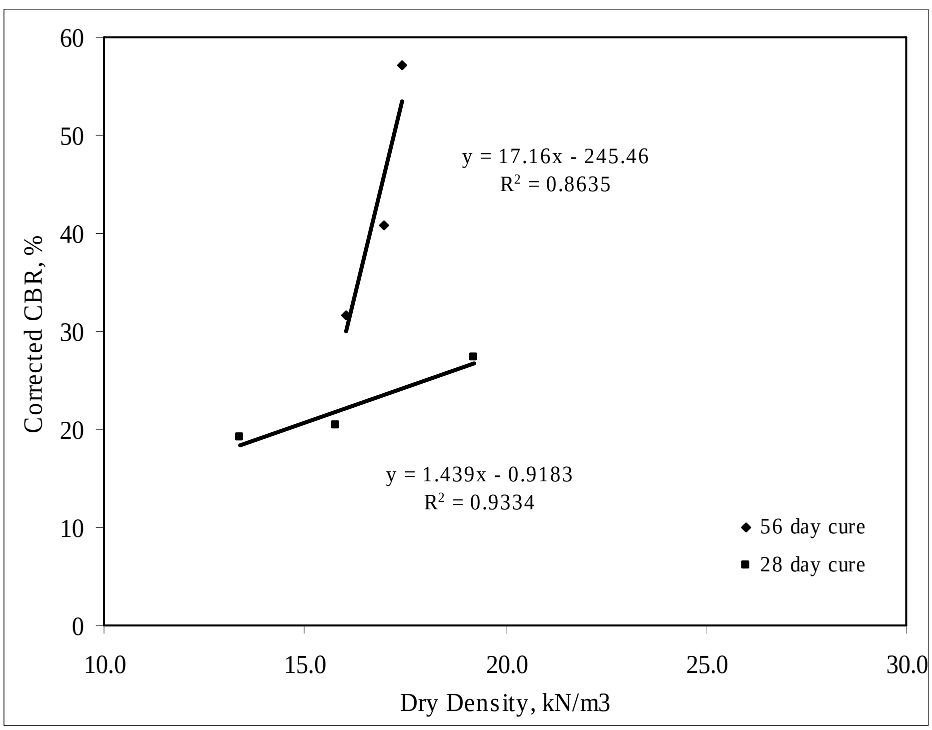

Figure 50: Effect of Cure Time on CBR, Lime Sludge to Fly Ash Ratio of 2:1

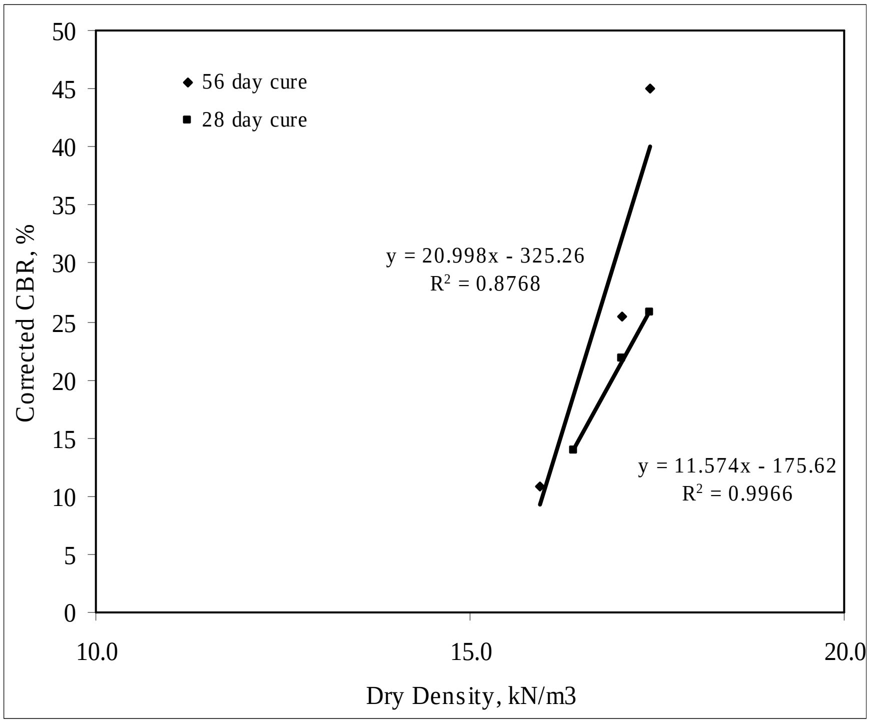

Figure 51: Effect of Cure time on CBR, Lime Sludge to Fly Ash Ratio of 1:1

<u>Durability of Lime Sludge Mixtures</u>

Table 35 and Figures 52 and 53 show the results of a brushed wet/dry durability test. The fly ash to lime sludge ratios used are within the same range as those used for the unconfined compressive strength testing (Figures 25 and 26). The moisture contents used were optimum as defined by Figure 25. Table 35 shows that only the high ratio mixes survived 12 cycles. Packard and Chapman (1963) evaluated several different soil-cement mixtures for mass loss after wet-dry durability tests. The data they reported showed that soils stabilized with 5% cement (dry weight basis) experienced mass losses ranging from 4% to 13%. Referencing these results, the losses in Table 35 indicate that stabilized lime sludge mixtures have insufficient wet-dry durability.

Table 36 and Figures 54 and 55 show results from a brushed set of specimens that endured the freeze/thaw test. The fly ash to lime sludge ratios and moisture contents used were the same as those used in the wet/dry tests. No brushed specimen made it all the way through 12 cycles of freeze/thaw testing. According to Packard and Chapman (1963), silty soils stabilized with 5% cement (dry weight basis) had mass losses ranging from 6 to 29%; however, a two silty soils that were stabilized with as much as 10% cement content experienced between 34 and 100% mass loss. These tests were not brushed specimens. Fredrickson (1963) stated that the AASHTO Designation T 136-57 limits the maximum allowable loss endured through a wet/dry or freeze thaw test to 10% for silty soils with the AASHTO classification of A-2-6, A-2-7, A-4, or A-5 and that standard should be considered for design of road bases. Table 37 shows that when the mass and volume of the specimen without brushing were measured, the volume changes were well above 10%.

Table 35: Mass Loss During Wet/Dry Durability Tests

Wet/Dry Material/stabilizer ratio[a]	Moisture Content (%)	Density (g/cm^3)	Soil-Cement Loss (%)	No. Cycles tested
Lime sludge, no binder	34	1.46	100	1
Ames FA / 0.1	27	1.45	100	3
Ames FA / 0.5	25	1.58	30	12
OGS FA / 0.1	26	1.45	100	3
OGS FA / 0.5	24	1.63	36	12
OGS FA & BA / 0.5	20	1.65	40	12
Portland cement / 0.1	37	1.56	100	5
Portland cement / 0.25	35	1.60	16	12

Note a: ratios are listed as dry weight of stabilizer divided by dry weight of lime sludge

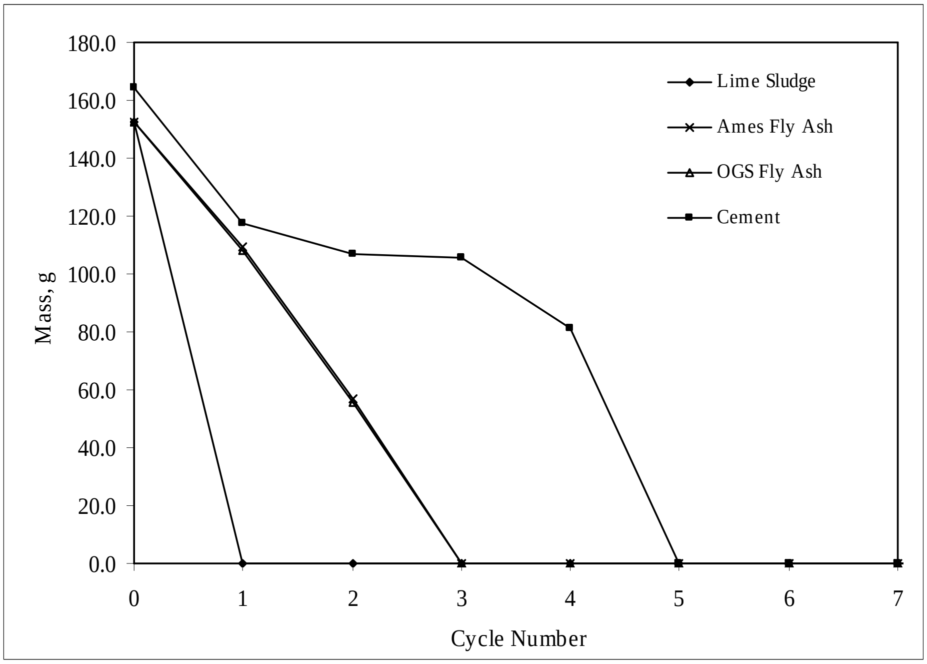

Figure 52: Mass Loss during Wet/Dry Cycles, Brushed Specimen, Fly Ash to Lime Sludge Ratio 0.1, Cement to Lime Sludge Ratio 0.1 (Dry Weight Basis)

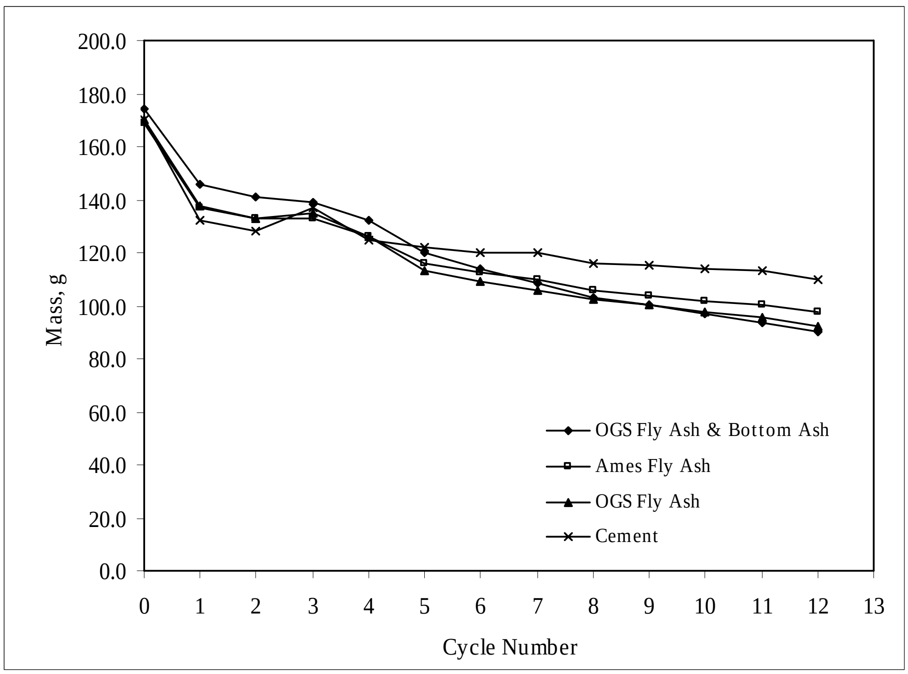

Figure 53: Mass Loss During Wet/Dry Cycles, Brushed Specimen, Fly Ash to Lime Sludge Ratio 0.5, Cement to Lime Sludge Ratio 0.25 (Dry Weight Basis)

Table 36: Mass Loss During Freeze/Thaw Durability Tests

Freeze/Thaw Material/Stabilizer Ratio[a]	Moisture Content (%)	Density (g/cm^3)	Soil-Cement Loss (%)	No. Cycles to Ultimate Failure
Lime sludge, no binder	34	1.64	100	1
Ames FA / 0.1	27	1.64	100	2
Ames FA / 0.5	25	1.72	100	5
OGS FA / 0.1	26	1.64	100	2
OGS FA / 0.5	24	1.68	100	6
OGS FA & BA / 0.5	20	1.79	100	5
Portland cement / 0.1	37	1.61	100	5
Portland cement / 0.25	35	1.61	100	6

Note a: ratios are listed as dry weight of stabilizer divided by dry weight of lime sludge

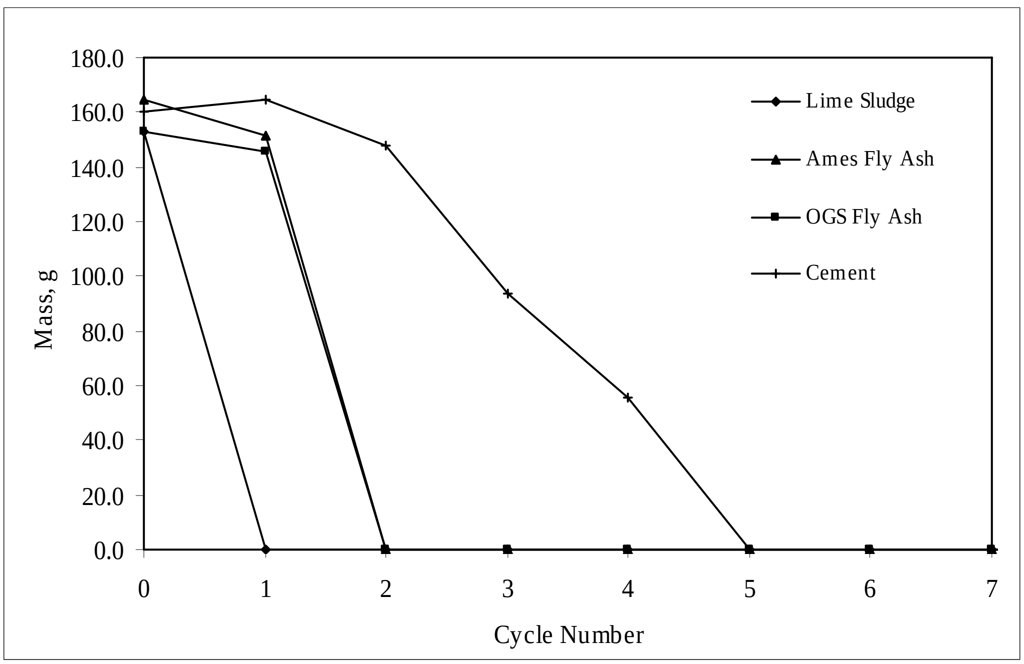

Figure 54: Mass Loss During Freeze/Thaw Cycles, Brushed Specimen, Fly Ash to Lime Sludge Ratio 0.1, Cement to Lime Sludge Ratio 0.1 (Dry Weight Basis)

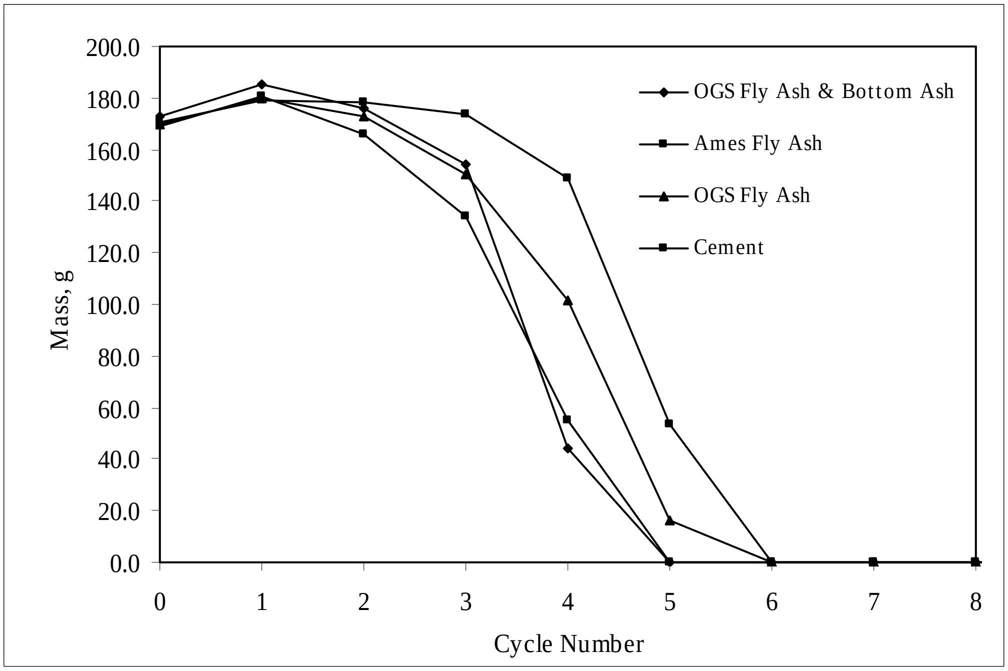

Figure 55: Mass Loss During Freeze/Thaw Cycles, Brushed Specimen, Fly Ash to Lime Sludge Ratio 0.5, Cement to Lime Sludge Ratio 0.25 (Dry Weight Basis)

Table 37: Freeze/Thaw Durability Testing on Lime Sludge and Ames Fly Ash.

Percent of Ames Fly Ash to Lime Sludge (Dry Weight Basis)	Specimen Type	Moisture Content (%)	Density (g/cm^3)	Soil-Cement Loss (%)	Volume Change (%)
20	Volume	23	1.46	n/a	38
20	Brush	23	1.43	100.0	n/a
40	Volume	30	1.65	n/a	19
40	Brush	30	1.63	100.0	n/a

Figure 56 shows specimens that went through 12 cycles of wet/dry durability tests with brushing. These were the higher stabilizer to lime sludge ratios. No specimens survived 12 cycles of freeze/thaw and brushing. Figure 57 demonstrates how freezing and thawing can take its toll on specimens (these were not brushed, only measured for volume change). As seen on Tables 35 and 36, the results of the first set of durability tests shows that the freeze/thaw test is the most aggressive.

Figure 56: Wet/Dry Durability Test Specimens, after 12 cycles with Brushing

Figure 57: Specimens after Freeze/Thaw Tests (Left and Center);
Steel Cylinder Control Volume (right)

The results demonstrate an important limitation of the mixes. While the mixes can carry sufficient compressive loads, they will benefit the best from being placed below the frost line to protect them from wet/dry and freeze/thaw action. As a practical example, a highway off-ramp's core can be made of the mixes and then covered with 1.5 m of a durable soil. Fredrickson (1963) recommended that unsuitable soils with respect to durability be placed below the upper 3 feet (0.91 m) of subgrade for highway construction. He also presented agricultural records from 1899 to 1938 indicating that the frost depth for Iowa ranged from 25 to 35 inches (63 to 89 cm) to support this recommendation.

Hydraulic Conductivity

Tables 38 through 40 summarize the results of the tests for hydraulic conductivity. The gradients used during the tests ranged from 2.5 to 5.1, and adequate saturation was accomplished for each test. For each set, three specimens were tested to determine three values of hydraulic conductivity. The three values were averaged together and a temperature correction applied to determine the final value for hydraulic conductivity. The values of hydraulic conductivity, as reported in Tables 38 through 40, suggest that when lime sludge is stabilized with fly ash, the hydraulic conductivity decreases.

The values for hydraulic conductivity fall within the range of the values published in the literature. According to Bowles (1997), clean gravel and sand mixtures range from 1 cm/s to 10 x 10^{-3} cm/s, sand and silt mixtures range from 10 x 10^{-3} cm/s to 10 x 10^{-7}, and clays range from 10 x 10^{-7} cm/s to 10 x 10^{-9} cm/s. The values for the lime sludge mixtures found in Tables 38 through 40 fall within the range for silts given by Bowles.

Table 38: Hydraulic Conductivity, Lime Sludge Only

Cell	Initial Moisture (%)	Initial Dry Density (g/cm^3)	Final Moisture (%)	Degree Sat (%)	Final Dry Density	Temp (^{o}C)	Temp Correction	Hydraulic Conductivity (cm/s)
1	42	1.00	67	100	0.97	22	0.953	1.66 x 10^{-5}
2	42	1.00	65	100	0.97	22	0.953	1.86 x 10^{-5}
3	42	1.02	66	100	0.98	22	0.953	1.61 x 10^{-5}
							Ave	1.71 x 10^{-5}

Table 39: Hydraulic Conductivity, Lime Sludge to Fly Ash Ratio 2:1

Cell	Initial Moisture (%)	Initial Dry Density (g/cm3)	Final Moisture (%)	Degree Sat (%)	Final Dry Density	Temp (^oC)	Temp Correction	Hydraulic Conductivity (cm/s)
1	17	1.26	40	100	1.27	23	0.931	1.07×10^{-5}
2	17	1.26	41	100	1.28	23	0.931	1.02×10^{-5}
3	17	1.25	42	100	1.26	23	0.931	1.10×10^{-5}
							Ave	1.07×10^{-5}

Table 40: Hydraulic Conductivity, Lime Sludge to Fly Ash Ratio 1:1

Cell	Initial (%)	Initial Dry (g/cm3)	Final (%)	Degree (%)	Final Dry Density	Temp (^oC)	Temp Correction	Hydraulic (cm/s)
3	10	1.21	44	100	1.21	23.5	0.920	2.21×10^{-5}
2	10	1.22	43	99	1.23	23.5	0.920	1.82×10^{-5}
1	10	1.21	44	100	1.21	23.5	0.920	2.80×10^{-7}
							Ave	1.35×10^{-5}

Conclusions and Recommendations

Larger additions of portland cement or Class C fly ash to lime sludge generally resulted in higher values for unconfined compressive strength, cohesion in direct shear tests, and CBR. The best moisture content to use for mixtures containing OGS fly ash is 28%, and that for those containing portland cement is 40%. A range of moisture contents was used for the Ames fly ash—24 to 40%. For mixes containing 33% Ames fly ash (dry weight basis), a moisture content of 40% was best; for those containing 9% Ames fly ash (dry weight basis), 24% moisture content was best.

Lime sludge and chemically stabilized lime sludge mixes result in high values for CBR and for internal friction angle for a material with a Unified Classification System symbol of ML. Increasing cure time resulted in higher values for cohesion in direct shear tests and for CBR of chemically stabilized lime sludge mixtures.

Lime sludge was chemically stabilized with Ames fly ash, OGS fly ash, or portland cement to produce satisfactory UCS results for construction fill. However, an important limitation of the lime sludge and the stabilized mixes was its lack of durability through cycles of weather extremes. As with other soils within its classification, stabilized lime sludge mixtures should be placed below the expected frost zone and covering it with a higher grade, weather-resistant material is logical for fill applications.

Hydraulic conductivity values averaged 1.71 x 10^{-5} cm/s for lime sludge alone and 1.07 x 10^{-5} cm/s for a 1:1 (by dry weight) lime sludge and fly ash mix. This is a relatively low permeability material, but not low enough to be used for primary environmental liner uses such as landfill liners. Landfill liners generally require a minimum hydraulic conductivity on the order of 1 x 10^{-7} cm/s (EPA, 2005).

PART III - IN SITU TESTING OF A TEST EMBANKMENT AND COST ANALYSIS

Introduction

The quantities of fill materials needed when building an embankment for a highway overpass are very large. In the Corporate Woods Drive project near Ankeny (Iowa DOT, 2005), adjacent to Interstate 35, over 690,000 cubic yards of material was needed to construct an embankment. The project design specified that there was only 390,000 cubic yards of fill available from within the project limits. The rest of the fill was taken from three other designated borrow areas. What if there was not enough affordable fill material for this project close to the project site? If lime sludge were used a source of some of the fill required, where would it come from and how much would it cost? This part will address these questions.

After reviewing the last report on this research project, the Iowa Highway Research Board expressed concern about using a material with poor durability in lab tests. Lab tests yielded mass loss and volume changes of greater than the benchmark value of 10% after enduring alternating freeze/thaw cycles. Therefore, the general condition of using lime sludge in fill below the frost line was given so that lime sludge could still be used as a strong fill material. Additional tests were performed to support this recommendation because of concerns about durability. A mix of one part fly ash (dry weight) to two parts dried lime sludge (wet weight, moisture content about 38%) was chosen for further durability and strength testing, and the chosen mix design was used during the construction of a test embankment (20 feet wide, 3.5 feet tall at center, and about 37 feet long) at the lime sludge processing site in Ames, Iowa. Taking the water in the lime sludge into account, the weight of the fly ash in this mix was close to 50% of the lime sludge on a dry weight basis.

Materials

<u>Lime Sludge</u>

The same source of lime sludge that was used to produce the results in Part II was used for construction of the test embankment, and the date of sampling was June 30, 2004. A large, front-end loader that could carry 5 to 6 cubic yards of material in one trip was used to move the lime sludge. Due to the amount of material taken per load, no effort was made to exclude the lime sludge on the surface of the stockpile.

During the embankment construction, a windrow machine (employed by BMG to turn over the sludge during drying) was used for mixing, and this machine easily broke up agglomerations of the lime sludge as it was mixed with the fly ash. The apparent size of the lime sludge particles after mixing was about 1 cm or less. Since the windrow machine is the machine used to dry the sludge, using it to mix the sludge could dry it further and make moisture control more difficult. The moisture loss caused by using this machine to mix was difficult to predict; therefore, defining this moisture loss through the test embankment construction was a seen as a benefit to the future use of chemically stabilized lime sludge as a fill material.

Fly Ash

The fly ash used in the test embankment was taken directly from the overhead storage bin at the Ames Power Plant on June 30, 2004. The fly ash was released into a rented cement mixer and transported about ¼ mile to the test embankment site where it was poured onto a bed of lime sludge. The temperature of the fly ash is hotter than boiling water and it is at about zero percent moisture content when it was released from the overhead storage bin at the Ames Power Plant.

The discussion presented in Part II with regards to Ames fly ash applies to this fly ash as well. Consistent with what was presented in Part II, it was assumed that the fly ash would not be of the same exact chemical composition as the Ames fly ash used in the lab experiments, but that it is still similar enough to cause the same strength gains seen in Part II. It was classified as a Class “C” fly ash just as the ash used in the laboratory experiments was. Therefore, no further presentation on the capabilities with regards to strength gain, moisture content for hydration, and reaction time (“set time test”) will be presented in this part.

Methods

Embankment Construction

Transitioning from lab testing to a larger scale, a test embankment was constructed outdoors on June 30, 2004. Locally available materials were mixed, placed, and compacted at a 2:1 lime sludge to fly ash ratio. No water was added, so the moisture available in the air-dried lime sludge was the source for the hydration for the fly ash. The lime sludge and fly ash were mixed dry of the optimum moisture content of 24%. Even though there were two significant rainfall events (more than 0.5-inch) within a week after construction, the 24% moisture content value was the goal for the construction. It was previously determined from analysis of the unconfined compressive strength test results for a 33% Ames fly ash addition to lime sludge specimens (presented in Part II).

Each of the five lifts that made up the test embankment was compacted with about eight passes of the self-propelled vibratory compaction machine. The thickness of each lift was about 20 cm (8 inches) after compaction. To determine the unit weight of each lift, samples 7.62 cm (3 inches) in diameter by 5.08 cm (2 inches) high were excavated from the compacted material. This was accomplished by driving an aluminum cylinder into the soil with a 4.54 kg (10 lb) rammer. The cylinder with compacted mix material was then excavated manually with a spade.

On the same day, the samples were taken back to the lab; their weight, height, and diameter were measured; and their densities were calculated. In addition, a sample of loose mix material was taken back to the lab and compacted with the Iowa State University 2x2 Procedure (O'Flaherty et al., 1963). The unit weights of the specimens compacted in the laboratory were then compared with those of the cylinders excavated from the field. The moisture content of the loose mix sample was determined in a drying oven and used to convert all moist unit weights to dry unit weights. Since fly ash starts to hydrate immediately after mixing, any delay in measuring moisture content will yield lower values. Due to the fast set time for the Ames fly ash (less than 15 minutes) and the drying effect of the machine used to mix the materials, it was expected that the measured moisture content of the mix samples would be lower.

On July 15, 2004, dynamic cone penetrometer (DCP) tests were performed on the test embankment at locations on the flat top of the embankment. The DCP with an 8 kg hammer with disposable tips was used. Four sets of readings were taken at different parts of the top of the embankment (i.e., not on side slopes or within 30 cm of the side of the top). The condition of the embankment was dry and firm to a finger pushed into its surface. A man of 190 lbs walked on the surface of the embankment and left no footprints of 1 cm depth or more. On April 8, 2005, four more sets were taken in the same manner as on July 15, 2004. The condition of the embankment was again dry and firm to finger pressure and a man weighing about 190 lbs left no footprints of 1 cm or more.

To demonstrate that the test embankment would endure freeze/thaw temperatures from July to April, devices that measure temperature every 15 minutes were buried in the approximate center of the embankment every 6 inches of depth. A tool was used to remove a core about a 7 cm in diameter and 84 cm in depth. Temperature devices were placed every 15 cm (6 inches) from 76 cm (30 inches) of depth and upward. Depth was measured by a metal tape measure. After the temperature device was emplaced at the bottom of the hole, the excavated material was used to fill the hole to the next depth. After each filling, the material was rodded with a steel pole about 1.5 cm in diameter for about 30 seconds to compact the material in the hole. There was a wire that ran from each temperature device to the surface, and each wire was labeled and suspended above the ground level. A small handheld computer was used to upload temperature readings. The temperature readings were transferred to a spreadsheet and plotted.

Test Results and Discussion

<u>Test Embankment at the Ames Water Treatment Plant</u>

Construction

Critics of using lime sludge as a construction fill material may say using lime sludge mixes for construction fill would be too complicated because of the control requirements associated with additive amounts and moisture content. This is valid for a contractor with no experience in road construction, but for the crews working on the large-scale projects this application aims to serve, controlling additive amounts and moisture content during road construction should be a standard practice. To show that it is not very complicated, the engineering graduate student assigned to this project and a few heavy equipment operators, with no prior construction experience with fly ash stabilization or compaction, constructed the test embankment.

Overall, the embankment constructed was about 20 feet wide, 3.5 feet tall at center, and about 37 feet long. The slopes of the sides were about 1:2 vertical to horizontal. Figures 58 through 60 show a few important steps in the process. In Figure 58, the lime sludge was laid out and the sides pushed up to help contain the fly ash as it was poured out. A cement mixer truck was used to transport and pour the ash since it was the best available equipment for controlling the flow of the ash and the dust generated when the ash was poured.

Figure 59 shows a small front-end loader, equipped with a windrowing device used to turn over the sludge during drying, being used to mix the materials. Due to the short amount of reaction time available with this particular fly ash (its set time was about 12 minutes in the lab), the mix was immediately placed and compacted after mixing. In this case, there was an area available adjacent to the construction site for mixing lime sludge and fly ash.

Figure 60 shows the vibrating pad foot compaction machine used to compact the mix. The embankment was built in five lifts. The thickness of each lift was about 10 inches after placement and 7 to 8 inches after compaction. The topsoil available on site, which consisted of mostly bottom ash, was placed on the embankment over a 4-inch thickness and packed down with the treads of the small loader shown in Figure 59. There was a large stockpile of bottom ash on the same site not far away.

Figure 58: Pouring Fly Ash on a Lime Sludge Bed

Figure 59: Mixing Lime Sludge and Fly Ash

Figure 60: Compacting the test embankment

Density and Moisture Content

The results of the density measurements for each compacted lift are tabulated in Table 41. Field specimens were trimmed to the size of the drive sleeve and weighed. These specimens did not hold together upon extraction, and some material was stuck to the inside of the drive sleeve; therefore, accurate measurements from an extracted specimen were not possible, and the inner dimensions of the sleeve were used to calculate the specimen volume. The volume used was 347.5 cm^3. The densities found in the field specimens were similar to those found in lab compacted specimens in the UCS and permeability testing (see Tables 14, 15 and 38–40). The lab compacted specimens were very fragile, and several broke upon extraction from the compaction mold. Two of seven compacted specimens were intact after extrusion, and these were used for density measurement.

Table 41: Density of the Embankment Materials on the Day of Construction

Lift No.	Sample No.	Weight (g)	Density (g/cm^3)	Ave. Density/ Lift (g/cm^3)
5	3	437.9	1.26	1.22
	2	435.4	1.25	
	1	403.1	1.16	
4	3	419.9	1.21	1.21
	2	423.3	1.22	
	1	415.1	1.19	
3	3	432.3	1.24	1.23
	2	424.5	1.22	
	1	426.9	1.23	
2	3	411.6	1.18	1.17
	2	406.7	1.17	
	1	406.3	1.17	
1	3	429.3	1.24	1.20
	2	425.1	1.22	
	1	394.8	1.14	
Lab	2	131.8	1.33	1.33
	1	136.3	1.32	

The moisture content of a sample of the loose material taken from the construction site was 18%. This sample was taken about 2 1/2 hours after the fly ash was poured onto the bed of lime sludge and mixing was commenced. Samples of processed lime sludge that came from the same stockpile as that used for the construction of the test embankment yielded a moisture content of 30%. This was about 10% less than the moisture content used in preliminary calculations for mixture design.

The dry placement of the chemically stabilized lime sludge worked to the embankment's advantage. According to the National Weather Service reports for Ames, Iowa, it rained 1.16 inches on the city 2 days after the construction. Three days after construction it rained 0.44 inches, and 5 days after construction it rained 1.24 inches. Each day's rainfall was steady, and no flood warnings were issued. The rainfall during the first 7 days of cure was considered a benefit.

Dynamic Cone Penetrometer (DCP)

Four DCP tests were performed on July 15, 2004 and April 8, 2005. Each location chosen was at least 2 feet from the top edge of the embankment and at least 2 feet from other DCP test locations. The results of the July 15, 2004 tests are shown in Tables 42 to 45. The tables use the correlation in Table 2 of the standard method to define the CBR value. The amount of stiffness or resistance to the DCP varied with each set. Weighted averages of the CBR values from Tables 42–45 were 9, 20, 8, and 13%, respectively, and the averages were weighted based on penetration. Figure 61 shows CBR plotted as a function of depth. The CBR shows increases from the single digits to 100% between 20 and 35 cm (8-14 inches) of depth in three of four tests. This indicates that the first 20 cm is relatively soft and then the embankment becomes very stiff very quickly in the next 15 cm of depth.

The results of the April 8, 2005 tests are shown in Tables 46 to 49. Weighted averages of the CBR values from Tables 42–45 were 6, 9, 12, and 11%, respectively, and the averages were weighted based on penetration. Figure 62 shows CBR plotted as a function of depth. The CBR did not increase from the single digits to 100% between 20 and 35 cm (8-14 inches)

Table 42: DCP Results from Embankment at Ames Water Treatment Plant, Set 1, July 2004

Number of Blows	Cumulative Penetration (mm)	Penetration Between Readings (mm)	Penetration per blow (mm)	Hammer Factor	DCP Index mm/blow	CBR % %
0	0	0	0	1	0	0
1	32	32	32	1	32	6
2	80	48	24	1	24	8
2	150	70	35	1	35	5
2	180	30	15	1	15	14
2	219	39	20	1	20	10
3	310	91	30	1	30	6
3	345	35	12	1	12	18
3	356	11	4	1	4	60
4	370	14	4	1	4	60
4	387	17	4	1	4	60
4	395	8	2	1	2	100
4	411	16	4	1	4	60
4	421	10	3	1	3	80
4	426	5	1	1	1	100

Table 43: DCP Results from Embankment at Ames Water Treatment Plant, Set 2, July 2004

Number of Blows	Cumulative Penetration (mm)	Penetration Between Readings (mm)	Penetration per blow (mm)	Hammer Factor	DCP Index mm/blow	CBR %
0	0	0	0	1	0	0
1	44	44	44	1	44	4.2
1	68	24	24	1	24	8
2	90	22	11	1	11	20
2	115	25	13	1	13	16
2	133	18	9	1	9	25
3	159	26	9	1	9	25
3	176	17	6	1	6	40
4	199	23	6	1	6	40
4	224	25	6	1	6	40
4	244	20	5	1	5	50
4	263	19	5	1	5	50
4	282	19	5	1	5	50
10	332	50	5	1	5	50
10	375	43	4	1	4	60
10	406	31	3	1	3	80
10	440	34	3.4	1	3	80
10	478	38	4	1	4	60

Table 44: DCP Results from Embankment at Ames Water Treatment Plant, Set 3, July 2004

Number of Blows	Cumulative Penetration (mm)	Penetration Between Readings (mm)	Penetration per blow (mm)	Hammer Factor	DCP Index mm/blow	CBR % %
0	0	0	0	1	0	0
2	96	96	48	1	48	3.8
2	178	82	41	1	41	4.6
2	220	42	21	1	21	10
3	260	40	13	1	13	16
3	306	46	15	1	15	14
3	362	56	19	1	19	11
3	432	70	23	1	23	9
4	493	61	15	1	15	14
4	543	50	13	1	13	16
4	617	74	19	1	19	11
4	656	39	10	1	10	20

Table 45: DCP Results from Embankment at Ames Water Treatment Plant, Set 4, July 2004

Number of Blows	Cumulative Penetration (mm)	Penetration Between Readings (mm)	Penetration per blow (mm)	Hammer Factor	DCP Index mm/blow	CBR % %
0	0	0	0	1	0	0
1	51	51	51	1	51	3.6
1	91	40	40	1	40	4.7
1	128	37	37	1	37	5
1	151	23	23	1	23	9
2	180	29	15	1	15	14
2	191	11	6	1	6	40
2	206	15	8	1	8	30
3	225	19	6	1	6	40
3	245	20	7	1	7	35
3	261	16	5	1	5	50
3	277	16	5	1	5	50
3	287	10	3	1	3	80
6	310	23	4	1	4	60
6	335	25	4	1	4	60
10	365	30	3	1	3	80
10	405	40	4	1	4	60
10	441	36	4	1	4	60
10	481	40	4	1	4	60

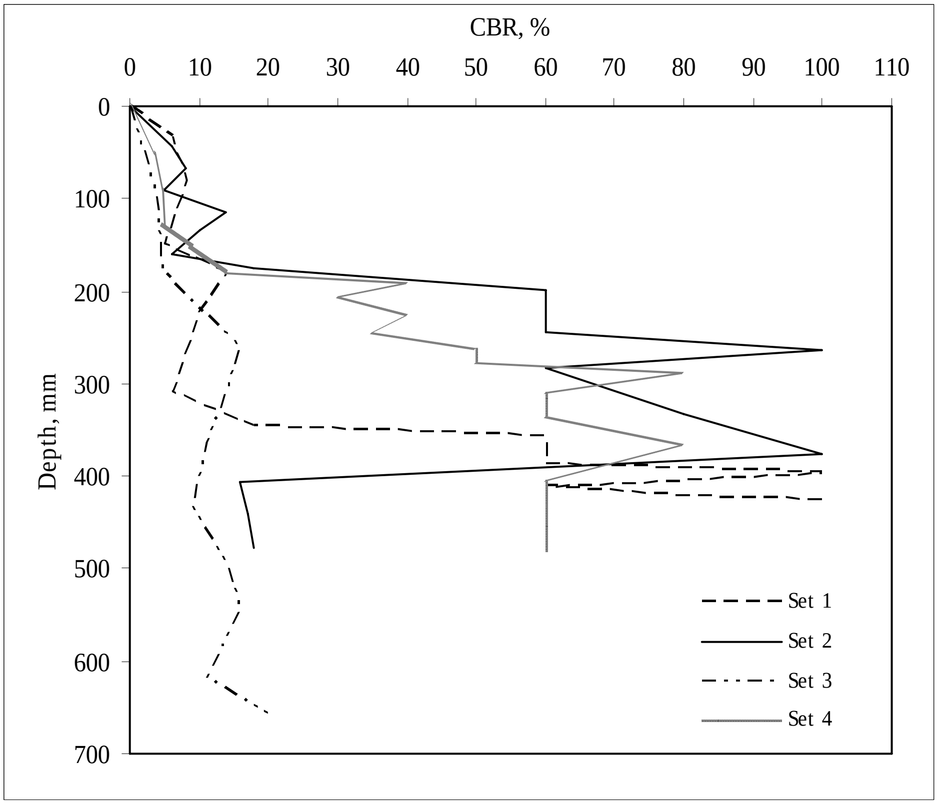

Figure 61: CBR as a Function of Depth for Test Embankment, July 2004

as it did in the July 2004 tests. Instead, the CBR did not show increases above 30% until about 30 cm (12 inch) of depth in all four test sets. This indicates that the depth of embankment between 20 cm and 35 cm softened since July 2004 as would be expected since it is within the expected freeze depth (the top 91 cm or 36 inches of depth).

These values for CBR derived from DCP index values were similar to the CBR results shown earlier (see Table 20). Referencing Table 20, for a 1:1 mix cured less than 28 days, we would expect the field compacted embankment to have a CBR in the range of 20 to 30%. An important difference between the CBR tests done in the lab and those derived from field DCP data was that the lab specimens were soaked in water for four days prior to penetration tests. As a coincidence, the specimens tested for the repeat CBR (see Table 20) tests were mixed at a moisture content about 10% less than calculated. Comparing Table 24 with Table 26 and Table 28 with Table 30, the CBR was 15-20% less with the lower moisture during mixing and compacting.

Table 46: DCP Results from Embankment at Ames Water Treatment Plant, Set 1, April 2005

Number of Blows	Cumulative Penetration (mm)	Penetration Between Readings (mm)	Penetration per blow (mm)	Hammer Factor	DCP Index mm/blow	CBR % %
0	0	0	0	1	0	0
1	65	65	65	1	65	2.7
1	89	24	24	1	24	8
1	107	18	18	1	18	11
2	146	39	20	1	20	10
2	196	50	25	1	25	8
1	238	42	42	1	42	4.4
1	285	47	47	1	47	3.9
1	298	13	13	1	13	16
3	313	15	5	1	5	50
3	325	12	4	1	4	60
4	339	14	4	1	4	60
4	354	15	4	1	4	60
4	366	12	3	1	3	80

Table 47: DCP Results from Embankment at Ames Water Treatment Plant, Set 2, April 2005

Number of Blows	Cumulative Penetration (mm)	Penetration Between Readings (mm)	Penetration per blow (mm)	Hammer Factor	DCP Index mm/blow	CBR % %
0	0	0	0	1	0	0
1	58	58	58	1	58	3.1
1	96	38	38	1	38	5
2	139	43	22	1	22	9
2	185	46	23	1	23	9
2	221	36	18	1	18	11
2	246	25	13	1	13	16
3	275	29	10	1	10	20
3	293	18	6	1	6	40
3	314	21	7	1	7	35
4	346	32	8	1	8	30
4	377	31	8	1	8	30

Table 48: DCP Results from Embankment at Ames Water Treatment Plant, Set 3, April 2005

Number of Blows	Cumulative Penetration (mm)	Penetration Between Readings (mm)	Penetration per blow (mm)	Hammer Factor	DCP Index mm/blow	CBR % %
0	0	0	0	1	0	0
1	48	48	48	1	48	3.8
1	84	36	36	1	36	5
2	124	40	20	1	20	10
2	148	24	12	1	12	18
2	166	18	9	1	9	25
3	191	25	8	1	8	30
3	215	24	8	1	8	30
3	242	27	9	1	9	25
2	262	20	10	1	10	20
2	280	18	9	1	9	25
2	297	17	9	1	9	25
2	314	17	9	1	9	25
2	328	14	7	1	7	35
3	346	18	6	1	6	40
4	366	20	5	1	5	50
4	386	20	5	1	5	50

Table 49: DCP Results from Embankment at Ames Water Treatment Plant, Set 4, April 2005

Number of Blows	Cumulative Penetration (mm)	Penetration Between Readings (mm)	Penetration per blow (mm)	Hammer Factor	DCP Index mm/blow	CBR % %
0	0	0	0	1	0	0
1	34	34	34	1	34	6
1	57	23	23	1	23	9
2	105	48	24	1	24	8
1	135	30	30	1	30	6
1	159	24	24	1	24	8
2	193	34	17	1	17	12
2	233	40	20	1	20	10
2	265	32	16	1	16	13
2	289	24	12	1	12	18
2	309	20	10	1	10	20
2	326	17	9	1	9	25
3	346	20	7	1	7	35
3	366	20	7	1	7	35
3	384	18	6	1	6	40
4	410	26	7	1	7	35

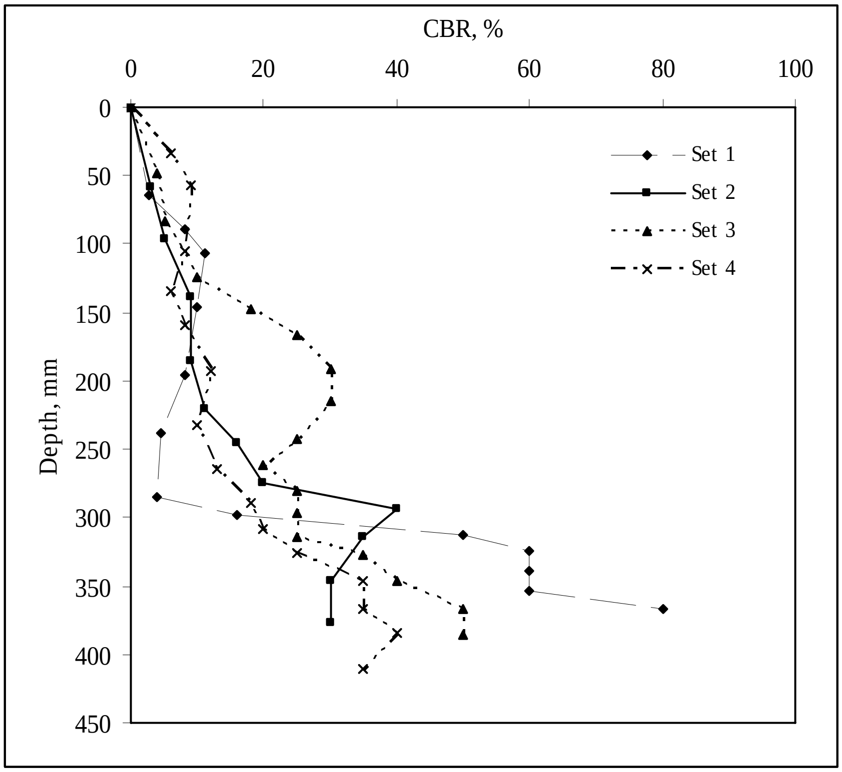

Figure 62: CBR as a Function of Depth for Test Embankment, April 2005

Temperature

Table 50 shows a summary of the average temperatures taken at various depths in the test embankment at different times of the year. Constant temperature readings from the summer through the winter and spring were planned when the temperature probes were buried in the test embankment. However, there were some problems encountered with the handheld computer that was used to upload the readings. Therefore, there are gaps in the dates and missing files. However, the information presented in Figures 63 through 67 show the readings that were successfully taken in September 2004, October 2004, November 2004, February 2005, March 2005, and April 2005. In each figure, the heavy black lines represent the shallowest (or ambient air) and deepest depths. These data sets define the range of temperatures most of the time.

In Figure 63, the temperature for most of the sensors falls in the range of 70 to 76^{o}F, and the diurnal swings in the ambient air temperature are clearly seen; the sensor at the deepest depth does not change much. Figure 64 shows that the temperatures are generally falling as summer turns to fall. Figures 65 and 66, taken in the end of fall and at midwinter show similar patterns of temperature change, but the average temperature is different, as seen in Table 50. From the average values in midwinter, only the first 46 cm of depth reached freezing temperatures in the embankment. Figure 67 shows two sensors at the same temperature thorough the period and give the appearance of a single ploy. Also in Figure 67, what appears to be a grey-shaded box is actually two sensors that frequently alternate between sequential temperatures. During February 2005, the ambient air sensor began to malfunction and posted temperatures and swings that were not realistic. The same sensor would not provide readings for the following month either (Figure 68). Figure 68 shows a general warming trend – the opposite of what happen in Figures 65 and 66.

Table 50: Average Temperatures in Profile of Test Embankment

Month Reported	Ambient Air	15 cm	30 cm	46 cm	61 cm	76 cm	Average
Sep-04	73.2	*	73.7	72.6	*	70.9	72.6
Oct-04	*	65.7	68.1	68.5	69.1	68.9	68.1
Nov-04	50.2	53.0	56.0	57.3	59.1	59.8	55.9
Feb-05	28.6	29.2	31.0	32.0	34.0	35.0	31.6
Mar-05	32.0	30.7	31.6	32.0	33.8	33.8	32.3
Apr-05	*	39.3	38.2	36.6	36.5	35.9	37.3
*No data available.							

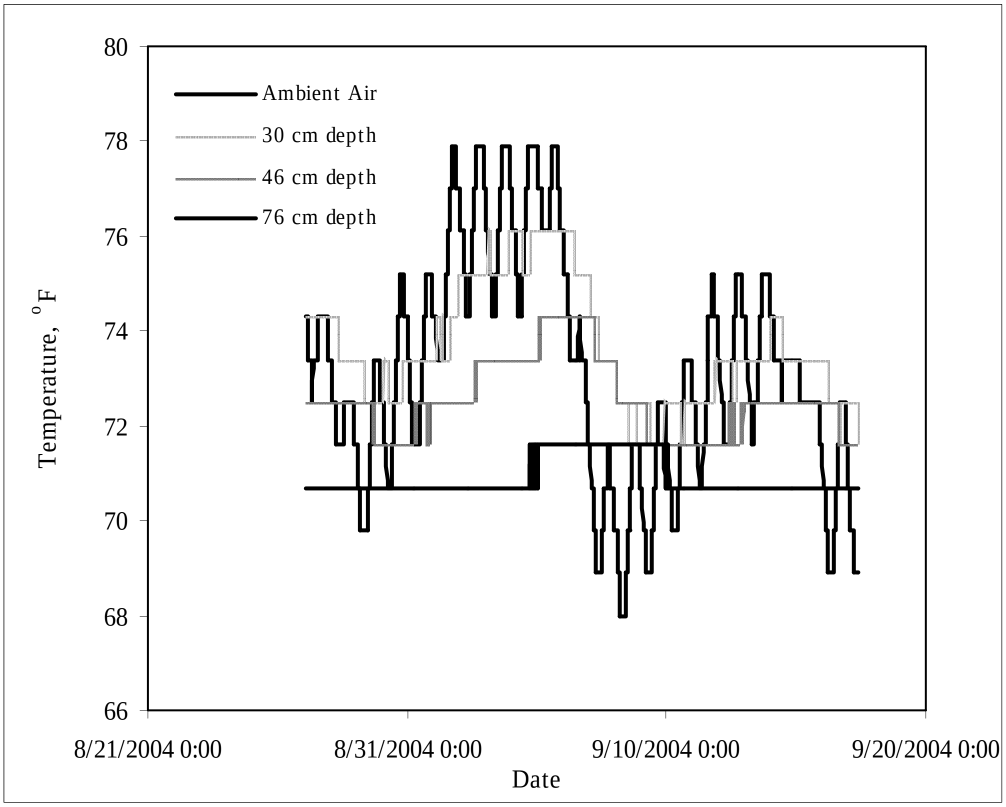

Figure 63: Temperature Readings from Test Embankment, 27 August to 17 September 2004.

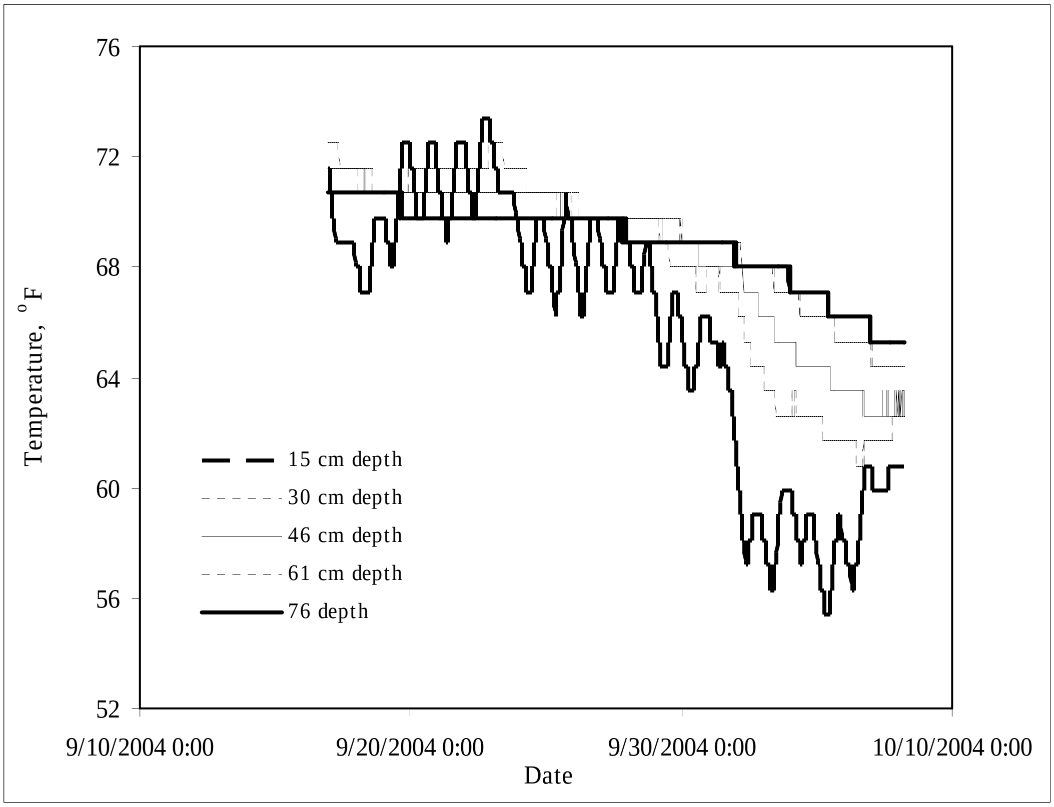

Figure 64: Temperature Readings from Test Embankment, 16 September to 8 October 2004

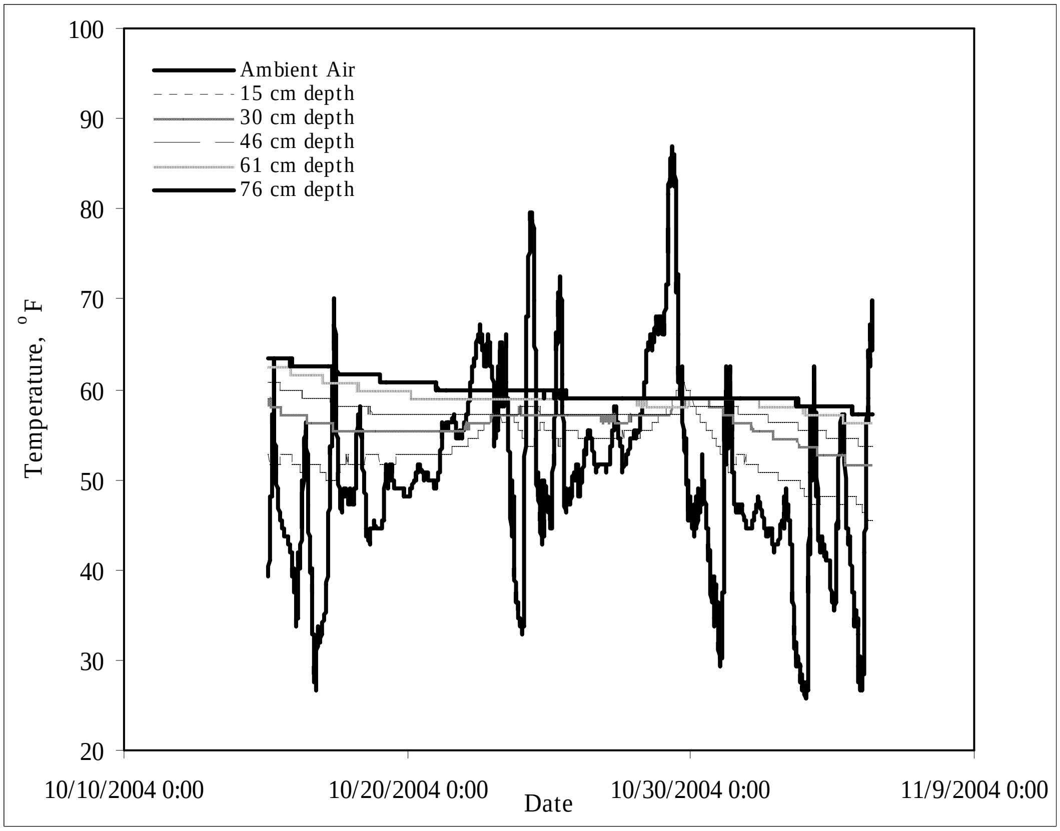

Figure 65: Temperature Readings from Test Embankment, 15 October to 5 November 2004.

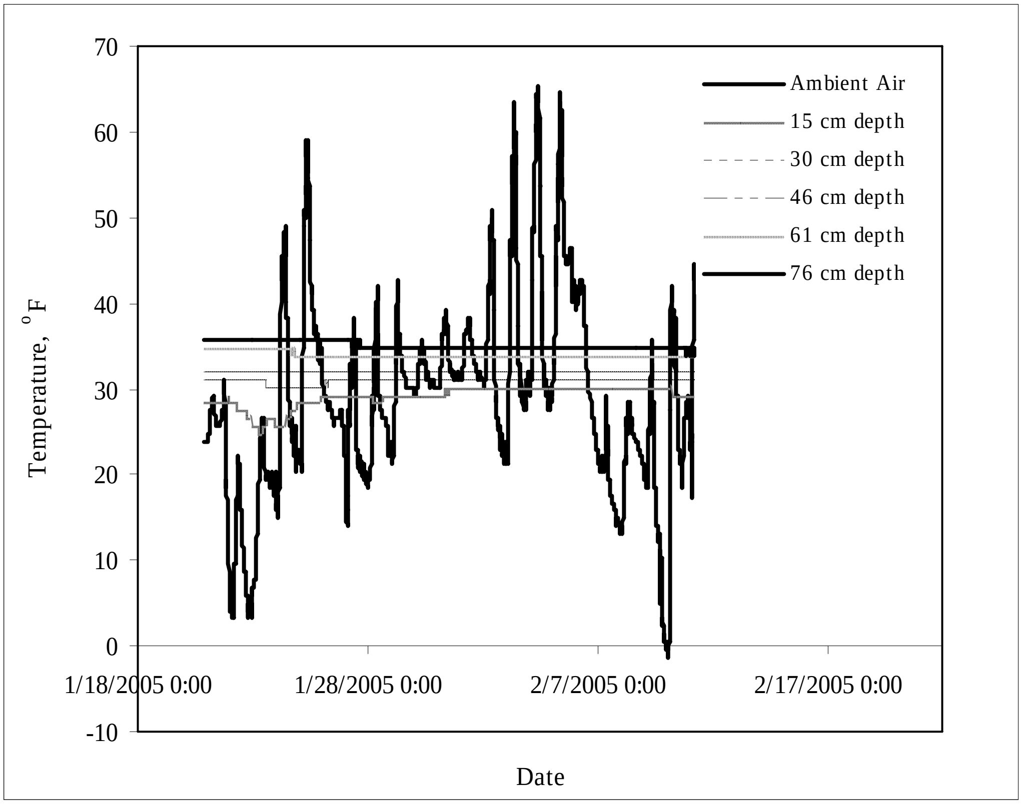

Figure 66: Temperature Readings from Test Embankment, 20 January to 11 February 2005.

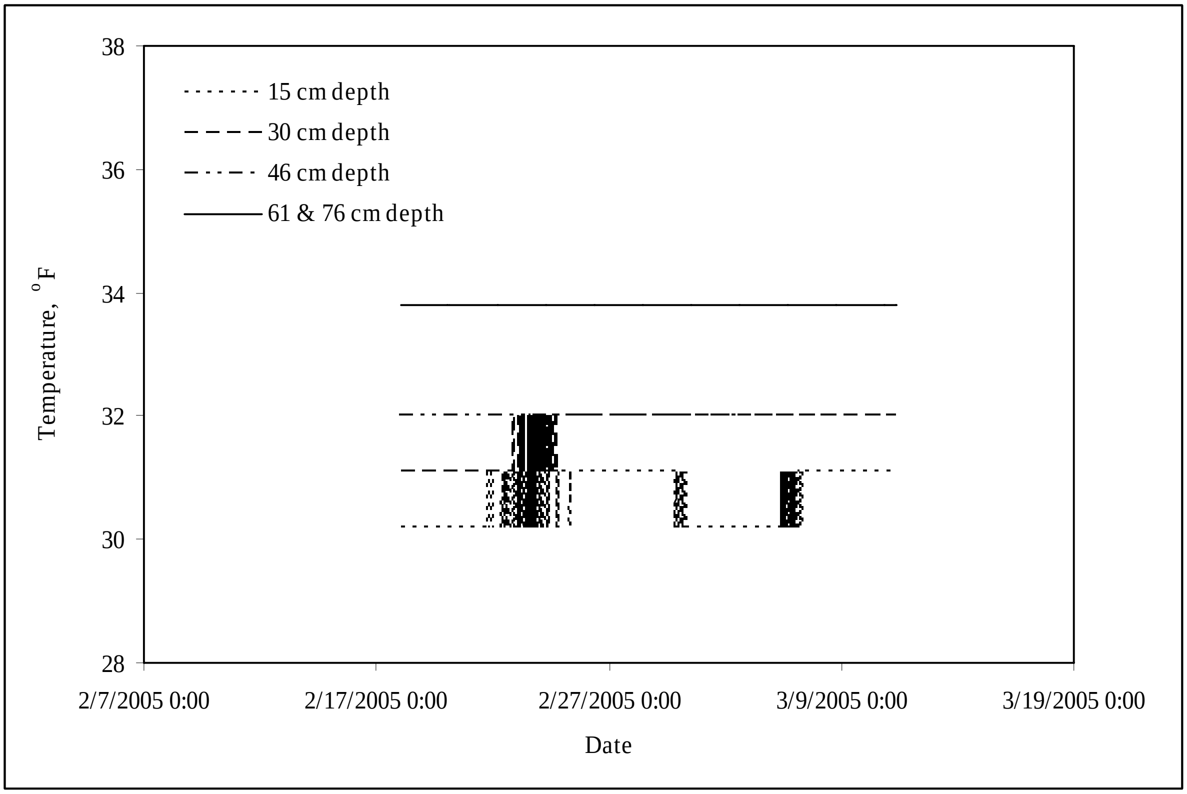

Figure 67: Temperature Readings from Test Embankment, 18 February to 11 March 2005

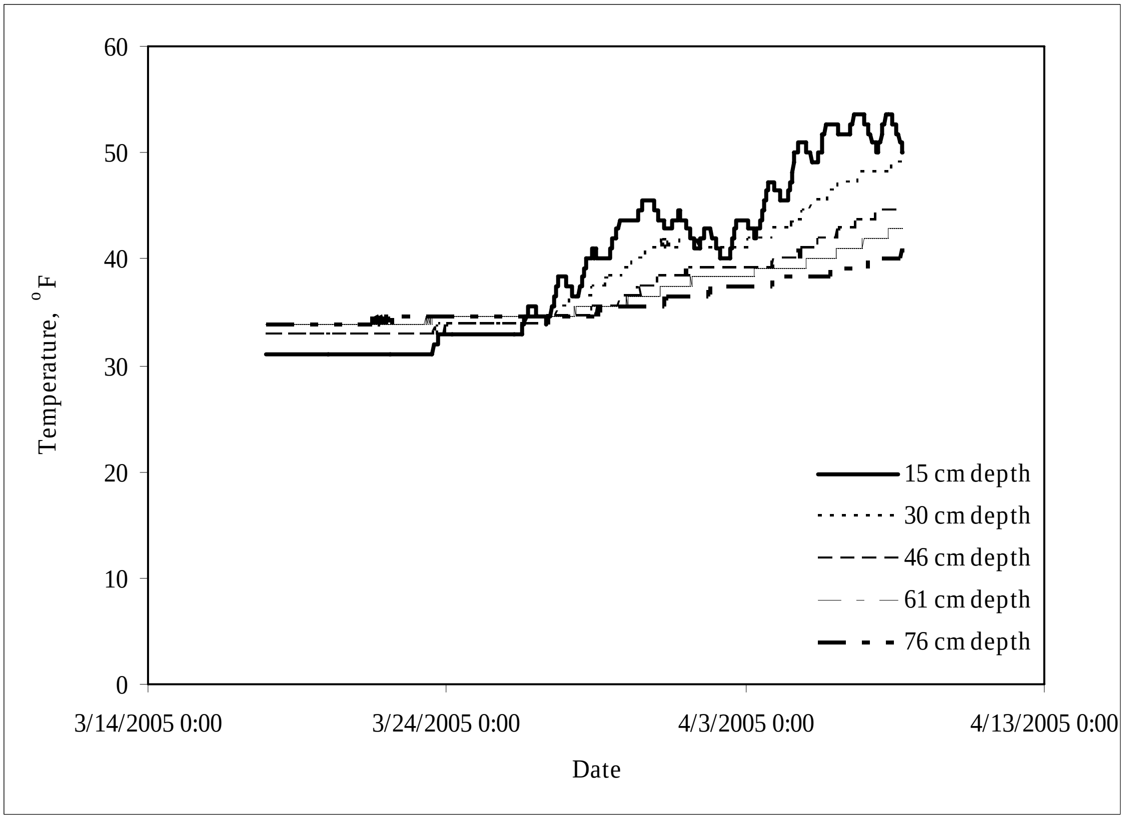

Figure 68: Temperature Readings from Test Embankment, 17 March to 8 April 2005

Cost analysis of Using Lime Sludge as a Fill Material

According to Ed Jasper at the Office of Contracts of the Iowa DOT, the 2004 average bid to excavate and place Class 10 Roadway Excavation (Fill and Borrow) is 2.52/cubic yard. Compaction with moisture control is an additional $0.35/cubic yard. Assuming a unit weight of borrow to be about 120 lb/ft^3 on average, this converts to about $1.77/ton for using fill available at and around the construction site and compacting it with moisture control. There is no combination of dried lime sludge and fly ash that can be used to compete with this unit cost since the cost of transportation must be included when using lime sludge. Therefore, a comparison will be drawn for a construction site that needs 142,000 tons of fill material from a source that is the distance equivalent to one hour round trip by truck from the construction site.

Scott Adair at Kelderman Lime estimated that 142,000 tons of lime sludge dried to about 42% moisture content would sell at a unit cost of $5/ton at Kelderman Lime’s stockpile source (Adair, 2005). Using the distance of a one-hour round trip by truck, he estimated that the unit transportation cost for moving 142,000 tons of lime sludge would be no less than $7/ton. Using the hourly rates quoted by Ames area businesses Iowa State Trucking and Conley Trucking as of April 2005, the cost of transporting about 142,000 tons of fill material to a construction site, within a one-hour round trip from the material’s source, was calculated to be about $7/ton (within $0.50/ton). This agreed with Scott Adair’s estimate. Scott also estimated that if the lime sludge were needed drier than 42% moisture content, then Kelderman would need to dry it in their kiln. Kiln drying increases the unit cost of the dried lime sludge by $3/ton as the kiln is fired by natural gas and has its own operating, maintenance, and overhead costs, according to Scott. For the purpose of cost analysis, the purchase cost of $5/ton for dried lime sludge and $7/ton for transportation will be used.

According to Gary Greene of ISG Resources, the company that sells fly ash for road construction in Central Iowa, the unit cost of buying about 10,000 tons of fly ash and having it delivered to a work site is $30/ton (Greene, 2005). The unit cost given for fly ash assumes that the work site is the Greater Des Moines Area and the delivery occurs during construction season (April to November), which is the peak time of year for fly ash demand. Due to this relatively high material and transportation cost, a low mix ratio of fly ash to lime sludge was selected for this example. If 10,000 tons of fly ash is mixed with 142,000 tons of lime sludge at 42% moisture content, then the resulting fly ash to lime sludge mixture ratio is 0.10 on a dry weight basis. The subtotal cost of purchasing 152,000 tons of dried lime sludge and fly ash and transporting it to the construction site is $13.18/ton.

Once the fly ash and lime sludge are delivered, the materials will need to be mixed and compacted. Assuming a unit cost of $1.77/ton for placement and compaction of lime sludge and fly ash once on site, the total of using stabilized lime sludge is $14.95/ton. Therefore, the cost of purchasing soil from a borrow site and transporting it to the construction site must be more than $14.95/ton for the lime sludge to be a viable option economically. In addition, the

Iowa DOT may also be motivated about using a stockpiled municipal by-product like lime sludge because it means that taxpayers save money on their water bills. This positive publicity may be important to the Iowa DOT since it is frequently inconveniencing the public with road construction projects.

Conclusions and Recommendations

The construction techniques involved with mixing the product with fly ash or cement are not complicated. Crews with little or no experience with soil stabilization and compaction techniques can be shown how to construct embankments with the product with little problem.

The densities of samples taken from the test embankment immediately after construction were similar to those tested in UCS and permeability tests. The correlated CBR values from DCP tests performed on the embankment 15 days after construction were similar to those found in the lab CBR tests for a 1:1 fly ash to lime sludge mix ratio (dry weight basis) and a 28 day cure.

The correlated CBR values that were derived from weighted averages from DCP tests on the embankment declined between July 2004 and April 2005. This declining trend demonstrated that the 30 cm of depth below the surface was softer and resisted penetration less. Average temperatures over the winter and spring show that the 45 cm of depth below the surface was exposed to multiple freezing and thawing temperatures. This again demonstrates that chemically stabilized lime sludge, when used as a construction fill, needs to be covered by an adequate layer of soil cover.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

While receiving 2 ½ years of funding, this research project spanned more than 3 years and this report contains all of the data collected, analysis performed, discussion recorded, and conclusions drawn. Very realistically, some of the experiments provided some promising potential for the use lime sludge and others did not. In this last Part of the report conclusions from each Part will be summarized in bullet format followed by recommendations.

Conclusions

- Feasibility tests for using the lime sludge product in cement manufacture, SO_x control in coal combustion, and wastewater neutralization had positive results.
- The most promising application investigated during the last 2 years was use of the product as a stabilized fill material for road construction.
- Unconfined strength tests demonstrated that lime sludge can be combined with fly ash or portland cement to produce a strong fill material. Lime sludge by itself does not possess sufficient UCS for fill and does not exhibit any stabilizing qualities (like portland cement or fly ash).
- Larger additions of portland cement or Class C fly ash to lime sludge generally resulted in higher values for UCS, cohesion in direct shear tests, and CBR. A moisture content of 28% for mixtures containing OGS fly ash was best in the UCS test, and a moisture content of 40% was best for mixtures containing portland cement for the same test. UCS peaked at a range of moisture contents when mixtures contained Ames fly ash as the stabilizer — 24 to 40%. For mixes containing 33% Ames fly ash (dry weight basis), a moisture content of 40% was best; for those containing 9% Ames fly ash (dry weight basis), 24% moisture content was best.
- Lime sludge and chemically stabilized lime sludge mixes result in high values for CBR and for internal friction angle for a material with a Unified Classification System symbol of ML. Increasing cure time resulted in higher values for cohesion in direct shear tests and for CBR of chemically stabilized lime sludge mixtures.

- An important limitation of using lime sludge and the stabilized mixes as a fill material is due to its lack of durability through freeze/thaw and wet/dry cycles. For the freeze/thaw test, mass losses were 100% for brushed specimens and volume changes were in excess of 19% for those not brushed. However, poor durability of silt-sized soils is common and can be frequently worked with nonetheless.
- Hydraulic conductivity values averaged 1.71 x 10^{-5} cm/s for lime sludge alone and 1.07 x 10^{-5} cm/s for a 1:1 (by dry weight) lime sludge and fly ash mix. This is a relatively low permeability material, but not low enough to be used for primary environmental liner uses such as landfill liners. Landfill liners generally require a minimum hydraulic conductivity on the order of 1 x 10^{-7} cm/s (EPA, 2005).
- The construction techniques involved with mixing the product with fly ash or cement are not complicated. Crews with little or no experience with soil stabilization and compaction techniques can be shown how to construct embankments with the product with little problem.
- The densities of samples taken from the test embankment immediately after construction were similar to those tested in UCS and permeability tests. The correlated CBR values from DCP tests performed on the embankment 15 days after construction were similar to those found in the lab CBR tests for a 1:1 fly ash to lime sludge mix ratio (dry weight basis) and a 28 day cure.
- The correlated CBR values that were derived from weighted averages from DCP tests on the embankment declined between July 2004 and April 2005. This declining trend demonstrated that the 30 cm of depth below the surface was softer and resisted penetration less. Average temperatures over the winter and spring show that the 45 cm of depth below the surface was exposed to multiple freezing and thawing temperatures. These findings support the recommendation that lime sludge needs to be placed under a durable soil to protect it from weathering due to freeze/thaw cycles.

<u>Recommendations</u>

- Each one of the applications discussed herein should be further investigated if changes to the existing facilities were made or new facilities were built to better accommodate lime sludge.
- Further investigation regarding the use of the product for dust control on gravel roads is not recommended, as the practical results did not confirm the theoretical expectations for beneficial effects from changing particle size distribution.
- The product must be dewatered and dried for use in all of the applications discussed. The recommended maximum level of moisture content for the product is 50% (67% solids concentration). The lowest moisture content required by the applications studied was 2% (98% solids concentration).
- As with other soils within its classification, stabilized lime sludge mixtures should be placed below the expected frost zone and covering it with a higher grade, weather-resistant material is logical for fill applications.

In summary, the research involving uses of lime sludge produced by water treatment plants in central Iowa demonstrated that lime sludge shows great potential in many applications in Iowa. As with any recycled material, it may not appear to be ideal for each application presented here in this report, but with further improvements in dewatering, drying, and transportation, costs of recycling lime sludge will come down. Further, capital improvements of the facilities that can use lime sludge and refinements of the processes may results in savings in material costs. Lime sludge is a solid waste material that cannot continue to be stockpiled until the ideal solution comes along. Creative and effective use of lime sludge in Iowa is needed now. Many, if not all, of the solid waste recycling programs in use today more than likely started out with a solid waste that did not appear to be ideal for anything. But with time, these recycling programs provided an additional source of raw material and placed less in costly landfills.

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