Final Report for TR-459

Reuse of Lime Sludge from Water Softening and Coal Combustion Byproducts

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

Sponsored by the
Iowa Department of Transportation
Highway Division and the
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TR-459 EXECUTIVE SUMMARY REPORT ON

REUSE OF LIME SLUDGE FROM WATER SOFTENING AND COAL COMBUSTION BYPRODUCTS

By Rob Baker, J(Hans) van Leeuwen, and David J. White,
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Disposal of lime sludge remains a major challenge to cities in the Midwest. Disposal of lime sludge from water softening adds about 7-10% to the cost of water treatment. Having effective and safe options is essential for future compliance with the regulations of the State of Iowa and within budget restrictions. Dewatering and drying are essential to all reuse applications as this affects transportation costs and utility. Feasibility tests were conducted on some promising applications like SO_x control in power generation facilities that burn coal, replacement of limestone as an ingredient in portland cement production, dust control on gravel roads, neutralization of industrial wastewater pH, and combination with fly ash or cement in construction fill applications. A detailed report and analysis of the construction fills application is presented in the second half of the report. A brief discussion of the results directly follow.

1. Dewatering and drying

Various tests were performed on lime sludge samples to observe any restrictions on drying the sludge. The tests indicated that 98% of the water in the sludge is free water. This provides for the potential to use low temperature and open air-drying techniques. Drying the sludge is important for two reasons. First, drying the sludge meets pneumatic transport requirements, and second, for it reduces bulk transportation costs.

2. Use in SO_x control at power plants

Lime sludge was tested for control of SO_x in flue gases at the Iowa State University (ISU) Power Plant and found effective, but only over short test runs. Since it was difficult for the plant to handle a calcium carbonate feed with a moisture content of greater than 2%, clogged feeding mechanisms prevented longer runs. Long term testing is required to adequately assess the operational impact of using lime sludge in place of ground limestone. Other plants may feed the treatment chamber differently and may accommodate the lime sludge at the moisture content that it is currently dried to.

3. Use in cement production

Tests were performed using 20 tons of lime sludge in the manufacture of about 80 tons cement. Plant personnel at Lehigh Cement in Mason City stated that the quality of the product was satisfactory. However, due to the long transportation distances for lime sludge and the on-site availability of limestone at Lehigh Cement, this application was considered uneconomical.

4. Use for dust control on unpaved roads

A truckload of lime sludge was applied to each of two test locations in Story County. The amount of dust generated was recorded, but the results were inconclusive. Dust control is being investigated by other researchers in the Geotechnical Division, Department of Civil and Construction Engineering at Iowa State. We hope to gain some more insights from that research.

5. Use as a construction fill material

The construction fill application was selected for a more thorough investigation. This was based on the initial test results and the potential for use in Iowa's road construction projects. Strength and durability testing have demonstrated that lime sludge can be combined with fly ash and portland cement to produce a useful construction fill material.

Lime sludge does not act like cement. Mixes containing lime sludge, bottom ash, and fly ash were designed and tested. According to Ferguson and Levorson (1999), if 50 psi (345 kPa) compressive strength can be achieved in soils stabilized with fly ash, the potential for settlement in deep fills is significantly reduced. The tests described in this report show that adding about 50% fly ash (dry fly ash to dry lime sludge, by weight), the unconfined compressive strength results are 1380 kPa or greater. Higher amounts of stabilizer in the lime sludge mixtures resulted increased unconfined compressive strength, higher internal friction angles in drained direct shear, and higher California Bearing Ratio (CBR) values.

Since particle size analysis and Atterburg Limits tests classify lime sludge as a silty material with low plasticity, durability was a concern. Freeze/thaw and wet/dry durability tests were performed. The freeze/thaw tests were the most aggressive. Results mandated that lime sludge mixtures should be used underneath a sufficient layer of soil that is not frost susceptible to protect it against freezing and thawing volume changes and strength loss.

To demonstrate the construction techniques of the mixtures in the field, a test embankment about 20 feet wide, 3.5 feet tall at center, and about 37 ft long was constructed over the summer using full-size equipment. Air-dried lime sludge was mixed with the fly ash in windrowed piles. Subsequent in-situ testing needs to be conducted to report density, stiffness, temperature, and signs of durability problems during the winter and spring.

Further testing regarding the effects of the mixes on the environment, as mandated by state regulations, needs to be completed to have this option ready to implement. In addition, geotechnical testing is still in progress. Peer-reviewed technical papers will follow. In the end, this work will move the State of Iowa closer to lower water treatment costs and an alterative source for construction fill materials.

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Introduction

In the past the common approach to lime sludge disposal was discharge into a lagoon excavated on site and left indefinitely (See Figure 1). When a lagoon was full, a new lagoon was excavated and the process started over again. According to water treatment plants managers, the Iowa Department of Natural Resources no longer a permits them to build additional lime sludge lagoons. At the same time, many water treatment plants now produce more drinking water to keep up with the demand, so the lime sludge accumulates faster. Some of the municipalities that own and operate the water treatment plants quickly sought to find economically sound disposal solutions. Iowa State University is assisting them in this cause by finding sensible reuse possibilities.

Figure 1: Lime Sludge Storage Lagoon (stockpiled)

Iowa State University's Department of Civil, Construction, and Environmental Engineering has evaluated some selected methods to dispose of this product over two years of research. These disposal options included using the lime sludge to treat SO_x containing stack gases in some coal-burning power plants, using lime sludge on gravel roads to reduce dust generation, using lime sludge in cement production and using lime sludge for fill in construction projects.

The recent focus of Iowa State's research has been using lime sludge/fly ash mixtures as an alternative fill material for construction. Test results concluded that when mixed with another industrial waste product, fly ash, that relatively incompressible and strong mixes of soil material could be produced. Herein incompressible is defined as a mix that has an unconfined compressive strength of 345 kilopascals (kPa) or 50 pounds per square inch (psi) or more. This research needs to continue to investigate how the mixes weather under extreme conditions, and to confirm that these mixtures are safe for the environment. The Iowa Administrative Code requires all fill materials derived form waste materials be tested for leaching toxic material. Once complete, this option can be a source of bulk fill for road construction projects nearby the cities that produce it.

Background

Water treatment sludges and coal combustion ashes have often been stockpiled at or near the source. In essence, these stockpiles are landfills. Environmental laws mandate that the organizations that place materials in landfills assume the responsibility and liability for these landfills. If there is an adverse effect on the environment, then the producer(s) that disposed of the material in the landfill is(are) liable. Ensuring that landfills are not a threat to the environment safe requires frequent inspection as long as the waste remains there. Landfills are costly enterprises in the long term. Therefore, it is to the waste producer's benefit to investigate all safe disposal options that divert the materials from bulk land disposal.

Lime sludge is dewatered, dried and sold as agricultural lime in some areas of central Iowa. However, production exceeds the demand and there are many stockpiles resulting from decades of lime sludge production. The strategy of developing several disposal options will better serve the diverse needs of the communities of Iowa. Local prospects for disposal options may differ. For example, some areas may not have a demand for agricultural lime, but may have a cement plant or be able to use lime sludge for SO_x control at a nearby power generation facility.

The Des Moines Water Works serves 350,000 people of the state and produces 60,000 tons of wet sludge (at about 50% solids concentration) per year from its main treatment plant. The disposal cost for this one treatment plant is $600,000 a year paid to a contractor, Kelderman Lime, for processing and selling it as agricultural lime. This product is dewatered and sold as agricultural lime to a developed market of farmers, which keeps the disposal cost per ton down to a reasonable level. The lime sludge from the Des Moines Water Works is processed by mainly by dewatering in a filter presses. This saves substantially on footprint, but capital, operating, and maintenance costs are high.

An alternative to filter presses, especially for small to mid-size water treatment plants, has been a dewatering lagoon. The lime sludge sediment from the water treatment clarifiers is pumped into a lagoon until it is full. Then the sludge output is switched to another lagoon, while the sludge in the first full lagoon is allowed to settle. The rates of evaporation and infiltration in Iowa are too small to dewater the sludge effectively. Above the lagoon, there is enough precipitation to offset the evaporation that occurs. Below the lagoon, Iowa soils have too low a permeability for good infiltration because high levels of fines (silts and clays). Of the plants that use dewatering lagoons, a full lagoon is left fallow for about a year while decanting assists in dewatering. Figures 2, 3, and 4 illustrate a dewatering lagoon in use at the Ames Water Treatment Plant.

After about a year in the dewatering lagoon, the remaining residual is excavated and dried. This amount of time could be reduced with more engineering work. Effective use of granular backfill material to facilitate better infiltration, slopes to induce flow, laterals to carry away infiltrated water, and efficient decanting devices to remove surface water are all options to make lagoons dewater faster.

Further drying can be effected by two different technologies. Kelderman Lime can dry lime sludge in a matter of hours using a natural gas fired rotary kiln. This is used to process the lime sludge from Des Moines, West Des Moines and Newton. Biosolids Management Group (BMG) dries the Ames sludge by solar drying. This is accomplished by spreading the lime sludge in windrows over a concrete pad and turning it over as needed until dry. This windrow method takes about one week during the warm weather months (See Figure 5). The length of the drying period depends on heat, sun exposure and low humidity.

Figure 2: Dewatering lagoon while filling (looking towards the end from which the sludge enters)

Figure 3: Dewatering Lagoon after 3 months settling

Figure 4: Dewatering lagoon after 10 months settling

Figure 5: Solar drying of sludge in windrows

The disposal methods were developed by considering the composition and structure of lime sludge and then comparing it with another commonly mined material. Lime sludge has the same composition as limestone, but is softer. Therefore, many of the uses for crushed limestone were identified, and then lime sludge was used as a substitute. The uses of cement production, SO_x removal in coal-fired power plants, and agricultural lime resulted from applying this approach. The construction fill option is a common solution for any solid waste material that is stockpiled. The dust control option was investigated to make use of the lime sludge's small particle size.

This report is organized by first presenting the testing on the drying properties of the lime sludge. Next, the results from the feasibility tests follow for the reuse options introduced here. Finally, the most feasible of these options, the construction fill application, became the focus of the research. This report describes that research in the most detail.

Tests on lime sludge drying

All applications of lime sludge require drying. Drying is important to reduce the bulk volume and mass before transportation, but it is also required to improve its mechanical properties. Drying is also the most expensive process the lime sludge has to undergo. Research was needed to understand the physical properties of lime towards efficient drying.

It is important to understand how water exists within the solids matrix. The water may bond to the lime sludge crystals or remain free from attractive forces altogether. If it bonds, then the bonding may be through weak hydrogen bonds (attraction energy of about 0.13 kcal) or through chemical covalent bonding.

Methodology and Results

Knowing the crystalline structure of the lime sludge can help design an optimal drying process. Using an optical microscope and a scanning electron microscope, several images of the lime sludge were taken. The micrographics (Figure 6) indicate that there is a crystalline structure, which could have some implications on the removal of the water.

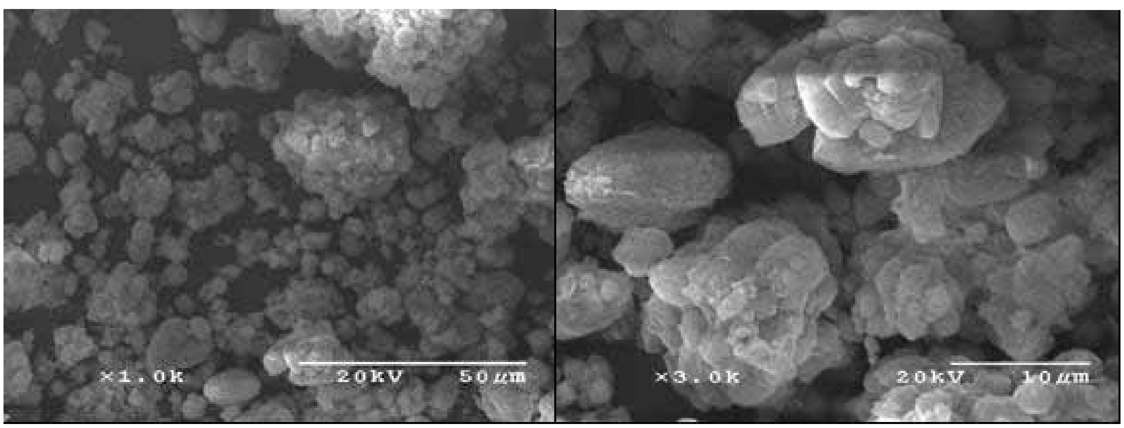

Figure 6. Scanning electron micrographics of the lime sludge

Lab tests to investigate the progress of drying were conducted. A convection oven set at 121 °C was used to simulate rotary kiln drying. Six samples that began the test at 23% moisture content were dried and temperatures recorded. The results are shown in Figure 7.

The shape of the drying curve indicates that most water in the system is free water and not bound water. This means that the energy required to remove this moisture would be equivalent to the energy required to evaporate water. The results show that it is possible to meet the 2% moisture content requirements for pneumatic transport.

Figures 8 and 9 show a thermogravimetric analysis of lime sludge. The heating was done on a slow rate until 110 °C then at a faster pace up to 1000 °C (Figure 3). Most of the moisture was driven off between 20 to 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 strong physically adsorbed water. The loss at 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 broken down.

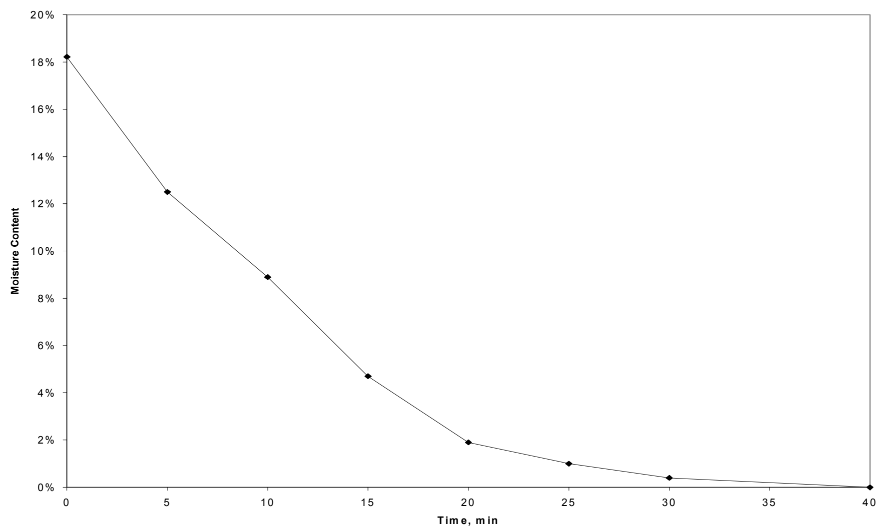

Figure 7: Drying Lime Sludge at 121 ^{o}C: Moisture percentage vs. Time

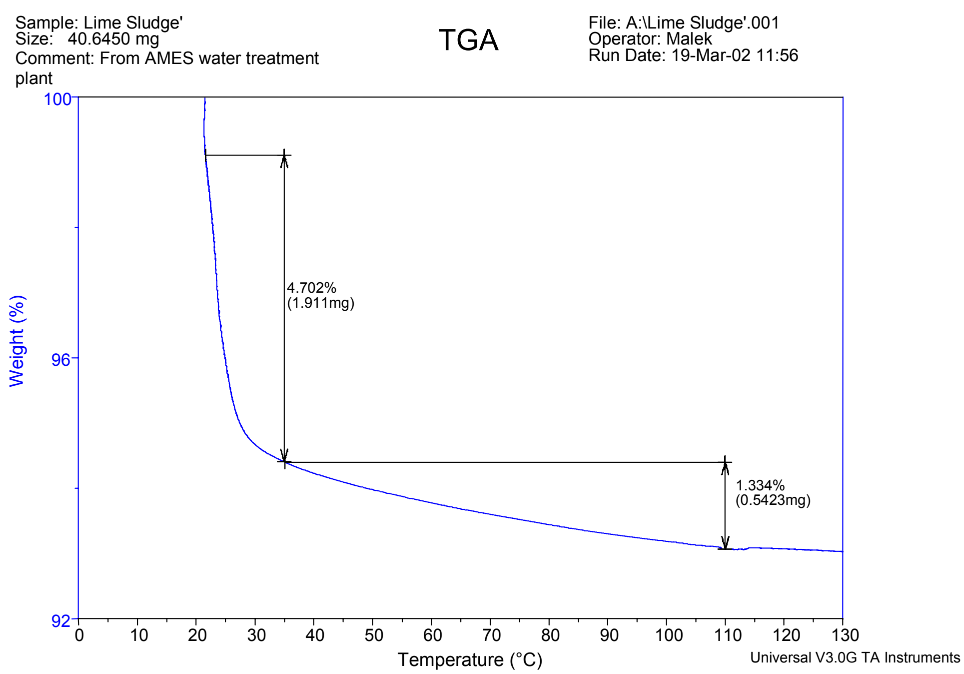

Figure 8: Thermogravimetric Analysis of Lime Sludge (20 - 130 ^{o}C)

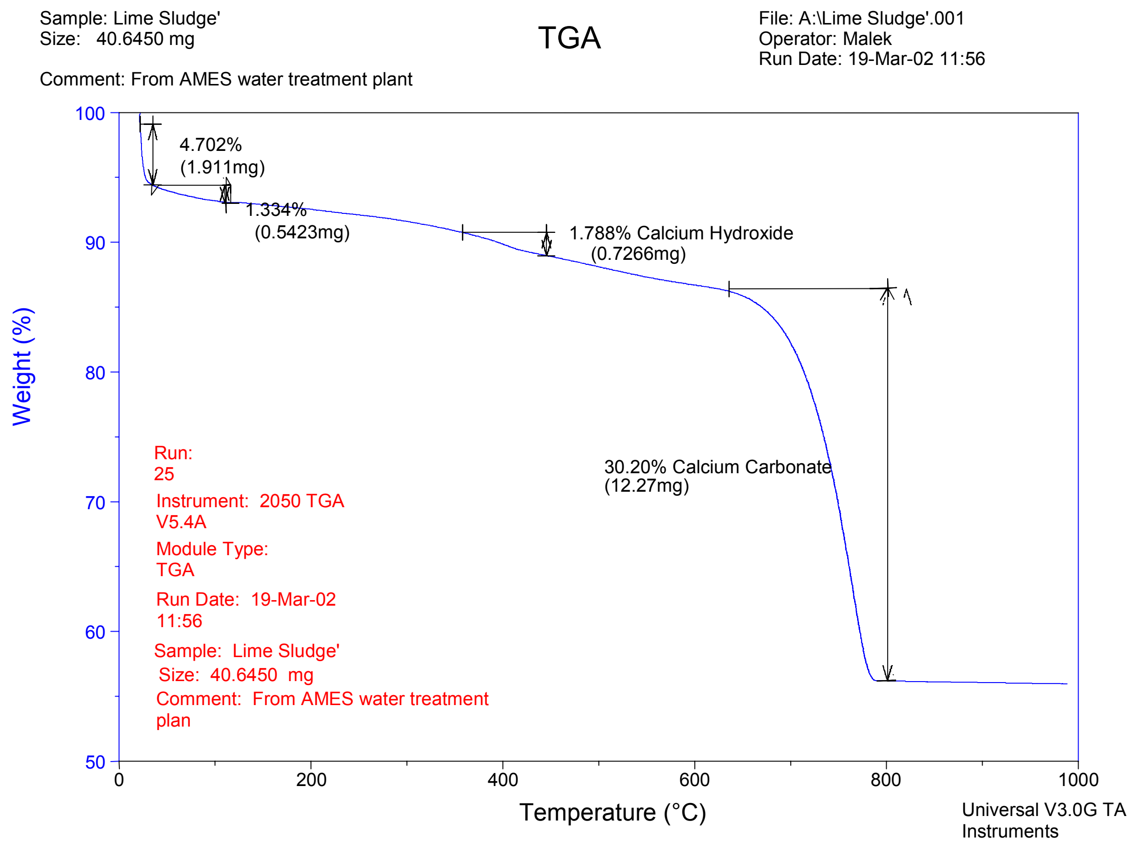

Figure 9: Thermogravimetric Analysis of Lime Sludge (20 – 1000 ^oC)

Next, six samples that were oven-dried to remove all moisture content, were allowed to cool at air temperature (around 20 ^oC) to determine the amount of moisture that the lime sludge would adsorb from the 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, then the ambient lab conditions would eventually reduce the moisture content to about 2%. Therefore, there is not a lot of value in drying beyond 2% moisture content.

Conclusions

Drying of lime sludge is not complicated by strongly bound water, except for the last 2%. The 2% level presents no limitation on any reuse possibility. A practical limitation on oven drying is that the sludge is reduced to small particles upon drying. This makes further drying difficult as the small particles are blown away. For most applications, a moisture content of between 20 and 35% is the most practical and ensures that the material does not generate dust.

Feasibility Studies of Selected Reuse Options

Use of Lime Sludge in Dry Scrubbing Power Plants

Ground limestone is used in some coal-fired power generation facilities to control the release of sulfur gases (SO_x) though the flue. This is known as the dry scrubbing process as opposed to the wet scrubbing process, where a slurry of ground limestone or calcium hydroxide is used for stack gas purification. The calcium carbonate, of which the limestone is composed, reacts with sulfur oxides in the gas to form calcium sulfites and calcium sulfates. The limestone needs to be ground to a fine texture to create a high surface area to react effectively with the sulfuric gases in the flue. This reduces the threat of acid rain in the region.

A complete study using lime sludge in place of ground limestone in a wet scrubbing process was done in Kansas (Shannon et al. 1999). First, researchers found that the lime sludge slurry was more reactive and soluble than the limestone was. Second, SO_2 removal was more effective using lime sludge than with ground limestone. Third, the power plant feeding mechanisms would need to be rebuilt to feed lime sludge rather than limestone. Finally, an economic analysis showed that using lime sludge could result in lower reagent demand and a savings in overall operations cost.

Grinding limestone is expensive. Since lime sludge has the same chemical composition as limestone and it has a high surface area, the feasibility of its use as a replacement for mined limestone had good potential. Iowa State University has the only dry scrubbing plant in Iowa and it was selected for testing. At this particular generation facility, the limestone was fed into combustion fluid stream pneumatically. Due to the pipework limitations of this site, the calcium carbonate must be in a very dry state (less than 2% moisture content) or else it will clog the feeding mechanism.

Methodology

Lime sludge was tested for feasibility as a substitute for limestone at the Iowa State University Power Plant on August 8, 2002. The lime sludge was delivered at a moisture content of 15% instead of the 2% requested. At this moisture content, the material was clumped into a range of ¼” to 3/8” diameter balls instead of a fine powder. This higher moisture content clogged the feeding mechanism and produced some sporadic results.

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

Results

The lime sludge material reacted well with the flue gas stream. 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 solely on the lime sludge product. 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 may have contributed to the erratic SO_2 and NO_X levels as depicted in Figure 10. SO_2 levels of 120-125 ppm and NO_X levels of 75-90 ppm were typical for this plant.

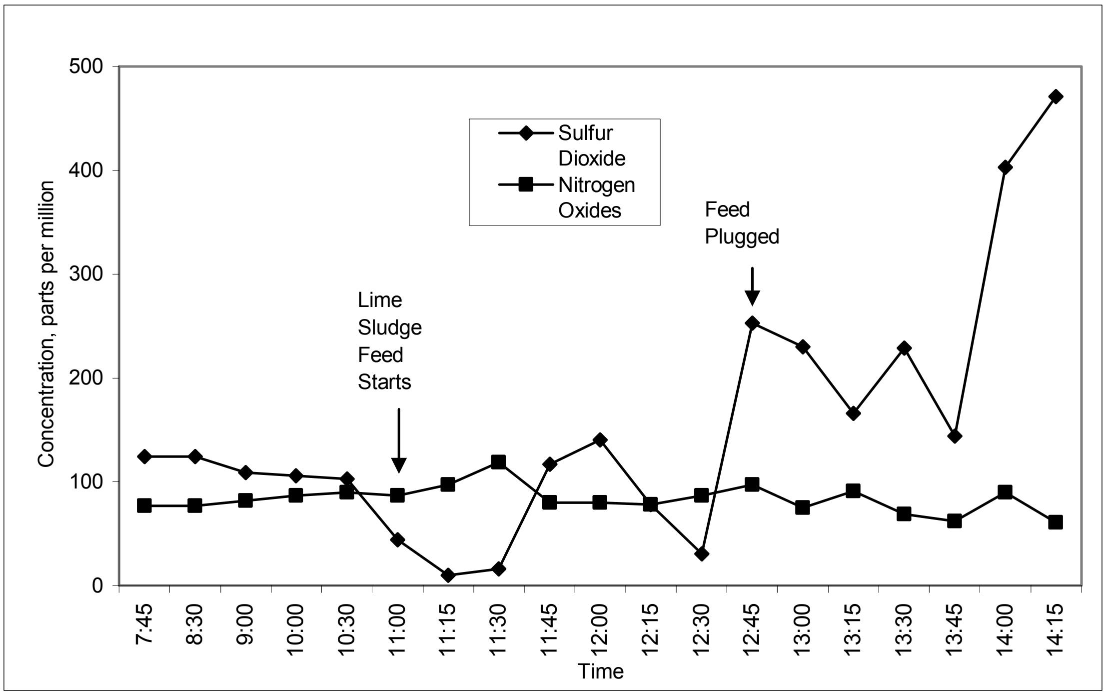

Figure 10: Tests with air pollution control at ISU Power Plant; Boiler Emission Levels

After the lime sludge feed was started, a few changes in the normal operation of the boiler bed were observed. First, a small decrease in the boiler bed temperature of about 2 to 3 ^oC was recorded. Second, the temperature leaving the combustor at the inlet to the cyclone increased about 14 ^oC. These two changes 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. Third, there was a slight, steady decrease in the boiler bed pressure throughout the test period. This change indicated a greater circulation rate, a reduction in bed material sizing, and possibly a reduction of bed inventory. Figure 11 shows a summary of these changes.

The test consumed about 4,500 lbs of lime sludge at a consumption rate of about 1,850 lbs per hour. This was a higher consumption rate than the rate for the limestone normally used. The lime sludge feed problems caused the operators to start the limestone feed to maintain SO_2 levels. This action lowers the accuracy of the lime sludge consumption rate significantly.

Discussion

Using lime sludge rather than limestone could improve boiler operations and would be more economical. However, 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 continued along this trend, it could present operational problems for the boiler. A reduction in the bed sizing can change NO_X emissions, but poor SO_2 control makes this observation inconclusive.

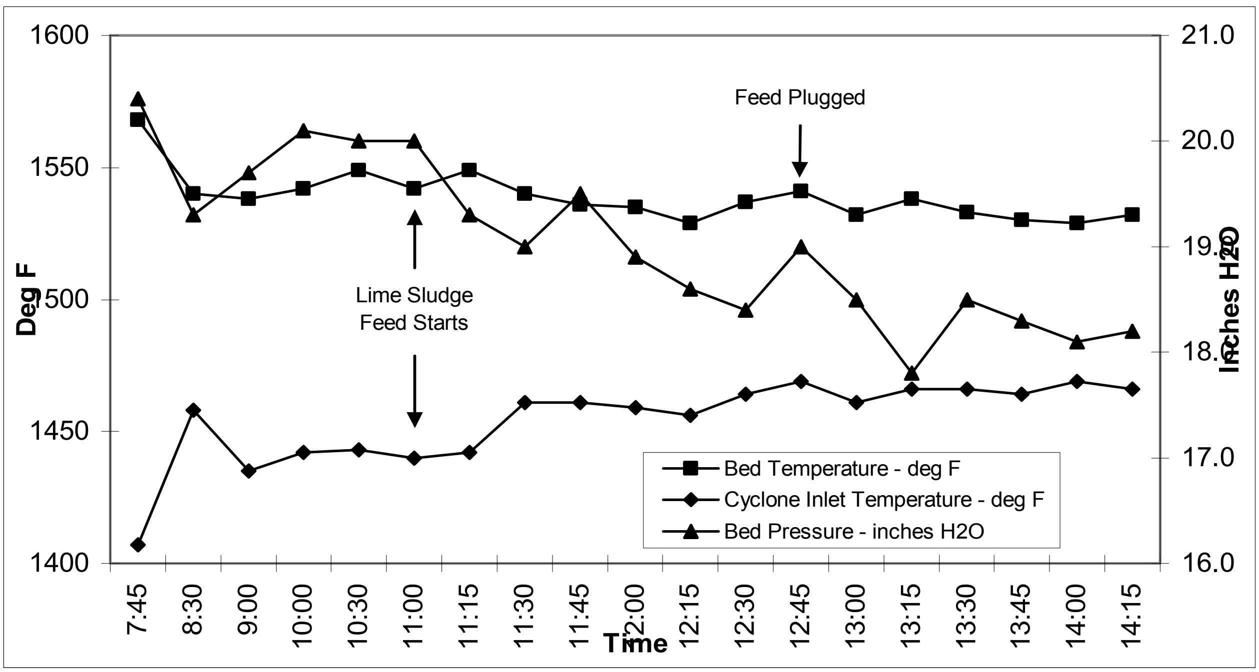

Figure 11: Boiler Bed Trends When Using Lime Sludge for SO_x Control.

Subsequent test runs would provide a more diverse data population 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 temporary equipment that was not available at the time, further testing at this facility was suspended indefinitely.

Power plants have low-grade waste heat that could be used for drying lime sludge. However, special equipment would have to be built to make use of this opportunity.

The Muscatine power plant would need some changes to equipment to be able to introduce lime sludge into their wet SO_2 scrubbers. 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 would be easier to convert to lime sludge than the dry pneumatic feed because it does not require extensive drying.

Conclusions

In summary, lime sludge appears to be very reactive with sulfur dioxide at the Iowa State Cogeneration Facility. The observed impacts to the boiler bed temperatures and bed pressures were not as dramatic as the operators expected. There was concern over the long-term impact that feed problems may have on the boiler beds. The impact on NO_X emissions and the consumption rate was inconclusive due the feed problems. These discrepancies can be addressed with an effective mechanism to control the feeding rate of the lime sludge, delivering the lime sludge at the prescribed moisture content, and more test runs.

Generally speaking, the results are encouraging. However, it was recognized that a full evaluation of the potential of lime sludge for dry scrubbing would require equipment that is not available to the ISU team. It would require a separate large project with a budget large enough to provide for the drying of at least 40 tons of lime sludge to close to 2% moisture and it should be recognized that such facilities are not available in Iowa. Such studies could result in a situation where all the lime sludge from the City of Ames could be consumed by the ISU Cogeneration Facility, if the two parties were willing to invest in a sludge drying facility. Such a facility would have environmental benefits and should easily pay for itself in limestone savings and lime sludge disposal cost reduction.

Replacing Limestone with Lime Sludge in Cement Kilns

Cement production plants use limestone as their main raw material. Lehigh Cement uses limestone also in SO_2 capture from its coal combustion process. Limited testing was conducted to see if lime sludge would be a suitable ingredient to augment or replace limestone.

Methodology and Results

Twenty tons of solar dried lime sludge were transported from Ames to Lehigh Cement in Mason City. The lime sludge was used in cement production, partially replacing some of the limestone used as raw material. About 80 tons of cement was produced containing about 15% of the lime sludge. The quality of the cement was satisfactory according to the Quality Control Manager, Mr. William Ulrich.

Discussion and Conclusion

Since the plant is located so close to where the limestone is mined, the cost of limestone at Lehigh Cement amounts to about $1 per ton. Therefore any alternative to limestone needs to be $1 per ton or less. Basically, if a water treatment plant wanted to send its sludge to Lehigh Cement for reuse, most of the cost of dewatering, drying, loading, and transportation would far exceed the cost of alternative disposal options. Use of lime sludge in cement production would only be feasible when a water treatment plant is within a few miles of a cement plant. Such an opportunity does not exist in Iowa as all cement plants are quite a distance from major water works.

Use of Lime Sludge for Wastewater Neutralization

Warren Foods in Altoona needs to neutralize their pasta processing wastewater. Sodium hydroxide was normally used, but this material was expensive and added unwanted salinity to the water. Tests using lime sludge for the neutralization of this wastewater were conducted at their treatment facility.

Methodology

Two tons of dry lime sludge that was dewatered by filter press and dried in a rotary kiln by Kelderman Lime was used. Dosing was done by hand as needed.

Results, Discussion and Conclusion

While successful, reuse of lime sludge at Warren Foods did not completely fulfill the goal of this research since it does not consume large enough amounts of sludge to empty stockpiles. At the time, Warren Foods produced wastewater at a rate of only 140,000 gallons per day.

For future reference, the following benefits of using lime sludge at Warren Foods are noted:

1. Savings for Warren Foods by using lime sludge, rather than sodium hydroxide, was estimated at $5000 per year.
2. This wastewater treatment process with lime sludge stayed within pH limits (most important, the pH was unable to exceed 8.0), and was easy to control.
3. Lime sludge served as a weighing agent on the sludge flocs, causing them to settle better. This could be a critical factor for this plant's wastewater treatment.

Lime sludge should definitely be considered for neutralization of acidic wastewaters. While dosing is not easy, dosage control is not an issue as over-dosage is not expensive and cannot lead to a pH higher than around neutrality.

Use of Lime Sludge for Dust Control on Gravel Roads

Dust is probably the main irritation resulting from the use of unpaved roads. 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-grained silt-sized material that could be applied to unpaved roads to change the material composition towards a more favorable grading.

Methodology

Lime sludge was tried on two test sections of gravel roads in Story County with the aid of county engineers personnel. The two test sites for the dust control test were Old Bloomington Road and 220th Street.

A truckload full of lime sludge was applied by a dump truck over about 100 ft stretches of the roads on May 29, 2002. The Old Bloomington Road is a gravel road and 220th Street is a crushed limestone road. A road grader made six passes over the 220th Street test section and 5 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. The lime sludge on the Old Bloomington Road test section was not as evenly spread as 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 there was no additional gravel added to the test sections.

A mid-sized SUV was driven in the middle of the road for a total of 10 times at a speed between 40 – 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. Dust deposition rates were measured with a bird-cage dust collector. Dust collection results are shown in Table 1.

Results

Table 1. 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)	Total Gross (g)
Bloomington Control	0.1324	0.3104	0.2204	0.051	0.7142
Bloomington Test	0.1503	0.4267	0.2745	0.0522	0.9037
220th Control	0.1599	0.2658	0.2904	0.3459	1.062
220th Test	0.1434	0.4254	0.1756	0.3763	1.1207

The gross amount of dust collected was greater on the test sections than on the control sections. This contradicted the hypothesis of the experiment. Figure 12 shows that the test section for 220th Street has a higher fines content (14%) than the control section (7%). Figure 13 shows that the control section for Old Bloomington Road has a higher fines content (9%) than the test section (6%).

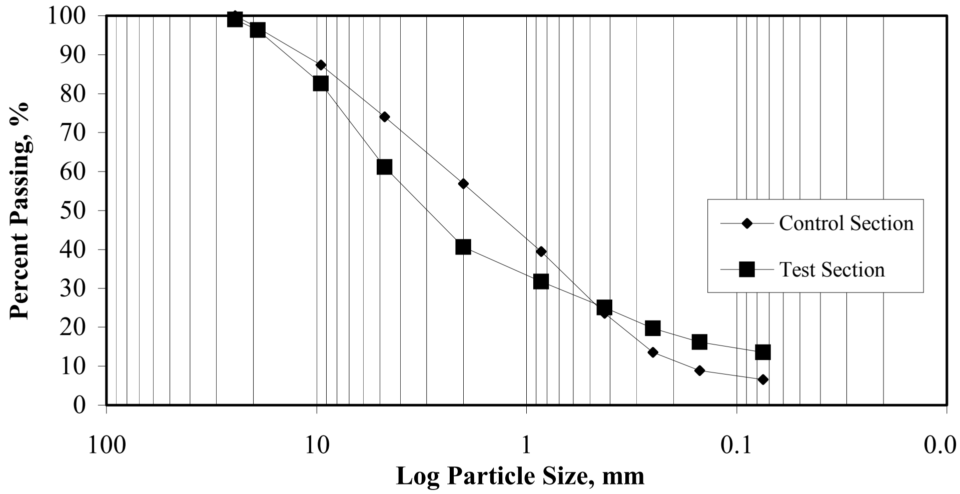

Figure 12: 220th Street Particle Size Distribution (Wet Sieved)

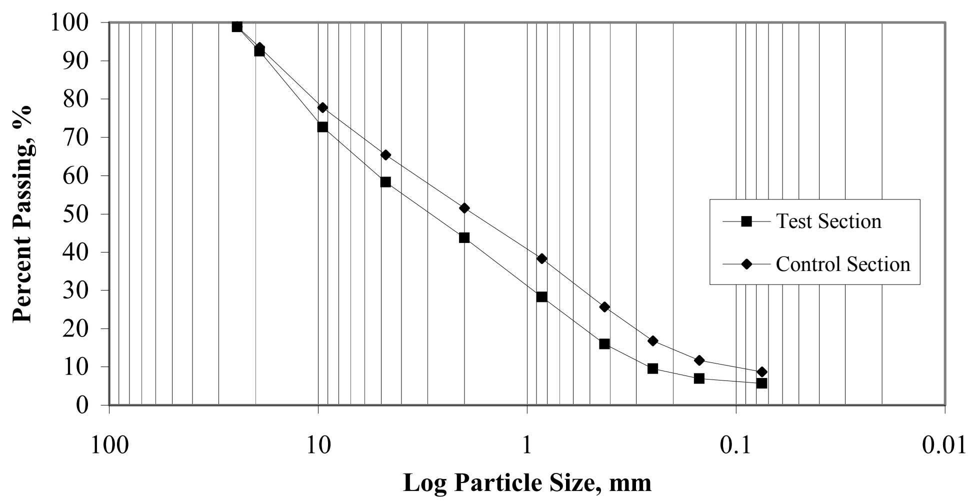

Figure 13: Old Bloomington Road Particle Size Distribution (Wet Sieved)

Since the experiment was mostly contradictory to its hypothesis, the test methods used need to be modified if experiments are repeated. In addition, the tests should be performed over a longer period and under more specific observations. Due to the choice to focus on the construction fill application, research on using lime sludge to suppress dust generation on gravel roads was suspended indefinitely. Further funding would be needed to continue research of this application.

Investigation of Lime Sludge Use for Construction Fill Applications

Construction fill is a common application for the disposal of excess solid waste products. Large quantities of materials are needed for fill and there are large quantities of wastes needing disposal. Settlement or leaching could present problems with some wastes, however. Stability and volume change potential are important engineering parameters to fully evaluate a construction fill material. Since road construction is the most intense around cities, the ability to use lime sludge as a fill material would be a good match, as water works are also close to or within cities. The suitability of dried lime sludge as is, mixed with soil and other solid materials, and modified with stabilizers was investigated.

When investigating a material for use as a construction fill, several engineering properties should be investigated. The particle size distribution, tendency for volume change, strength under compression, shear strength, comparison with other geomaterials, hydraulic conductivity, and durability in variable weather conditions are examples of these properties. Once these properties are quantified, engineers can incorporate this information into design of pavements and embankment fill applications.

Methodology

First, some index properties of interest were investigated for lime sludge alone. Second mixtures of lime sludge, a silty soil (loess), portland cement, bottom ash, and fly ash were tested. Third, amounts of additive and moisture were varied within the mixes. Last, a mix was chosen for further durability and strength testing. In addition, a mix was used in the construction of a test embankment 20 feet wide, 3.5 feet tall at center, and about 37 ft long at the Ames Water Treatment Plant's lime sludge processing site.

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 to a moisture content of about 2% and then thoroughly pulverized. 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.

In defining the moisture density relationship, 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. Figure 14 illustrates the compaction device that produces 2 inch by 2 inch (2x2) cylinders used in this experiment. This compaction method was developed at Iowa State University several years ago (O'Flaherty et al, 1963) and produces 2-inch diameter by 2-inch high specimens. The materials are screened through a No. 4 sieve (4.75 mm opening) prior to compaction using 5 blows of the drop hammer on each side of the specimen. This typically yields a maximum dry density similar to standard Proctor compaction (4-inch diameter by 4.6-

inch high specimen). After compaction, the molded specimen is extracted using a hydraulic jack and the weight and dimensions are measured. Density is calculated by dividing the weight by the volume. The moisture content is determined by oven-drying.

When developing the mixtures, 2x2 cylindrical specimens and the unconfined compression test was used. The Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders (ASTM D1633) was used. Exceptions to the standard methods were the use of 2x2 molded cylinders, and in a few cases, the mix designs were not tested in triplicate. (Those unconfined compressive strength figures in this report that have error bars show the tests in which specimens were tested in triplicate. Those without were single specimen results).

When using a stabilizer, such as portland cement or Class C fly ash, specimens were wrapped in saran wrap, wrapped again in aluminum foil, and then sealed in a ziplock 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 resulting strength.

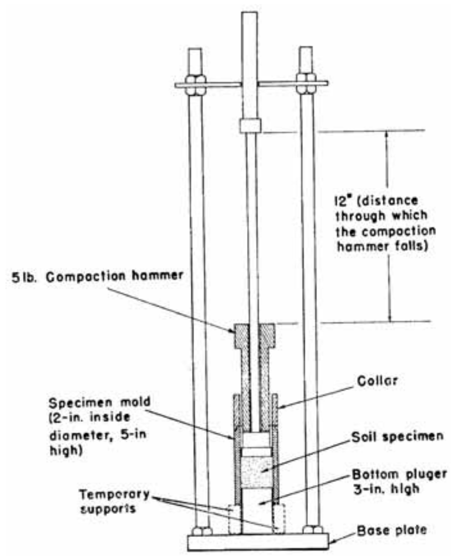

Figure 14: Compaction Apparatus (O'Flaherty et al., 1963)

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, this only required breaking up clumps of material into its original form. However, since the bottom ash had many particles larger, those particles retained on the Standard No. 4 sieve were discarded.

A major point of this research was to find uses for stockpiled municipal waste products. Therefore, testing mixtures of water treatment and power generation byproducts was an important goal in this work. Even though portland cement tested better as a stabilizer, mixtures with lime sludge, fly ash, and bottom ash were used throughout.

The weather cycles in Iowa's temperate climate can take an expansive or weak soil beyond its limits and result in large settlements or strength failures. Lab tests that simulate alternating cycles of freezing and thawing and flooding and drought were done. 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 and varied additive rates, then compacted, and finally cured under a controlled moisture and temperature 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 the brushed specimen. Volume change measurements were not taken in the first set. Freezing and thawing was the most aggressive test for these mixes. No specimens survived a full 12 cycles of brushing regardless of additive amount. A second set of freeze/thaw durability tests was done 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 were conducted until specimen failure or until they reached 12 cycles. Since the wetting and drying test was not the most aggressive, the test 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 lb) after the drying part of the cycle. This is the simulated abrasion or erosion component of the test. Brushing while dry was to the specimen's benefit because if they were brushed while saturated they would not have lasted as long. Durability testing showed that the lime sludge mixtures are thixotrophic. Simply stated, the specimens harden when they are dried, but become plastic or gelatinous when saturated.

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. After thawing, one of the two specimens was brushed. The specimen that was not brushed was only measured for volume and mass change.

The Standard Test Method for Direct Shear Test of Soils Under Consolidated Shear Conditions, (ASTM D3080) was performed to characterize the shear strength parameters presented in this report. Three test specimens were tested at normal stresses of 34.49 kPa (5 psi), 68.97 kPa (10 psi), or 103.5 kPa (15 psi). The first set of specimens tested was lime sludge without the fly ash additive. The second and third sets each tested specimens containing one part fly ash mixed with two parts lime sludge (by dry weight) and one part fly ash mixed with one part lime sludge (by dry weight). The second set was tested after 28 days of cure time and the third set was tested after 56 days of cure time.

ASTM D3080 requires the freshly mixed soil and water to stand for about 18 hours for silt-sized materials 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. Tests indicated that the fly ash from the Ames Power Plant will react with water and set to a penetration resistance of 4.6 tons per square foot in 18 minutes (in specimens of fly ash only). Thus, 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 starting of consolidation. The direct shear box was submerged in the pool of water. The consolidation and shearing parts of the test were done submerged as well.

The Standard Test Method for California Bearing Ratio (CBR) of Laboratory Compacted Soils (ASTM D1883), was used to quantify strength and stiffness of the lime sludge mixes. A lime sludge control set of 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. Lime sludge alone was compacted at 42%.

The bearing ratio was determined varying the compaction energy. Each set of three specimens had a specimen corresponding 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 was tested 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 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 with no fly ash additive, and a 1:1 fly ash to lime sludge mix. Specimens containing fly ash and lime sludge were cured in the test cell under no pressure for one week prior to commencement of saturation and consolidation. De-aired water was used as a permeant.

Saturation was achieved through the applying 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, then the specimen was considered to be saturated. Beginning and final height measurements were taken, but none taken while in the test cell. Since lime sludge has a low plasticity, it was assumed that test specimens would have minimal volume change during saturation. The starting and ending heights of the specimens were recorded for calculations.

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 material with a hydraulic conductivity of 10^{-6} cm/sec. For each trial, the permeation was performed under two gradients. Whenever possible, the permeability value chosen for calculations and 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 equation listed in 10.1.1 of the ASTM D5084.

Transitioning from lab testing to a larger scale, a test embankment was constructed outdoors in July 2004. Locally available materials were mixed, placed, and compacted at a lime sludge to fly ash ratio of two to one. The lime sludge was the same source as the material used in all of the lab testing. The fly ash was from the Ames Power Plant. No water was added, so the moisture available in the air-dried lime sludge was the source for the hydration of the fly ash. The lime sludge and fly ash were mixed dry of optimum, but there were two significant rainfall events (more than ½-inch) within a week of construction.

Temperature sensors were embedded in the embankment for every 6 inches of depth to monitor temperatures. Throughout the fall, winter and spring, data will be collected through actual weather cycles and be reported under a separate cover. Dynamic penetration tests and density measurement were performed directly after construction and will be compared with tests performed in Spring 2005. Temperature profiles will be developed as well.

Results and Discussion

Index Properties of Lime Sludge

In the previous feasibility tests, the lime sludge appeared to be a very fine and lightweight material without cohesive properties (when air-dried). The unconfined compressive strength tests confirmed this initial observation. However, weak materials can still be used effectively if a stabilizing additive such as portland cement or fly ash is used. The following data demonstrate the testing used to identify properties of interest and the mix design used to incorporate portland cement and fly ash stabilization.

The particle size distribution of the lime sludge from the Ames Water Treatment Plant is shown in Figure 15. Liquid limit test results on the same sludge are shown in Figure 16. The logarithm of the moisture content corresponding to the logarithm for 25 drops was found. The data line on Figure 16, not the trend line, was used for finding the liquid limit since the trend line did not have a good correlation factor (linear regression produced an r^2 of 0.001). The data line resulted in a liquid limit of 42%. 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 5%.

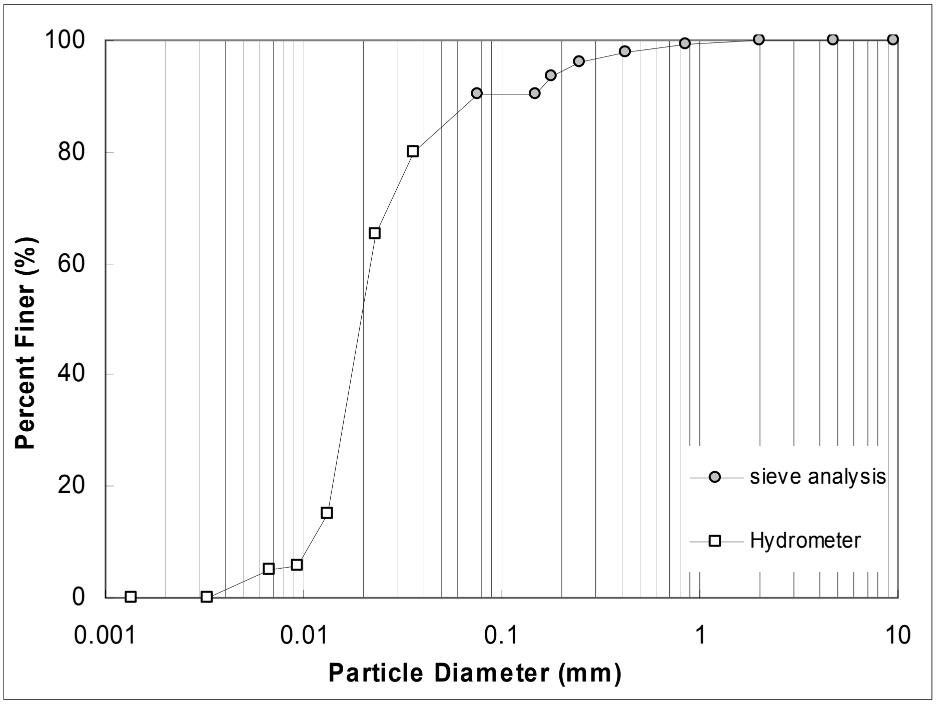

Figure 15: Particle Size Distribution for Lime Sludge

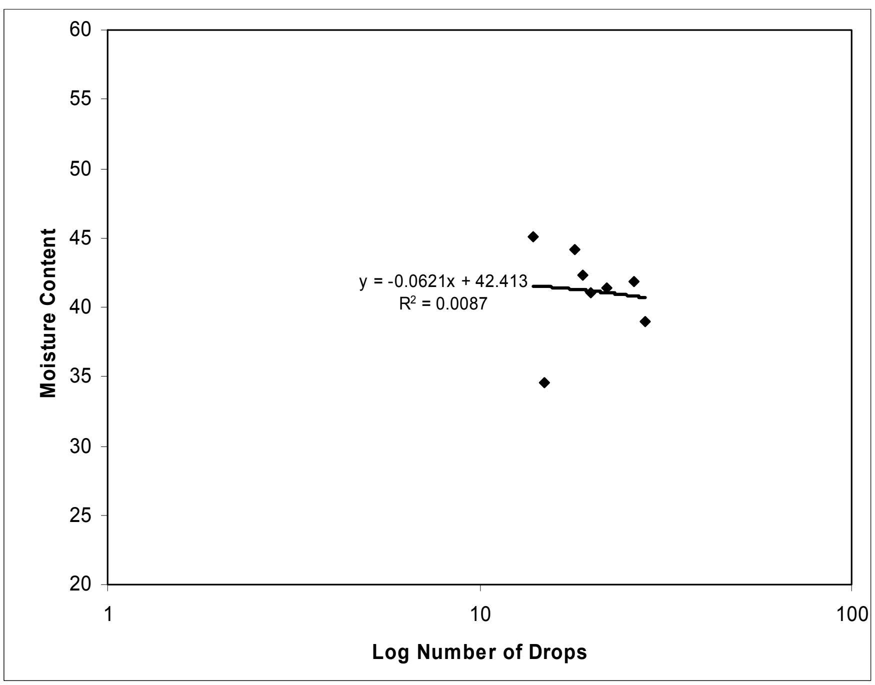

Figure 16: Liquid Limit Data for Lime Sludge.

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 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 test quantified the effects of standard compaction effort on samples of lime sludge. The end result was a relationship between the moisture content and the density of the material. The density of a soil material has strong influences on strength, stiffness, and permeability. Figure 17 shows the results of the moisture-density relationship. For comparison purposes, the same procedure was performed on a soil commonly found in Iowa of similar particle size – loess. The moisture density relationship for loess is also provided in Figure 17.

Most soil materials have a distinct hump in their moisture-density curves indicating the optimum moisture correlating to maximum density. As seen in Figure 17, lime sludge does not. This is to be expected since the density of the dry material is close to that of water.

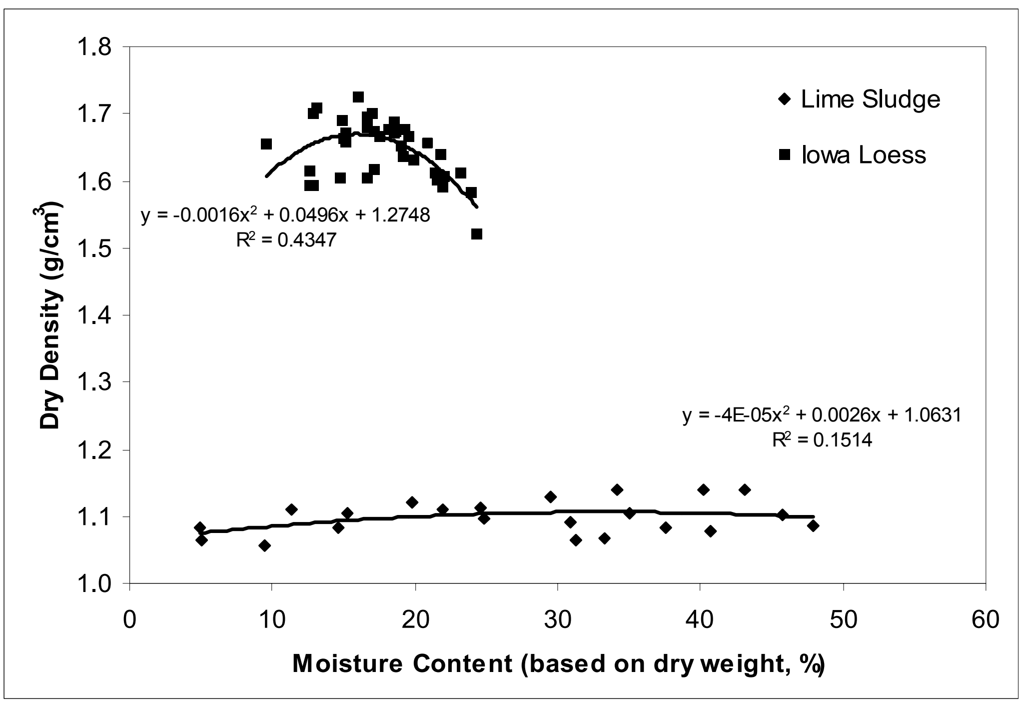

Figure 17: Moisture Density Relationship

Unconfined Compressive Strength Tests

Lime sludge by itself is not strong in unconfined compression. After being mixed with fly ash or portland cement, it was not difficult to find a mix design that would surpass the target strength of 345 kPa (about 50 psi) in unconfined compression. Table 1 lists the type of tests performed, materials used, and moisture contents tested. Following, more detailed results are presented by material types and amounts, cure time, and moisture content of the mix.

Table 1: Summary of Types of Strength Tests Completed

Graphics	Materials	Water Content, %	Type Test	Parameter varied
Fig 18	C-LS-L	13.5 to 16	UCS	C, LS, and L amounts
Fig 19	LS-FA-C	5 to 45	UCS	water content
Fig 20	LS-FA	36-25	UCS, FT, WD	stabilizer amount
Fig 21	LS-C	29-37	UCS, FT, WD	stabilizer amount
Fig 22	LS-FA	36 to 51	UCS	cure time
Fig 23	LS-C	40-51	UCS	cure time
Fig 24	LS-CS-FA-BA	19-24	UCS	cure time
Table 2, Fig 25	LS	37-40	DS	none, control for next line
Tables 3-6, Figs 26-29	LS-FA	14-20	DS	cure time, stabilizer amount
Table 7	LS	69-74	CBR	none, control for next line
Tables 8-11	LS-FA	31-49	CBR	cure time, stabilizer amount
Key: L=Loess soil; LS=lime sludge; CS=concrete sand; C=portland cement; FA-fly ash; BA=bottom ash; FT=Freeze/thaw durability; WD=wet/dry durability				

Figure 18 shows how a common additive, portland cement, increases the strength of soil. When lime sludge is added in a similar manner, no strength advantages are realized. From these tests, the finding that lime sludge does not add strength to a soil, as portland cement does, was made. Lime sludge has no binding properties.

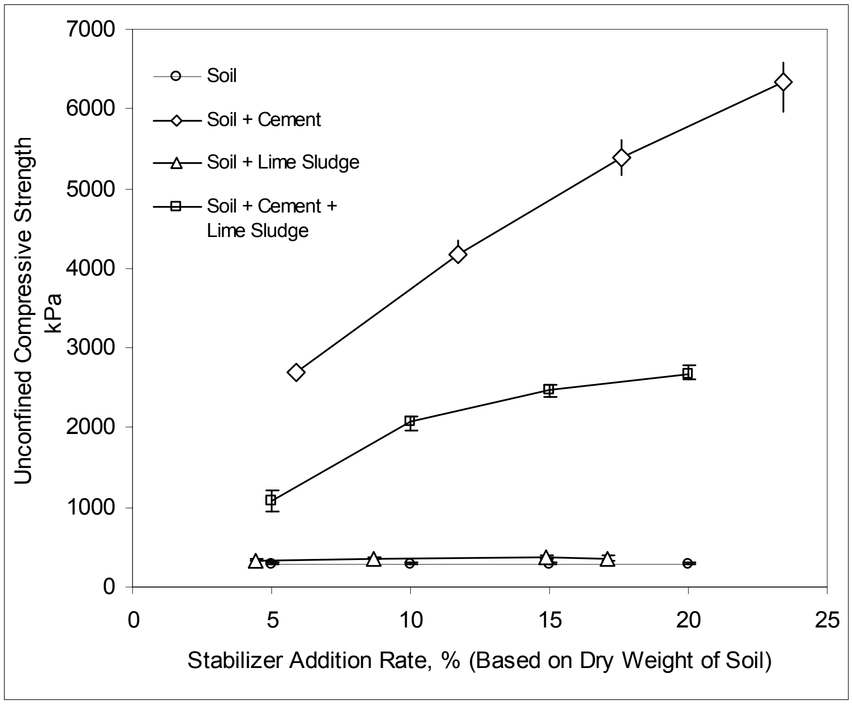

Figure 18: Effects of Mixing Cement and Lime Sludge with Loess Soil

The two major parameters that need to be controlled when adding portland cement or fly ash are moisture content and the amount of additive added. Controlling the amount of portland cement and/or fly ash is obvious, but too little or too much moisture in the mix can drastically affect the resulting strength. Lime sludge crystals are very small (mostly fine material as shown in Figure 15). The small particle sizes result in a high surface area. High surface area coupled with the water molecule's attraction to the lime sludge (opposite surface charges) means that lime sludge can attract well over twice its weight in water without any outside sources of energy. Too much moisture in the mix will cause water to displace the fly ash particles. When this happens, the lime sludge particle will not make contact with the reactive materials in fly ash that form the high-strength bonds.

Figure 19 shows a set of tests completed to discover what the best mix moisture content would be for each type of stabilizer. Two sets of stabilizer amounts were tested over varying moisture contents. The ratios of fly ash to lime sludge on Figure 19 that were tested were 0.5 and 0.1, and the ratios of cement to lime sludge that were 0.05 and 0.2. All ratios were based on dry weights. Figure 19 shows that the OGS fly ash and portland cement specimens peaked at one moisture content. However, the Ames fly ash varied between the two stabilizer to lime sludge ratios.

The best mixture moisture content for the OGS fly ash and lime sludge was about 28%. Similarly, the two portland cement mixtures peaked at a mixture moisture content of 32%. The two ratios for the Ames fly ash and lime sludge mixtures did not agree. Their peaks were 39% for the 0.1 ratio and 24% for the 0.5 ratio. The moisture contents that resulted in peak strength in Figure 19 were next used in a set of tests that held moisture constant as a constant and varied the stabilizer amount.

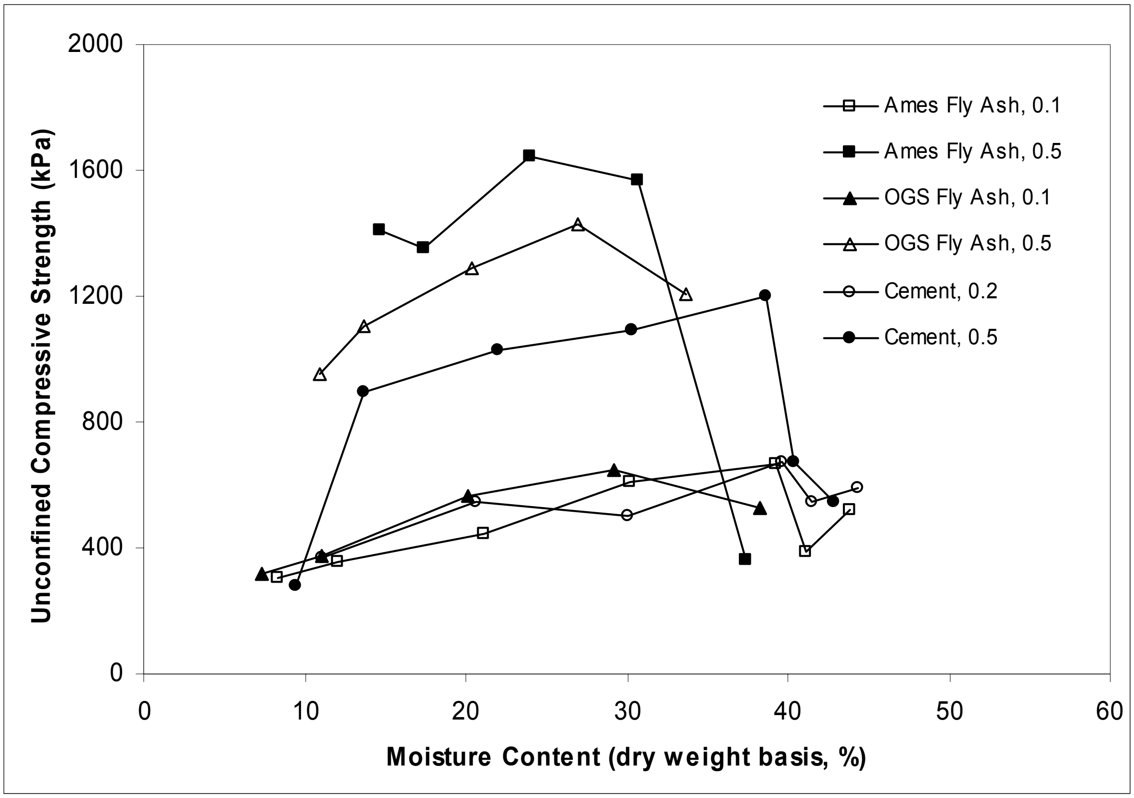

Figure 19: Effects of Moisture on Strength of Lime Sludge Mixes.

While using the peak moisture contents found in Figure 19 for the portland cement and OGS fly ash, tests were performed on specimens of lime sludge mixtures with varying amounts of fly ash and portland cement while the moisture content was held constant. For the specimens containing the Ames fly ash, the stabilizer amounts were varied and the moisture contents were chosen over the moisture content range resulting from Figure 19 – 24%-39%. Figures 20 and 21 show the results. The points represent an average of three specimens and there are error bars to represent the data ranges. Figures 20 and 21 clearly show that mixing higher percentages of stabilizer produces a higher strength. As an example, if the target unconfined compressive strength was 700 kPa, Figures 20 and 21 could be referenced to estimate a stabilizer to lime sludge ratio to achieve that desired strength. Figure 19 could be referenced to select a moisture content.

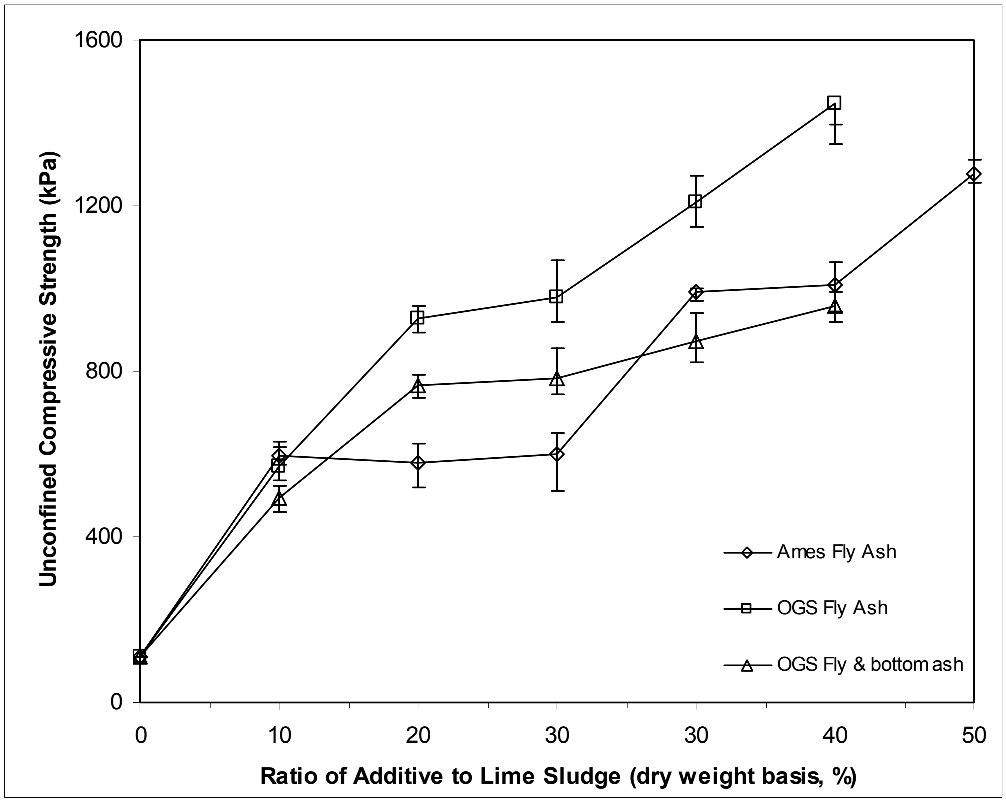

Figure 20: Effects of Admixture Content on Strength of Lime Sludge and Fly Ash Mixes

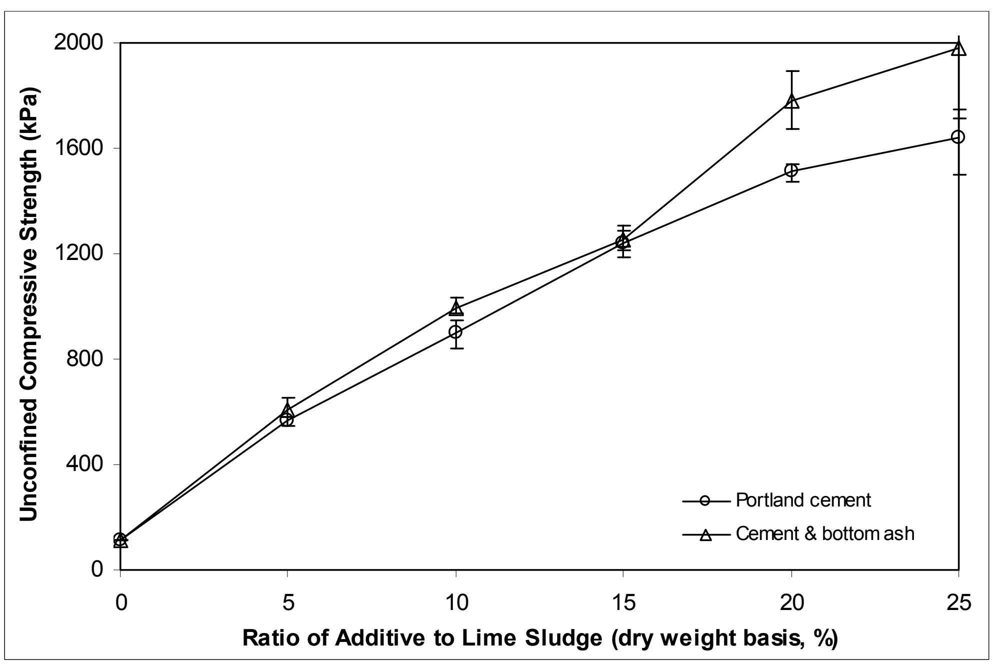

Figure 21: Effects of Admixture Content on Strength of Lime Sludge and Cement Mixes

Bottom ash did not add unconfined compressive strength to a mixture, but adding it to the mixture did not result in a significantly lower strength. As well, adding bottom ash to lime sludge made the particle size distribution less uniform. In theory, less uniformity in fill materials is good since we could achieve better packing of solid particles in the fill. Better packing leads to higher densities and so the quality of the product should increase.

In general, stabilizers like portland cement and fly ash bond soil particles together. While the mixtures are allowed to cure, a strength gain results. The next set of tests considered time as a variable in strength gain. Figures 22 and 23 show that for lime sludge only, no strength gain happens with additional curing time. However, there was strength gain associated with cure when either portland cement or fly ash was present – especially in the first 28 days. The strength achieved with bottom ash compared fairly well as compared to another coarse material, concrete sand as seen in Figure 24.

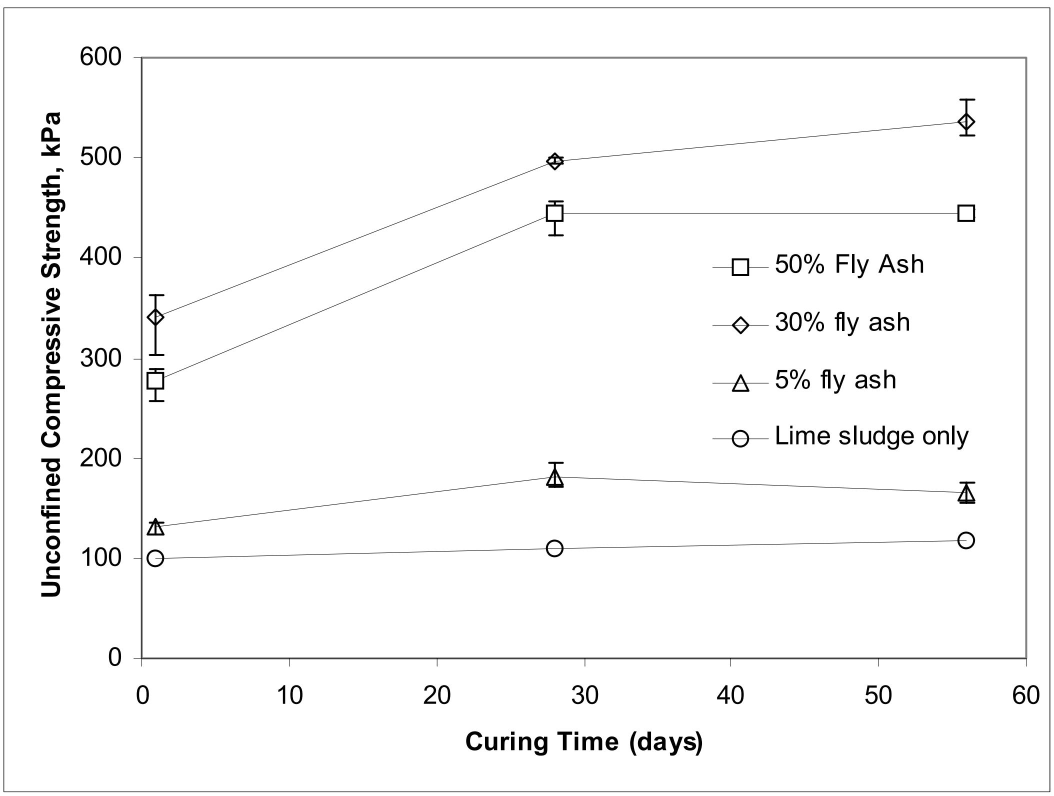

Figure 22: Effect of Curing Time on Lime Sludge and Fly Ash Mixtures

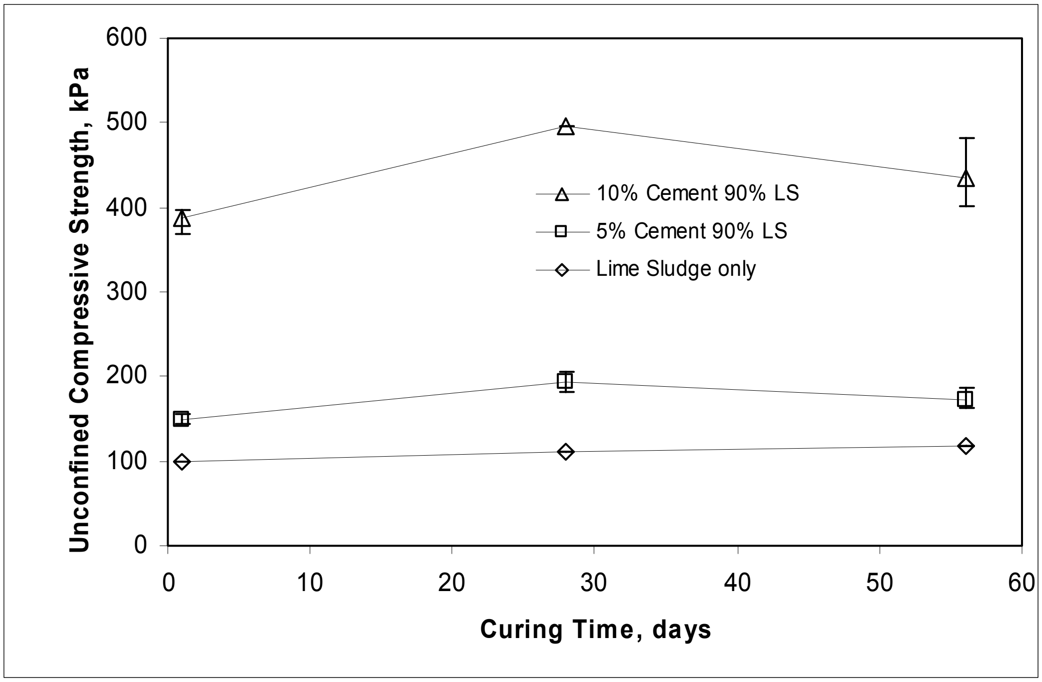

Figure 23: Effect of Curing Time on Lime Sludge and Cement Mixtures

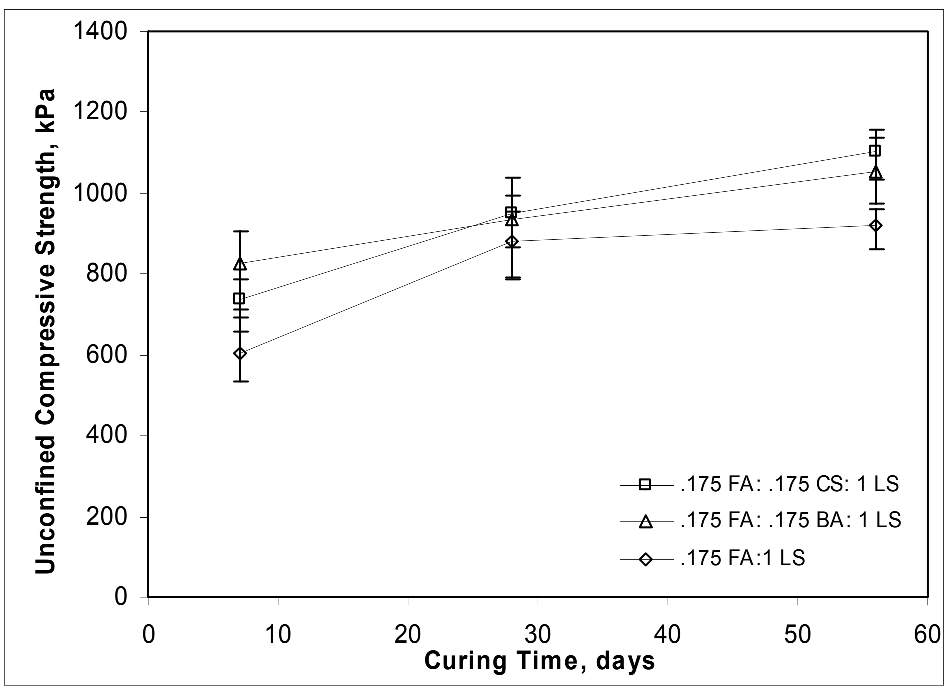

Figure 24: Effects of Curing Time on Mixes Containing Fly Ash and Bottom Ash

Direct Shear Strength Tests

The direct shear tests showed high friction angle values from 64 to 71 degrees and cohesion intercepts of 35 to 52 kPa in both lime sludge only and lime sludge and fly ash mixes. The lime sludge to fly ash specimens mixed at a ratio of 2:1, cured to 56 days, strayed from the other results with a low friction angle value of 24 degrees, and a high cohesion intercept of 213 kPa. Typical values of drained friction angles for sands with angular grains range from 30-45 degrees and for silts range from 26-35 degrees (Das, 2002). Since the friction angle values are relative high, values for other wastes and byproducts were consulted. Wang et al. (1992) found friction angles on water treatment sludges that fell in the UCS classification of CH using the triaxial compression test (consolidated-undrained with pore pressure measurements). Their friction angles based on effective stress ranged from 42 to 44 degrees for three different sludges. Based on total stress, they reported friction angles ranging from 17 to 19 degrees for the same sludges. According to results from Charlie (1977), papermill sludges had effective friction angles as high as 76 degrees.

There was a cementation effect with the fly ash stabilized mixes. The maximum shear stress values reported in Figures 26 to 29 are based on residual shear after the spike in shear stress caused by the cementation of the fly ash. These spikes in shear stress were inconsistent and did not result in interpretable friction angles and cohesion intercepts.

By comparing the values for the shear strength parameters in Tables 2 through 6, the amount of stabilizer (fly ash) added increased the friction angle. Tables 2 through 6 also show an increase of friction angle with curing time. Once the cementation bonds are broken during shear, residual shear stresses are consistent. In Tables 2, 5, and 6, the diameter to thickness ratio of the specimens tested were not all the same. In these cases, the same trimming ring was not available in the lab throughout the tests. The only difference in the specimens produced was 5mm in height, while the diameter was constant. Both of the diameter to thickness ratios reported were within the limits of the standard method (ASTM 3080).

Table 2: Direct Shear Test Summary, Lime Sludge Only

Normal Stress kPa	Initial Moisture %	Initial Dry Unit Wgt g/cm^3	Diameter thickness Ratio	Final Moisture %	Cohesion Intercept kPa	Friction Angle (degrees)
34.49	40	1.35	2	60		
68.97	39	1.36	2.5	60		
103.5	37	1.43	2.5	60	36.8	64

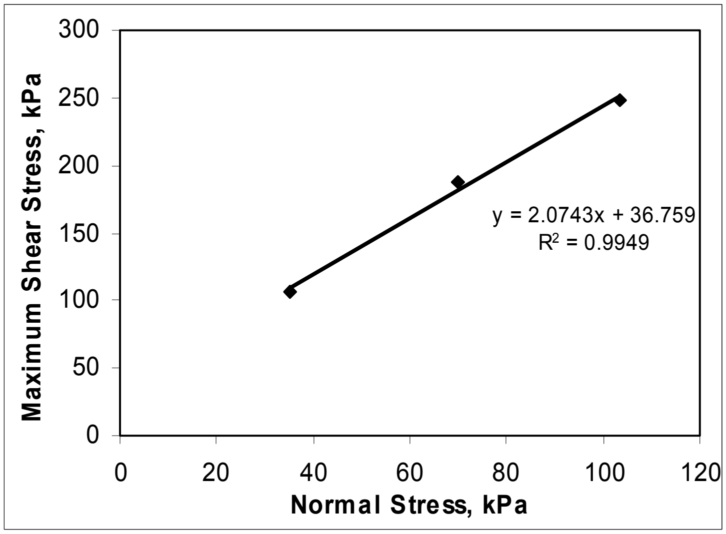

Figure 25: Direct Shear Test, Lime Sludge Only

Table 3: Direct Shear Test Summary, Lime Sludge to Fly Ash Ratio of 2:1, 28 days

Normal Stress kPa	Initial Moisture %	Initial Dry Unit Wgt g/cm^3	Diameter thickness Ratio	Final Moisture %	Cohesion Intercept kPa	Friction Angle (degrees)
34.49	15	1.96	2	42		
68.97	22	1.79	2	39		
103.5	21	1.82	2	41	176.1	61

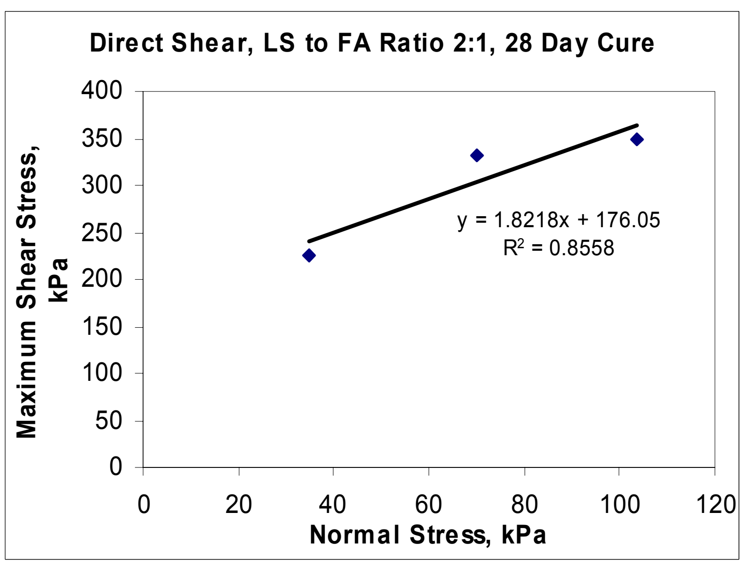

Figure 26: Direct Shear Test, Lime Sludge to Fly Ash Ratio 2:1, 28 days

Table 4: Direct Shear Summary, Lime Sludge to Fly Ash Ratio 1:1, 28 Days

Normal Stress kPa	Initial Moisture %	Initial Dry Unit Wgt g/cm³	Diameter thickness Ratio	Final Moisture %	Cohesion Intercept kPa	Friction Angle (degrees)
34.49	18	1.91	2.5	40		
68.97	18	1.95	2.5	39		
103.5	20	1.87	2.5	40	52.32	71.2

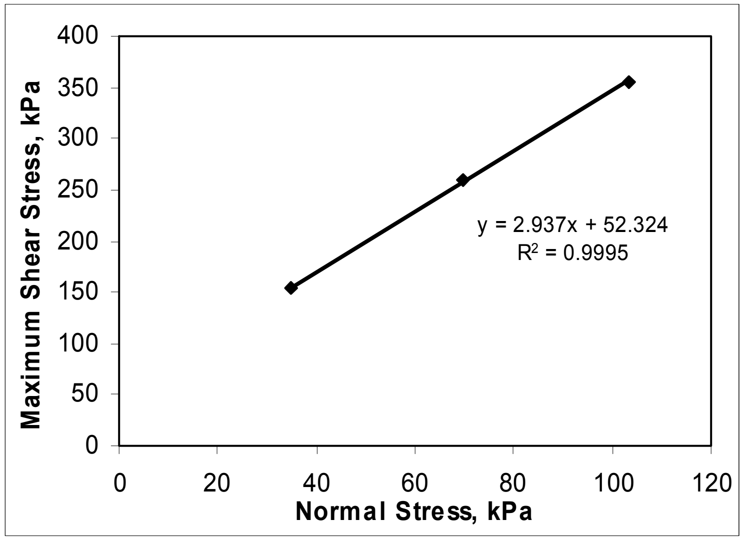

Figure 27: Direct Shear Test, Lime Sludge to Fly Ash Ratio 1:1, 28 days

Table 5: Direct Shear Summary, Lime Sludge to Fly Ash Ratio 2:1, 56 Days

Normal Stress kPa	Initial Moisture %	Initial Dry Unit Wgt g/cm^3	Diameter thickness Ratio	Final Moisture %	Cohesion Intercept kPa	Friction Angle (degrees)
34.49	16	1.98	2	38		
68.97	20	1.81	2.5	42		
103.5	14	1.9	2.5	43	213.5	24

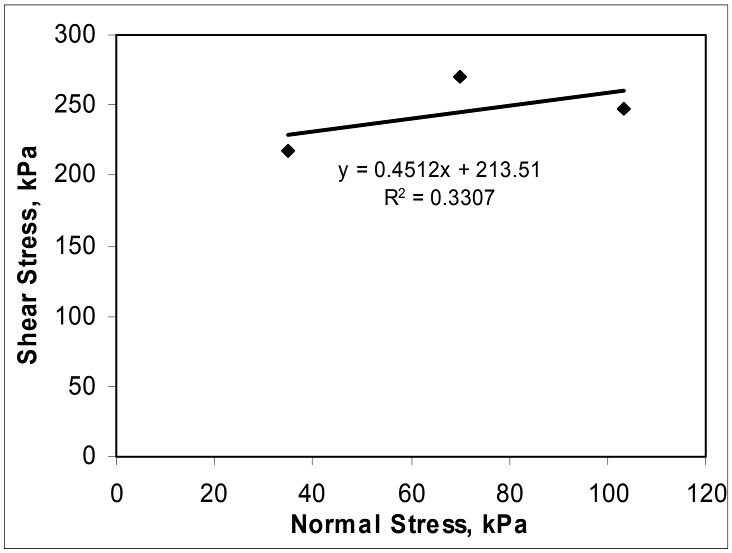

Figure 28: Direct Shear Test, Lime Sludge to Fly Ash Ratio 2:1, 56 days

Table 6: Direct Shear Summary, Lime Sludge to Fly Ash Ratio 1:1, 56 Days

Normal Stress kPa	Initial Moisture %	Initial Dry Unit Wgt g/cm^3	Diameter thickness Ratio	Final Moisture %	Cohesion Intercept kPa	Friction Angle (degrees)
34.49	17	1.84	2	41		
68.97	18	1.84	2	50		
103.5	18	1.89	2.5	40	113.4	61

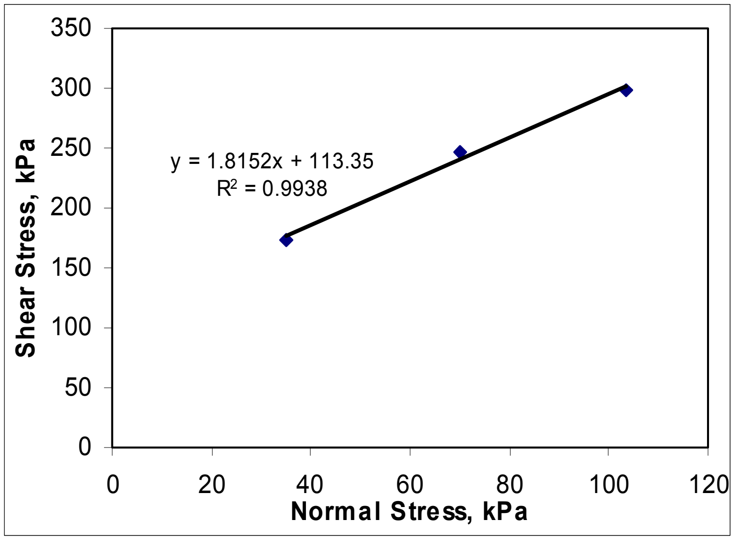

Figure 29: Direct Shear Test, Lime Sludge to Fly Ash Ratio 1:1, 56 days

California Bearing Ratio Tests

The CBR test results are found in Tables 7 through 11. Three tests should be repeated per the standard method because bearing ratio the 0.200 inch penetration is greater than that of the 0.100 inch penetration. The tests that should be repeated include the 2:1 lime sludge to fly ash ratio for the 12-blow and 25-blow specimen for the 28-day cure time and the 12-blow specimen for the 56-day cure time. Overall, the CBR values are relatively high when compared to other soils in the same classification. According to Rollings and Rollings (1996), CBR ranges from 20-40% for silty sands, 10 to 20% for clayey sands, 5-15 for silts and sandy silts.

Table 7: CBR Data for Lime Sludge Only

	12 blows	25 Blows	56 Blows
Moisture Content after Compaction, %	43	43	43
Moisture Content top 1" after Soak	74	71	69
Dry Density Before Soak, pcf	74.6	76.1	96.2
Dry Density After Soak, pcf	93.0	89.6	108.3
Height before soak, inches	4.584	4.584	4.584
Height After Soak, inches	4.501	4.584	4.521
Swell, % (negative indicates settlement)	-1.8	0	-1.3
Bearing Ratio, 0.100 penetration, %	1.2	2.0	4.7
Bearing Ratio, 0.200 penetration, %	1.1	2.0	4.4

Table 8: CBR Data for Lime Sludge to Fly Ash Ratio of 2:1, 28 days

	12 blows	25 Blows	56 Blows
Moisture Content after Compaction, %	26	28	28
Moisture Content top 1" after Soak	44	47	43
Dry Density Before Soak, pcf	75.1	81.0	103.9
Dry Density After Soak, pcf	85.2	100.4	122.3
Height before soak, inches	4.584	4.584	4.584
Height After Soak, inches	4.584	4.579	4.582
Swell, % (negative indicates settlement)	0	-0.11	-0.04
Bearing Ratio, 0.100 penetration, %	19	21	27
Bearing Ratio, 0.200 penetration, %	21	19	26

Table 9: CBR Data for Lime Sludge to Fly Ash Ratio of 1:1, 28 days

	12 blows	25 Blows	56 Blows
Moisture Content after Compaction, %	22	17	19
Moisture Content top 1" after Soak	40	47	43
Dry Density Before Soak, pcf	80.1	90.6	96.0
Dry Density After Soak, pcf	104.3	108.3	110.8
Height before soak, inches	4.584	4.584	4.584
Height After Soak, inches	4.573	4.579	4.584
Swell, % (negative indicates settlement)	-0.24	-0.11	0
Bearing Ratio, 0.100 penetration, %	14	22	26
Bearing Ratio, 0.200 penetration, %	14	22	20

Table 10: CBR Data for Lime Sludge to Fly Ash Ratio of 2:1, 56 days

	12 blows	25 Blows	56 Blows
Moisture Content after Compaction, %	26	28	28
Moisture Content top 1" after Soak	42	31	33
Dry Density Before Soak, pcf	91.3	100.2	106.4
Dry Density After Soak, pcf	102.1	108.1	110.8
Height before soak, inches	4.584	4.584	4.584
Height After Soak, inches	4.584	4.585	4.579
Swell, % (negative indicates settlement)	0	0.02	-0.11
Bearing Ratio, 0.100 penetration, %	32	41	57
Bearing Ratio, 0.200 penetration, %	36	42	52

Table 11: CBR Data for Lime Sludge to Fly Ash Ratio of 1:1, 56 days

	12 blows	25 Blows	56 Blows
Moisture Content after Compaction, %	22	22	19
Moisture Content top 1" after Soak	49	n/a	38
Dry Density Before Soak, pcf	91.3	100.2	106.4
Dry Density After Soak, pcf	101.3	108.3	110.7
Height before soak, inches	4.584	4.584	4.584
Height After Soak, inches	4.585	4.579	4.584
Swell, % (negative indicates settlement)	0.02	-0.11	0
Bearing Ratio, 0.100 penetration, %	11	26	45
Bearing Ratio, 0.200 penetration, %	10	22	38

According to Figure 30, increased amount of stabilizer in the mix does not increase the CBR in a dry density range of 85 and 120 pcf. Above a dry density of about 110 pcf for the mixtures, the CBR increased with high amounts of stabilizer. Figures 31 and 32 show that as the cure time increases, so does the CBR.

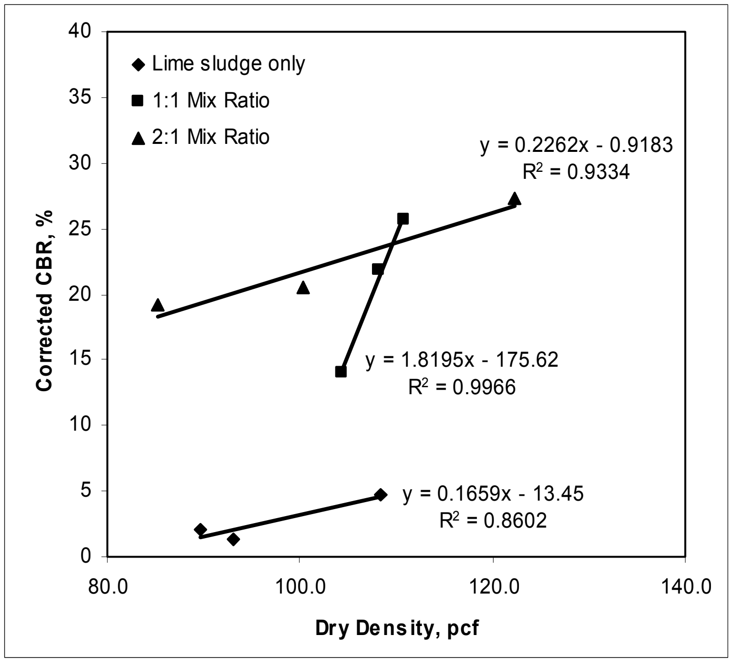

Figure 30: Effect of Additive amount in CBR Tests

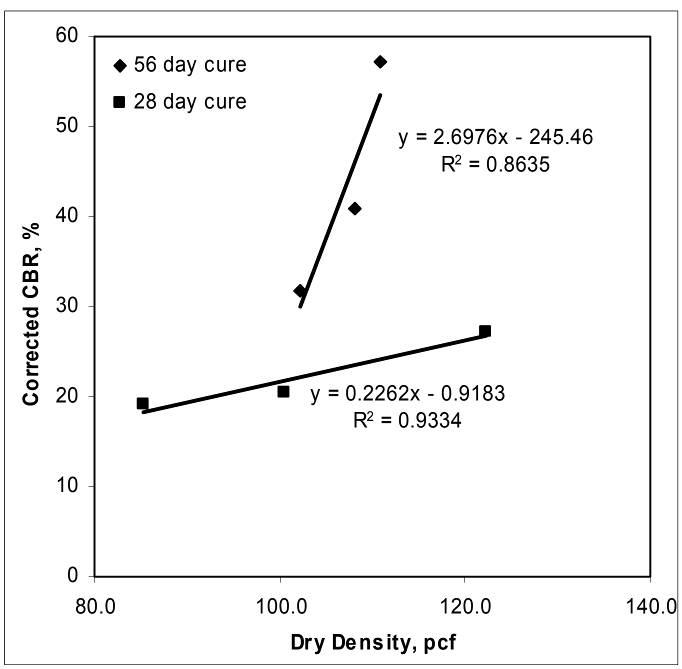

Figure 31: Effect of Cure Time on CBR, Lime Sludge to Fly Ash Ratio of 2:1

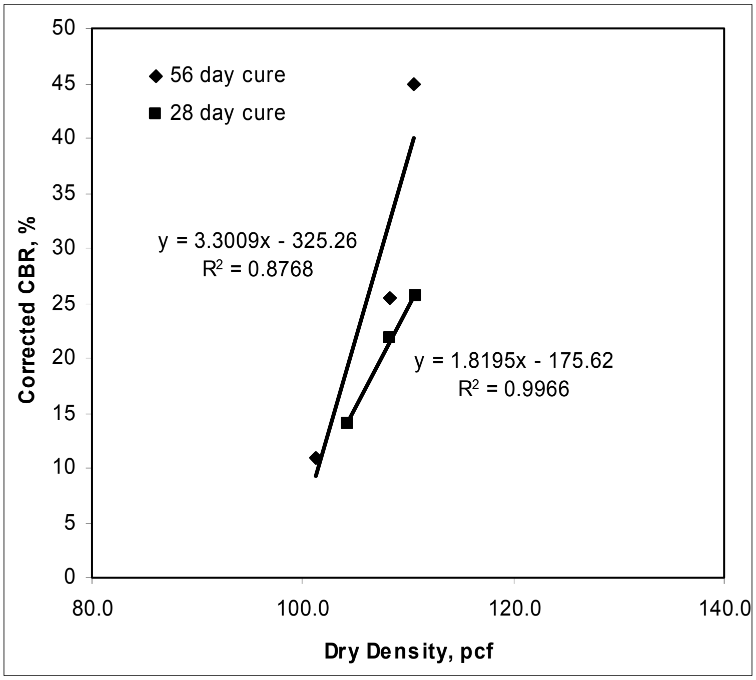

Figure 32: Effect of Cure time on CBR, Lime Sludge to Fly Ash Ratio of 1:1

Durability of Lime Sludge Mixtures

Figure 30 demonstrates how freezing and thawing can take its toll on specimens (these were not brushed). As seen on Tables 12 and 13, the results of the first set of durability tests showed that the freeze/thaw test is the most aggressive.

Table 12 shows a set of results from a brushed wet-dry durability test. These ratios reference on the table were used as the boundaries in the unconfined compressive strength testing (Figures 19, 20, 21). Table 12 shows that only the high ratio mixes survived twelve cycles. A soil-cement loss of more than 5% indicates poor durability, so these specimens did not fare well with values well above that guideline. Table 13 shows results from a brushed set of specimens that endured the freeze-thaw test. No specimen made it all the way through 12 cycles of freeze-thaw testing.

Table 13 shows that the amount of stabilizer positively affects the durability of the mix. However, the stabilizer amounts were too low to adequately illustrate the effect of additive in a brushed specimen. Volume change and soil-cement losses were still too high.

Figure 33: Wet/dry durability test samples after
12 cycles of being worked over with a Steel Brush

Figure 34: Freeze/thaw durability test in progress

Figure 35: Comparison of specimens (left, center) after
freeze/thaw tests with a steel cylinder (right) that is
the same size as the specimens were initially

Table 12: Mass Loss During Wet/Dry Durability Tests

Wet Dry Identification	Moisture Content %	Density (g/cm^3)	Soil-Cement Loss %	No. Cycles until ultimate Fail
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

Table 13: Mass Loss During Freeze/Thaw Durability Tests

Freeze Thaw Identification	Moisture Content %	Density (g/cm^3)	Soil-Cement Loss %	No. Cycles until ultimate fail
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

Table 14: Freeze/Thaw Durability Testing on Lime Sludge and Ames Fly Ash

% of fly ash to Lime Sludge, based on dry wgt	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	n/a
40	Volume	30	1.65	n/a	19
40	Brush	30	1.63	100	n/a

The results demonstrate an important limitation of the mixes. While the mixes can carry sufficient compressive loads, the mixes will benefit the best from being placed below the frost line to protect them from abrasion/erosion and freezing. As a practical example, a highway off-ramp's core can be made of the mixes, and then a topsoil cover material with vegetation can be placed on it so that the depth of the frost zone occurs in the topsoil layer. Further investigation with regards to durability has been started on a larger scale at a test embankment at the Ames Water Treatment Plant. This testing needs to be continued during the entire winter and spring to evaluate freeze-thaw cycles.

Hydraulic Conductivity

Tables 15 and 16 summarize the results of two test sets for hydraulic conductivity. The gradient used during the tests was about 5.1. 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 data below suggest that lime sludge stabilized with fly ash lowers the hydraulic conductivity.

The values for hydraulic conductivity fall within the range of the values published in literature. According to Bowles (1997), clean gravel and sand mixtures range from 10E-02 cm/s to 10E-05 cm/s, sand silt mixtures range from 10E-05 cm/s to 10E-09, and clays range from 10E-09 cm/s to 10E-11 cm/s. The values for the lime sludge mixtures found in Tables 15 and 16 fall within the expected range for their UCS classification.

Table 15. Hydraulic Conductivity, Lime Sludge Only

Cell	Initial Moisture %	Initial Dry Unit Weight g/cm3	Final Moisture %	Degree Sat %	Final Dry Unit Weight	Temp °C	Temp Correction	Hydraulic Conductivity cm/s
1	42	1.00	67	100	0.97	22	0.953	1.66E-05
2	42	1.00	65	100	0.97	22	0.953	1.86E-05
3	42	1.02	66	100	0.98	22	0.953	1.61E-05
							Ave	1.71E-05

Table 16. Hydraulic Conductivity, Lime Sludge to Fly Ash Ratio 1:1

Cell	Initial Moisture %	Initial Dry Unit Weight g/cm3	Final Moisture %	Degree Sat %	Final Dry Unit Weight	Temp °C	Temp Correction	Hydraulic Conductivity cm/s
1	17	1.26	40	100	1.27	23	0.931	1.07E-05
2	17	1.26	41	100	1.28	23	0.931	1.02E-05
3	17	1.25	42	100	1.26	23	0.931	1.10E-05
							Ave	1.07E-05

Construction of a Test Embankment

The process of producing the embankment was an exercise worth doing. 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 reason is valid for a contractor with no experience in road construction, but for the crews that will be completing the large scale projects that this application aims to serve, controlling additive amounts and moisture content during sub-base construction should be a standard practice. To show that it is not very complicated, an engineering graduate student and a few heavy equipment operators, with no prior construction experience with fly ash stabilization or compaction, constructed the test embankment.

Overall, the embankment 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 36 through 39 show a few important steps in the process. In Figure 36, 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 to control the flow of the ash and the dust generated when the ash was poured.

Figure 36: Pouring Fly Ash on a Lime Sludge Bed

Figure 37 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 (it sets up in about 20 minutes) the mix was immediately placed and compacted after mixing. This reaction varies for different fly ashes and retardants can also be used to slow the reaction if necessary. In this case, there was area available adjacent to the construction site for mixing lime sludge and fly ash.

Figure 37: Mixing Lime Sludge and Fly Ash

Figure 38 shows the vibrating pad foot compaction machine used to compact the mix. The embankment was built in 5 lifts. The thickness of each lift was about 10 inches after placement and 7 to 8 inches after compaction. Figure 39 shows the embankment 7 days after construction. The topsoil available on site, which coincidentally consisted of mostly bottom ash, was placed on the embankment over a four inch thickness and packed down with the treads of the miniature loader.

Figure 38: Compacting the test embankment

Figure 39: Test embankment with topsoil cover after 7 days

Conclusions

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 strength for fill and does not exhibit any stabilizing qualities (like portland cement or fly ash). However, lime sludge alone does exhibit a high friction angle in direct shear tests.

As expected, higher additions of portland cement or Class C fly ash generally resulted in higher unconfined compressive strengths, friction angles, and CBR values of stabilized lime sludge mixtures. The moisture content range for recommended for these mixes is 30% to 45% (77% to 69% solids concentration, respectively), but using a moisture content specific to the stabilizer being used is best. Adding more stabilizer does not result in higher residual shear strength once cementation bonds were broken.

Lime sludge and lime sludge mixes amended with fly ash result in high CBR values for a material with a Unified Classification System symbol of ML. Increasing cure time resulted in higher values for unconfined compressive strength, friction angle, and CBR values of stabilized lime sludge mixtures. The recommended minimum cure time for these mixtures is 28 days.

Lime sludge was combined with loess soil, concrete sand, and bottom ash to produce satisfactory strength results for construction fill. However, an important limitation of the lime sludge and the mixes tested here is its lack of durability through weather extremes. It must be protected from freezing, thawing and abrasion/erosion. The method of using an economical fill material at the bottom of an embankment and covering it with a weather-resistant material is not new and often used in places with temperate climates.

Hydraulic conductivity values averaged out to 1.71E-05 cm/s for lime sludge alone and 1.07E-05 cm/s for a 1 part to 1 part (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 1E-07 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.

Further testing of the constructed embankment at the Ames Water Treatment Plant will be required to establish whether there are any environmental concerns and how the materials stand up to weathering with respect to wet and dry cycles and particularly freeze thaw conditions.

General Conclusions

- Feasibility tests for using the lime sludge product in cement manufacture, SO_x control in coal combustion, and wastewater neutralization had positive results. Each one of these applications could be further investigated for more positive results given changes to the facilities that would use the product. The ultimate possibilities for application will depend on the proximity of end users of these applications.
- Further investigation regarding the use of the product for dust control on gravel roads is not recommended.
- The product must be dewatered and dried for use in all of the applications discussed. The recommended range minimum level of dryness for the product is 50% moisture content (67% solids concentration). The lowest moisture content required by the applications discussed was 2% (98% solids concentration).
- The most promising application during the last two years was using the product in construction fill material.
- 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 strength for fill and does not exhibit any stabilizing qualities (like portland cement or fly ash). However, lime sludge alone does exhibit a high friction angle in direct shear tests.
- As expected, higher additions of portland cement or Class C fly ash generally resulted in higher unconfined compressive strengths, friction angles, and CBR values of stabilized lime sludge mixtures. The moisture content range recommended for these mixes is 30% to 45% (77% to 69% solids concentration, respectively), but using a moisture content specific to the stabilizer being used is best. Adding more stabilizer does not result in higher residual shear strength once cementation bonds were broken.
- Lime sludge and lime sludge mixes amended with fly ash result in high CBR values for a material with a Unified Classification System symbol of ML. Increasing cure time resulted in higher values for unconfined compressive strength, friction angle, and CBR values of stabilized lime sludge mixtures. The recommended minimum cure time for these mixtures is 28 days.
- Lime sludge was combined with loess soil, concrete sand, and bottom ash to produce satisfactory strength results for construction fill. However, an important limitation of the lime sludge and the mixes tested here is its lack of durability through weather extremes. It must be protected from freezing, thawing and abrasion/erosion. The method of using an economical fill material at the bottom of an embankment and covering it with a weather-resistant material is not new and often used in places with temperate climates.
- Hydraulic conductivity values averaged out to 1.71E-05 cm/s for lime sludge alone and 1.07E-05 cm/s for a 1 part to 1 part (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 1E-07 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 construct embankments with the product with little problem.

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