Pozzolan Stabilized Subgrades

Nebraska Department of Roads
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16. Abstract

Samples of seven Nebraska soils were collected and tested for optimum moisture content and maximum dry density in their natural state. Soils were then tested for maximum dry density, optimum moisture content and unconfined compressive strength after being stabilized with specified percentages (by weight) of hydrated lime, fly ash and cement kiln dust (CKD). After an optimal percentage of each pozzolan had been determined for each soil type based upon unconfined compressive strength, cohesive soils were tested for durability using swell, freezing-thawing and wet-dry testing procedures. Pozzolans were found to be effective in reducing the Atterberg Limits of all soils to a greater or lesser extent. Addition of CKD produced the greatest gains in unconfined compressive strength for most soils. Hydrated lime performed better than the other two pozzolans for controlling swell. Other test results varied with the type of soil and the type and percentage of pozzolan used. Recommendations for optimal percentage of each pozzolan (by weight) for each soil type were determined and are included in the recommendations. Laboratory testing of resilient modulus for nine stabilized soil samples was completed and is included. Three values for resilient modulus based upon testing with a Geogauge were determined and researchers attempted to correlate those with resilient values obtained from laboratory tests.

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Chapter 1

Introduction

Poor quality of subgrade soil can result in inadequate pavement support, which stresses pavement structure and reduces the lifespan of both rigid and flexible pavement. Cementitious additives such as lime, fly ash and cement kiln dust (CKD) can be incorporated into subgrade soils to improve their strength and stability. This process is called subgrade stabilization; the cementitious additives used are commonly referred to as pozzolans. The Nebraska Department of Roads (NDOR) encourages the use of subgrade stabilization as this process creates an improved foundation for pavements which allows construction activities to be completed in less time. Contractors now must develop a pozzolan mix design for each project on an "as needed" basis. There exists no published NDOR standard for the design or construction of pozzolan-stabilized subgrades.

Objective of This Research

This research investigated the performance of lime, cement kiln dust (CKD) and fly ash for use as stabilization agents with a variety of Nebraska soils. It will provide guidance and a draft set of specifications for incorporating these pozzolans into Nebraska soils to improve soil stability, increase soil strength and reduce the swell characteristics of subgrades.

Expected Benefits of this Study

Early pavement deterioration due to improper concentration of pozzolan, inappropriate methods of application and/or mixing, early traffic loading, and improper curing of stabilized soil will decrease. Use of locally available, recycled materials will increase. Autogenous healing of subgrade cracks is greater for pozzolan-stabilized subgrades, which will extend the life of both rigid and flexible pavements.

The results of this research can be shared with contractors, posted on the NDOR website or disseminated to other parties at the NDOR's discretion. Dissemination of this information will provide contractors and NDOR personnel with alternatives that can be used to improve subgrades for long-term or short-term use. This study could result in significant savings in pavement cost, particularly with regard to shoulders along some State highways. Lime, fly ash or CKD stabilization can be used to increase soil strength beneath road shoulders to the extent that a base course may prove unnecessary, resulting in significant savings.

Chapter 2

Literature Review

Methods and materials associated with pozzolan soil stabilization were reviewed and the pertinent information is discussed later in this chapter. Pozzolans researched included fly ash, Cement Kiln Dust (CKD), and hydrated lime.

2.1 Fly Ash

Approximately 1100 million tons of coal are consumed each year by coal fired electric plants in the United States (DOE 2004). Burning coal produces over 68 million tons of fly ash each year, of which only 32% is used for commercial applications (American Coal Association 2003). The demand for electricity is expected to increase, which will result in increased consumption of coal and increased production of fly ash.

Burning of coal in electric or steam plants produces fly ash and bottom ash. Bottom ash, sometimes referred to as wet bottom boiler slag, is the coarse particles that fall to the bottom of the combustion chamber. Lighter particles, termed fly ash, remain suspended and are removed by particulate emission control devices. Fly ash is stored in silos or other bulk storage facilities. Equipment and procedures for handling fly ash are similar to those for handling Portland cement products. Typically, fly ash is finer than Portland cement and lime. It consists of silt-sized particles, which are generally spherical, ranging in size between 10 and 100 micron. One of the important properties contributing to pozzolanic reactivity of fly ash is its fineness. Fly ash typically consists of oxides of silicon, aluminum iron and calcium. Present in a lesser degree are oxides of magnesium, potassium, sodium, titanium and sulfur (American Coal Association 2003).

A study by Lin, Lin, and Luo (2007) showed the effects of both sludge ash and fly ash. The research indicated that both sludge ash and fly ash reduced the PI and swelling characteristics of many soils. The addition of 8% fly ash increased the CBR value from a 2 (native) to 15, and when 16% fly ash was added the CBR value increased to 20. With the addition of 8% and 16% fly ash, the Unconfined Compressive Strength (UCS) was 241% and 275% higher than the native soil.

Ferguson (1993) has shown that addition of fly ash can decrease the plasticity of heavy clay soils, which then decreases the swell potential of the soil. Cocka (2001) found that with increasing fly ash percentages, plasticity and swell potential of soil decrease. Fly ash percentages greater than 20% are comparable to a lime percentage of 8% for reducing plasticity and swell in soils containing 85% kaolinite and 15% bentonite. Unconfined compressive strength of stabilized soils with fly ash are normally around 100 psi, but can be as high as 500 psi depending on fly ash properties, percentage, and soil type (Ferguson 1993, Ferguson and Leverson 1999). Milburn and Parsons (2004) showed that with the addition of fly ash there can be a significant increase in UCS while decreasing the PI and swelling potential for soils in Kansas.

2.2 Cement Kiln Dust

While manufacturing Portland cement material containing lime, silica, alumina, are iron are blended together and sent into the upper end of a kiln. The kiln rotates as materials pass through. Fuel is introduced into the lower end of the kiln producing temperatures between 1400º C to 1650º C, which changes the materials into a cement clinker. During this process a small percentage of dust, cement kiln dust (CKD), is captured as waste. CKD has become a major concern as it poses significant disposal problem; more than 3.85 million tons of CKD is created annually in the United States (Todres et al. 1992).

The chemical and physical properties of CKD can vary dramatically from plant to plant depending on the types of raw materials and collection process used. The CKD used from the same kiln and producing the same cement can be relatively consistent (Baghdadi et al 1995).

Cement kiln dust has been used in numerous applications. Eoery (1972) researched a stabilization process by which CKD and other waste products could meet environmental and engineering specifications for stabilized fill. This stabilization process used various combinations of CKD, fly ash, slag cement, and Portland cement, to achieve the desired engineering properties. Morgan and Halff (1984) researched the effectiveness of oil sludge solidification with CKD, using field data obtained from a landfill site. CKD was found to be more efficient and cost effective as a solidifying agent when compared to lime, fly ash and sulfur. Baghdadi (1990) found that the use of CKD in kaolinitic clay increased the compressive strength considerably. With the addition of 16% CKD, the UCS of the clay increased from 30 psi to 161 psi. For highly plastic clay Bagdadi (1990) showed a decrease in the PI of approximately 60% with the addition of 8% CKD.

When 11% CKD was incorporated with dune sand plus hot mix asphalt and used for pavement bases, Fatani and Khan (1990) reported stability improvements approximately ten times that of native soil. Zaman (1992) found an increase in UCS and a reduction in PI with the addition of 15% CKD. Research performed by Azad (1998) suggests that CKD can be an effective modifier for soils having moderate to low plasticity, but indicated that for soils with higher PI, higher CKD percentages do not result in significantly greater improvement.

In a field study was performed by FHWA at the Oklahoma PRACHIC 12(1) Guy Sandy Area of Chickasaw National Recreation Area (Marquez 1997), CKD was found beneficial and resulted in a $25,000 savings. Ten percent CKD was used for the project, which lowered the PI from 28 to 15. The CBR value increased from slightly less than ten without CKD to around fifty when CKD was added.

2.3 Hydrated Lime

Lime is produced by the crushing of limestone and heating it to a high temperature. Powder produced from this process is then sold as some form of lime. Lime reacts chemically and physically with soil, providing both textural and chemical changes. Lime is most commonly used in treating clay soils to enhance their engineering properties (Parsons 2001).

Lime generally should be used on soils with a PI of ten or higher; it is dependant on sodium clay for a reaction to take place (Perry et al 1995). A study by Currin (l976), sponsored by the U. S. Air Force, recognized PI and percent fines as simple and effective components in selecting soils for lime stabilization. Soil being considered for lime stabilization should possess at least 25% passing the #200 sieve and have a PI of at least ten. Epps, Dunlap, Gallaway, and Currin (1971) studied lime stabilization and found that, in general, a soil should contain at least 7% clay and a PI of at least ten before using lime as a stabilization agent.

Several studies have illustrated beneficial changes in soil properties resulting from addition of hydrated lime. Little (1995) studied the effects of lime and found that the addition of lime caused a significant reduction in the PI. Jan and Walker (1963) stated that as the percentage of hydrated lime increases the PI is reduced. Laguros (1965) found that with the addition of 6% hydrated lime, PI was reduced from 47 to 15. Hydrated lime reduced the potential for swell in fine grained soils (Kennedy et al 1987). Little (1998) found that with the addition of lime a significant reduction in plasticity index and swell potential occurred. Addition of lime results in long-term strength gain when stabilizing soils and aggregates. Research performed (Thompson, 1970, Petry and McAllister, 1990, and Little 1995) verified soil can be effectively modified with addition of lime, which reduces PI, swell potential and improves strength. Research by Dempsey and Thompson (1968) and by Little (1995) demonstrated strength loss due to wet-dry testing and freeze-thaw testing in soils and aggregates is usually significantly improved by lime stabilization. Thompson and Robnett (1976) showed that high lime reactive and low lime reactive soils both benefited from lime stabilization, and there was a substantial improvement in resistance to freeze-thaw damage for both types of soils.

Chapter 3

Procedures and Methods

This section contains a description of materials and methods used in this study. Standard test procedures were used wherever possible. Modifications to standard procedures are annotated. Non-standard procedures used in this study are described in detail.

3.1 Materials

3.1.1 Soil

Seven different classifications of native soil were selected and tested at the NDOR's request. Native soils types were selected based upon their Nebraska Group Index (NGI), a soil classification system similar to the AASHTO Group Index. The seven native soils roughly correspond to the soil types shown in Table 1. Also Table 1 shows the Nebraska group indices associated with each soil type by the NDOR.

Table 1: Soil Types

Soil Type	NGI
Gravel	-2
Fine sand	-1 to 1
Sandy silt	2 to 7
Loess	8 to 12
Loess/till	13 to 14
Till	15 to 21
Shale/alluvium	22 to 24

The native and pozzolan modified soil properties were determined for each soil type according to ASTM standards listed in Table 2 and described in the following sections.

Table 2: ASTM Standard Test Methods

Test Method	ASTM
Dry Preparation of Soil Samples	D 421
Wetting and Drying of Compacted Soil Cement Mixtures	D 559
Freezing and Thawing of Compacted Soil-Cement Mixtures	D 560
Laboratory Compaction of Soil Using Standard Effort	D 698
Material in Soil Finer than No. 200 Sieve	D 1140
Compressive Strength of Soil-Cement	D 1633
Liquid Limit, Plastic Limit, and Plasticity Index of Soils	D 4318
One-Dimensional Swell	D 4546
Unconfined Compressive Strength of Compacted Soil-Lime Mixtures	D 5102
Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization	D 6276

3.1.2 Pozzolans

The pozzolans used in this stabilization study included hydrated lime, class C fly ash, and cement kiln dust (CKD). Hydrated lime was obtained from Pete Lien & Sons, Inc. located in Rapid City, SD. Class C fly ash was obtained from Nebraska Ash Company in Omaha, NE and the CKD was obtained from Ash Grove Cement Co. in Chanute, KS. The additives were mixed with each of the soil types in various percentages and each soil's engineering properties were subsequently tested.

The hydrated lime percentages were determined using ASTM D 6276 procedures. Three percentages (10, 13, and 15% by weight) of class C fly ash were tested with each soil type. Three percentages of CKD tested with each soil type included 5, 7, and 9%. These respective amounts were evaluated using procedures listed in Table 2 to determine an optimum percentage of each pozzolan for use with each soil type.

3.2 Laboratory Procedures

3.2.1 Soil Preparation

After soil samples were collected and transported to the lab, each was air dried in large pans and broken down over a No. 4 sieve. Samples of soil were dried at 75º F and ground until particles passed the No. 40 sieve. The Atterberg Limits (ASTM D 4318) were determined, including the liquid limit (LL) and plastic limit (PL), as well as the plasticity index (PI). The Atterberg Limits were measured for all native soils to verify that acceptable samples had been collected (the NGI fell within the expected range).

3.2.2 Moisture Density Testing

3.2.2.1 Hydrated Lime

The percent of hydrated lime added to each soil type was determined using ASTM D 6276 procedures. The soil and hydrated lime were mixed together dry, water was then added to bring the moisture content to the desired percentage, and the samples were allowed to mellow for 48 hours. After the mellowing period, the soil-lime mixtures were then compacted in a standard 4-inch proctor mold using a standard proctor hammer (ASTM D 698). Specimens were then weighed and cured at 75º F near 100% humidity for six days. At the end of the six days, the specimens were cured in the open atmosphere at 75º F for 24 hours. Unconfined compression tests were then performed using procedures described in ASTM D 5102.

3.2.2.2 Fly Ash

The optimum percent of fly ash for each of the soil types was determined using trial percentages of 10, 13, and 15% by weight. The soil was initially mixed with water to a predetermined moisture content and allowed to mellow for 16 hours. The soil and fly ash were then mixed together and compacted in a standard 4-inch proctor mold using standard compaction effort (ASTM D 698). After the specimens were weighed, they were cured at 75º F near 100% humidity for six days. Specimens were then cured in the open atmosphere at 75º F for 24 hours. At the end of the 24 hour period, unconfined compression tests were performed (ASTM D 1633). Data was subsequently plotted. The optimum fly ash percentage used for each of the soil types was determined based upon maximum unconfined compressive strength of each sample.

3.2.2.3 CKD

The optimum percent of CKD incorporated in each soil type was determined based upon the three most common CKD percentages incorporated into Nebraska soils by the NDOR. Five, seven, and nine percent CKD was blended with each soil type. The soil was initially mixed with water to a predetermined moisture content and allowed to cure for 16 hours. The soil and CKD were then mixed together and compacted in a standard 4-inch proctor mold using the standard compaction effort (ASTM D 698). Specimens were then weighed and cured at 75º F near 100% humidity for six days. Next each was cured for 24 hours in open atmosphere at 75º F. Unconfined compression tests were performed in accordance with ASTM D 1633. Test data was then plotted to determine the optimum CKD percentage for each soil type.

3.2.3 Atterberg Limits Testing

3.2.3.1 Hydrated Lime

The Atterberg Limits were determined for native soil and for the soil-lime mixtures. The optimum percentage of hydrated lime, as determined by ASTM D 6276, was mixed with dry soil and water so the moisture content was above the liquid limit. The soil-lime mixture was placed in a sealed plastic bag and allowed to mellow for 48 hours at room temperature. After 48 hours, the liquid limit, plastic limit and plasticity index of the soil-lime mixtures were determined in accordance with ASTM D 4318 procedures.

3.2.3.2 Fly Ash

The Atterberg Limits were determined for the native soil and for the soil-fly ash mixture. The optimum percentage of fly ash, based upon maximum unconfined compressive strength, was mixed with dry soil. Water was then added and the soil-fly ash mixture was covered and allowed to mellow for one hour. After one hour, the liquid limit, plastic limit, and plasticity index of the soil-fly ash mixture were determined in accordance with ASTM D 4318 procedures.

3.2.3.2 CKD

The Atterberg Limits were determined for the native soil and for the soil-CKD mixture. The optimum percentage of CKD, based upon maximum unconfined compressive strength, was mixed with dry soil. Water was added and the soil-CKD mixture was covered and allowed to mellow for one hour. After one hour, the liquid limit, plastic limit, and plasticity index of the soil-CKD mixture were determined in accordance with ASTM D 4318 procedures.

3.2.4 Swell Testing

3.2.4.1 Native Soils

Swell testing was conducted in accordance with ASTM D 4546 procedures. The optimum moisture content was added to each of the soil types and allowed to mellow for 16 hours. The specimens were then prepared at the optimum moisture content for each native soil and compacted in a standard 4-inch proctor mold, using the standard compaction effort (ASTM D 698). After each specimen was compacted, porous stones were placed on both sides and the specimens were submerged in water. Measurements of vertical deformation were recorded for up to 72 hours. Free swell is expressed as the change in specimen height divided by the initial specimen height multiplied by 100. Swell testing was not performed on soil types that will not exhibit swell characteristics, such as the gravel and fine sand.

3.2.4.2 Hydrated Lime

The swell test procedure for hydrated lime samples was similar to the native soil swell test procedure. The main difference was the soil-lime specimens were mixed at the optimum moisture content and optimum percent hydrated lime and allowed to mellow for 48 hours instead of 16 hours. The swell test was then conducted using procedures identical to the native swell test.

3.2.4.3 Fly ash and CKD

The swell test for fly ash and CKD were performed using procedures identical to as the native swell test with one exception. The soil and water were blended at the optimum moisture content and allowed to mellow for a period of 16 hours, just as when testing native soils. The specimens were then mixed with the optimum percent of each pozzolan and allowed to mellow for one hour. The fly ash and CKD swell testing was otherwise identical to testing of the native soil specimens.

3.2.5 Freeze-Thaw Testing

The freezing and thawing of compacted soil-cement mixtures tests were conducted using ASTM D 560 procedures. Two identical specimens were prepared according to ASTM D 698 for each soil-pozzolan mixture. Hydrated lime was mixed with the soil type at optimum moisture content and optimum hydrated lime percentage and allowed to mellow for 48 hours. Fly ash and CKD were mixed with the soil type at optimum moisture content and optimum pozzolan percentage and allowed to mellow for one hour prior to compaction. After specimens were prepared, each was placed in a moist room for seven days.

Each freeze-thaw cycle consisted of placing specimens in a freezer at –10º F for 24 hours. The specimens are then placed in a moist room at 70º F and relative humidity of 100% for 23 hours. After removal of a specimen from the moist room, each was weighed and measured. The second specimen was given two firm strokes on all areas with a wire brush. Eighteen to twenty strokes were required to cover the sides of the specimen and four strokes were required to cover the ends. This constitutes one cycle (48 hours) of freezing and thawing. The test procedure continued until twelve cycles were completed or until the brushed specimen disintegrated. Percent soil loss is determined by using original calculated oven-dry mass minus final corrected oven-dry mass divided by original oven-dry mass times 100.

3.2.6 Wet-Dry Testing

Wetting and drying testing of compacted soil-cement mixtures was conducted in accordance with ASTM D 560 procedures. Two identical specimens were prepared according to ASTM D 698 for each soil-additive mixture. Hydrated lime was mixed with the soil type at the optimum moisture content and optimum percent lime and allowed to mellow for 48 hours. Fly ash and CKD were mixed with each soil type at the optimum moisture content and optimum pozzolan percentage and allowed to mellow for one hour prior to compaction. After specimens were prepared, each was placed in a moist room for seven days prior to wet/dry testing.

Each wet-dry cycle began with five hours submerged in a water bath at room temperature. The specimen was then removed and the mass and dimensions of the first specimen recorded. Both specimens were placed in an oven at 160º F for 42 hours. The weight and dimensions of specimen number one was recorded. The second specimen was given two firm strokes on the sides and ends with a wire brush. Eighteen to twenty strokes were required to cover the sides of the specimen and four strokes were required to cover the ends. This constituted one cycle (48 hours) of wetting and drying. This process was continued for twelve cycles or until the brushed specimen disintegrated completely.

Percent soil loss is determined by using original calculated oven-dry mass minus final corrected oven-dry mass divided by original oven-dry mass times 100.

3.2.7 Unconfined Compressive Strength

Specimens were prepared and compacted at each of the points shown on the moisture-density curves and cured at 75º F near 100% humidity for 6 days, then at 75º F for 24 hours, totaling seven days of curing . Specimens were then tested using ASTM D 1633 and D 5102 procedures to determine their unconfined compressive strength. The procedures used differ from ASTM only in cure time. ASTM 5102 procedures require that the samples remain in the moisture room for the entire seven days before the unconfined compressive strength determined.

3.2.8 Soil Stiffness Testing

Specimens were compacted in a standard 6-inch proctor mold using the standard compaction effort (ASTM D 698). A Humboldt Stiffness Gauge (GeoGauge) was used to evaluate loess, till, and shale. The GeoGauge readings were taken for native and pozzolan mixtures at various times up to 28 days.

The GeoGauge is a hand-portable instrument that provides simple, rapid and precise means of directly measuring layer stiffness and Young's modulus of compacted soils. The GeoGauge measures the impedance at the surface of the soil. In other words, it measures the stress imparted to the surface and the resulting surface velocity as a function of time.

3.2.9 Resilient Modulus Testing

Samples of loess, till, and shale were sent to Terracon Consultants, Inc. in Oklahoma City, OK for evaluation of resilient modulus testing AASHTO T 309-99. Results of all resilient modulus testing are located in Appendix E.

Chapter 4

Results

Tests were performed on seven different soils subsequently stabilized using three different pozzolans. This chapter includes native soil properties and properties of native soils blended with pozzolans.

4.1 Native Soil Properties and Pozzolan Percentages

Native soil properties were determined using the Atterberg Limits, sieve analysis, laboratory compaction using standard Proctor procedures. Seven soils were tested and classified into their respective Nebraska Group Index (NGI). A summary of the test results is shown in Table 3.

Table 3: Properties of Native Soils

Soil Properties	Gravel	Fine Sand	Sandy/ Silt	Loess	Loess/ Till	Till	Shale
NGI	-2	0	5	8	13	15	26
Liquid Limit	NP	NP	25	31	42	45	65
Plasticity Index	NP	NP	5	9	21	25	43
% Minus #200	6	18	60	96	85	90	92
Max Dry Density, lb/ft^3	112.5	111.5	111.2	98.5	94.5	105.5	94.5
Optimum Moisture, %	10.0	11.5	14.9	20.0	22.0	20.0	22.0

4.2 Atterberg Limits

The Atterberg Limits test results for both native and soil/pozzolan mixture are tabulated in Table 4. Gravel and fine sand were not tested for Atterberg Limits, because these soils are non-plastic (NP).

Table 4: Atterberg Limits Results

Soil	Gravel		Fine Sand		Sandy Silt		Loess		Loess/Till		Till		Shale	
NGI	-2		0		5		8		13		8		13	
Atterburg Limits	LL	PI	LL	PI	LL	PI	LL	PI	LL	PI	LL	PI	LL	PI
Native	NP	NP	NP	NP	25	5	31	9	42	21	44	28	65	43
Lime														
2%	NP	NP	NP	NP	-	-	-	-	-	-	-	-	-	-
4%	-	-	-	-	NP	NP	-	-	-	-	-	-	-	-
5%	-	-	-	-	-	-	NP	NP	NP	NP	NP	NP	-	-
6%	-	-	-	-	-	-	-	-	-	-	-	-	NP	NP
Fly Ash														
10%	NP	NP	NP	NP	NP	NP	30	6	39	9	47	17	62	32
13%	NP	NP	NP	NP	NP	NP	27	4	38	5	44	15	59	28
15%	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	59	29
CKD														
5%	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	49	13	64	20
7%	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
9%	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP

Native sandy silt liquid limit (LL) and plasticity index (PI) values were 25 and 5 respectively. The addition of hydrated lime, fly ash, and CKD to sandy silt reduced the plasticity index from a value of 5 to non-plastic (NP) for all percentages of pozzolans.

Native loess had LL and PI values of 31 and 9. When 5% hydrated lime was added, the PI was NP. The PI value was reduced to 6 when 10% fly ash was added, to a

PI of 4 when 13% fly ash was added, and to NP at 15% fly ash. When CKD was added to loess at 5, 7 and 9%, the PI was NP for all percentages.

The native loess/till had LL and PI values of 42 and 21 respectively. At 5% hydrated lime the PI was NP. With the addition of fly ash at 10% the PI value was 9, at 13% the PI value was 5 and loess/till was NP when 15% fly ash was added.

Till had LL and PI values of 44 and 28 in its native state. With the addition of hydrated lime, the PI was NP. When fly ash was added at 10% the PI was 17, at 13% till had a PI of 15, and at 15% fly ash it was NP. When CKD was incorporated with till at 5%, the PI was 13, and with the addition of 7% and 9% CKD, the PI of till was NP.

Native shale had LL and PI values of 65 and 43 respectively. The addition of hydrated lime at 6% reduced the PI to NP. Fly ash at 10, 13, and 15% had a PI range of 32 to 29 not having much of a difference at any percentage. When 5% CKD was added the PI value was 20, when 7% and 9% were added the shale was NP.

4.3 Maximum Dry Density and Optimum Moisture Content

Optimum moisture content and maximum dry density for each native soil and soil/pozzolan mixture are shown in Table 5. A typical maximum dry density curve is presented in Figure 1. Maximum dry density curves for each soil type, native and with each pozzolan mixture, are located in Appendix A.

Table 5: Maximum Dry Density and Optimum Moisture Contents

	Native		Fly Ash 10%		Fly Ash 13%		Fly Ash 15%		CKD 5%		CKD 7%		CKD 9%		Hydrated Lime		
Soil Type	omc	Density lb/ft³	omc	Density lb/ft³	omc	Density lb/ft³	omc	Density lb/ft³	omc	Density lb/ft³	omc	Density lb/ft³	omc	Density lb/ft³	omc	Density lb/ft³	Hydrated Lime %
Gravel	10.0	112.5	8.0	122.0	8.5	122.5	8.5	125.0	9.5	122.0	8.5	115.0	9.0	116.5	9.0	115.5	2
Fine Sand	11.5	111.5	9.5	119.0	8.5	120.5	8.5	121.0	9.5	116.0	8.5	117.0	9.0	115.5	10.5	115.5	2
Sandy-Silt	15.0	111.0	14.0	115.0	12.0	115.0	11.0	115.0	15.0	94.5	15.4	95.0	15.0	96.0	16.0	106.5	4
Loess	20.0	98.5	18.5	101.0	18.0	101.0	18.0	101.5	20.5	95.5	22.0	95.5	18.5	95.0	27.0	87.5	5
Loess/Till	22.0	94.5	20.5	103.5	18.5	102.5	18.0	103.0	20.0	94.0	21.0	94.5	21.5	94.0	27.5	88.5	5
Till	20.0	105.5	17.5	107.0	16.5	108.0	15.5	109.0	18.5	103.5	17.5	102.0	17.5	102.5	19.5	92.5	5
Shale	22.0	94.5	23.5	95.0	22.5	95.0	24.0	96.5	26.0	91.0	22.5	91.0	22.5	92.5	25.5	84.0	6

Densities of the native sand soils (NGI's of -2 to 5) ranged from 111.0 lb/ft^3 to 112.5 lb/ft^3 while optimum moisture contents ranged from 10 to 15%. When mixed with fly ash, maximum dry densities increased and optimum moisture contents decreased. When mixed with CKD, the gravel and fine sand dry densities increased and optimum moisture contents decreased. Dry density of sandy silt, when mixed with CKD, decreased and optimum moisture contents were virtually identical to the native soil sample. Dry densities of gravel and fine sand when mixed with hydrated lime increased, while optimum moisture contents decreased. Sandy silt dry density was lower when mixed with hydrated lime but optimum moisture content was higher.

Native loess and loess/till (NGI's of 8 to 13) soils had densities ranging from 94.5 lb/ft^3 to 98.5 lb/ft^3 and optimum moisture contents ranging from 20 to 22%. When mixed with fly ash maximum dry density increased and optimum moisture content decreased. Maximum dry density of loess was lower when mixed with CKD. Optimum moisture contents varied depending upon the percentage of CKD. Maximum dry density of loess/till was the same when mixed with CKD and optimum moisture contents were slightly lower. When mixed with hydrated lime, both loess and loess/till densities were lower and optimum moisture contents were significantly higher.

Density of native till soil (NGI of 15) was 105.5 lb/ft^3 at optimum moisture content of 20%. When fly ash was added, density of till increased and optimum moisture content decreased. When mixed with CKD, till density and optimum moisture contents decreased. Addition of hydrated lime significantly lowered dry density while optimum moisture content was only slightly lower.

Native shale (NGI of 26) had a maximum dry density of 94.5 lb/ft^3 and an optimum moisture content of 22%. When mixed with fly ash, maximum density was slightly higher and optimum moisture content increased. Addition of CKD decreased maximum dry density while optimum moisture content increased. When mixed with hydrated lime, maximum dry density was significantly lower and optimum moisture content was higher.

Figure 1: Maximum Dry Density Curve

4.4 Unconfined Compressive Strength

Unconfined compressive strength data (Figure 2) were measured on specimens compacted in accordance with standard Proctor procedures (ASTM D 698) to create a moisture-density curve. Unconfined compressive strengths were not tested for gravel (NGI of –2) and fine sand (NGI of –1 to 1) as these specimens represent non-cohesive soils that have little to no unconfined compressive strength. Each compacted standard proctor specimen was cured in a moist room for six days, then cured in air for one day (NDOR 2006 procedure). Unconfined compressive strength was determined in accordance with ASTM D 5102 and ASTM D 1633. An example of the unconfined compressive strength curve used to determine maximum strength is shown in Figure 3.

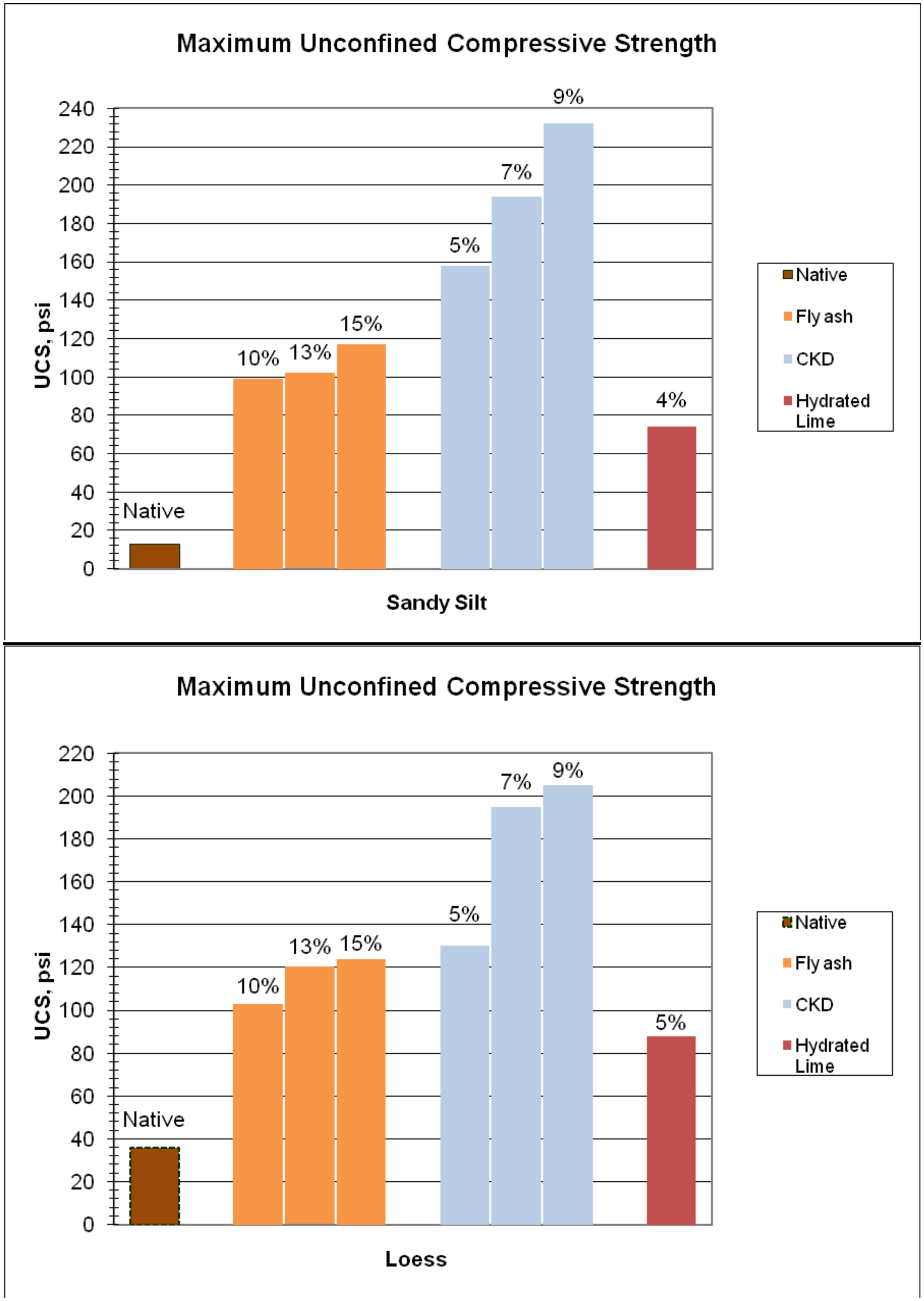
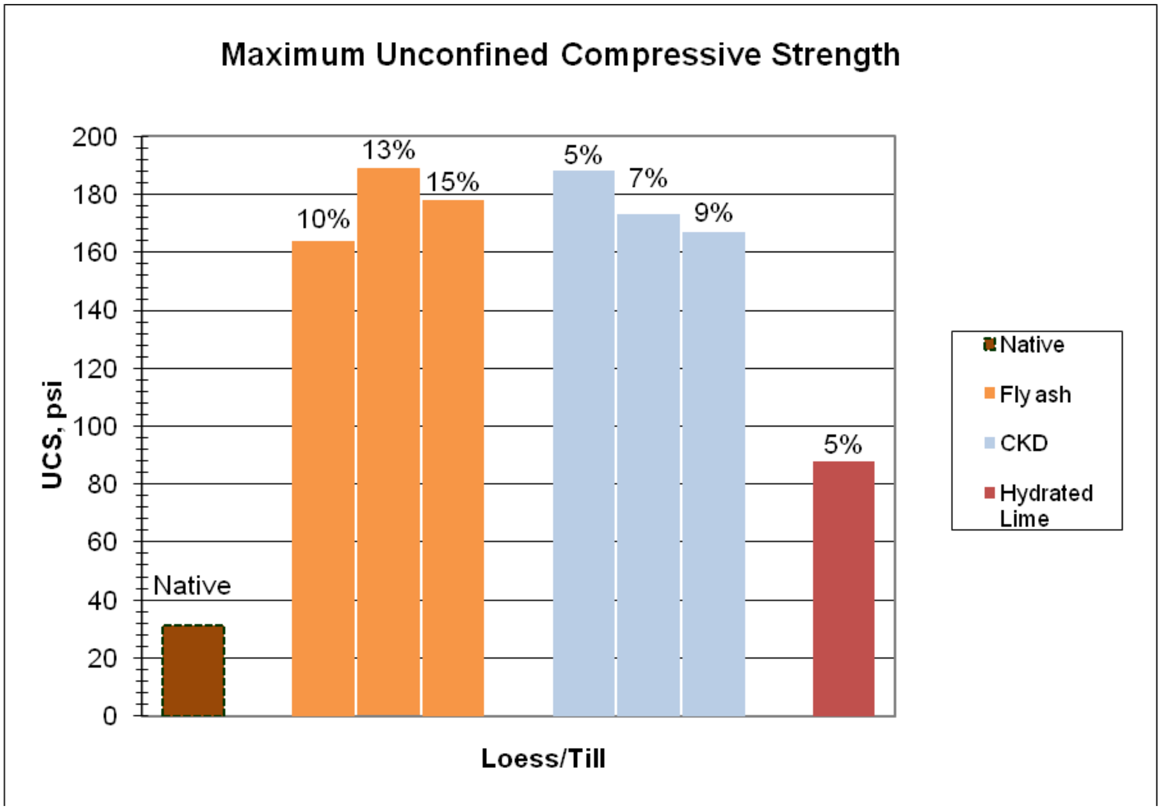


Figure 2: Maximum Unconfined Compressive Strength for Each Soil Type



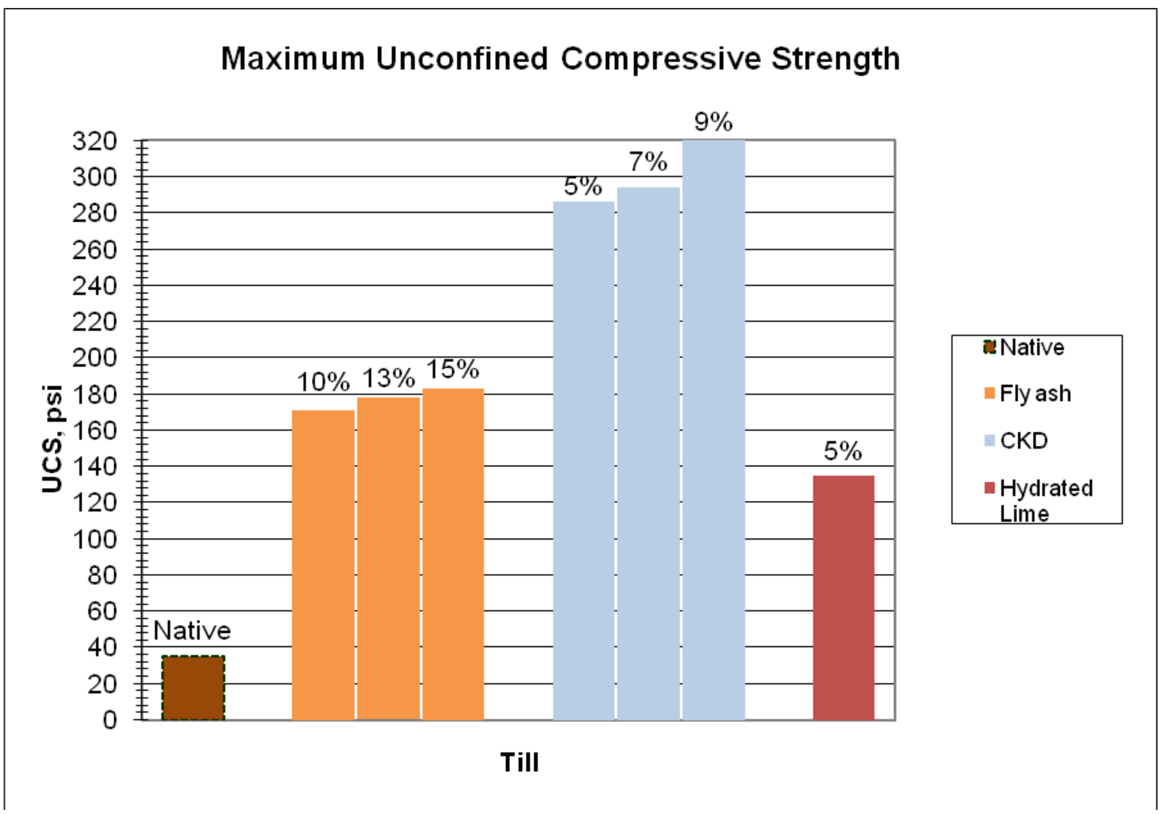


Figure 2 (continued): Maximum UCS for Each Soil Type

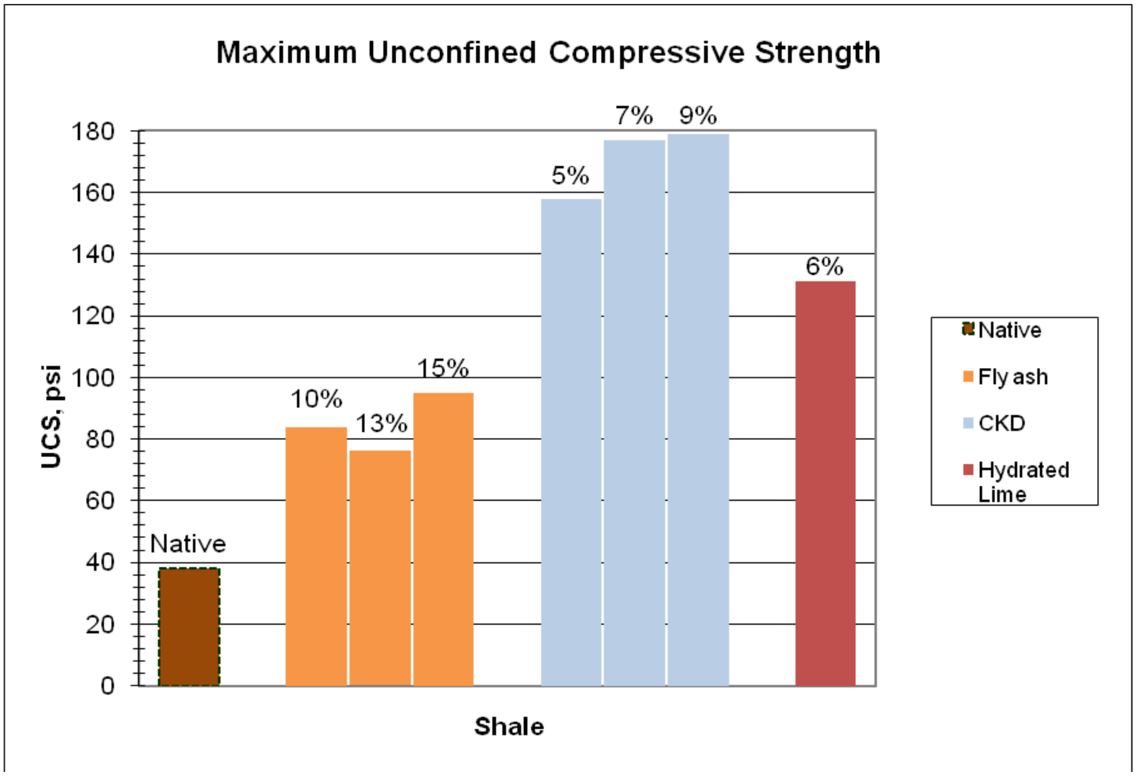


Figure 2 (continued): Maximum UCS for Each Soil Type

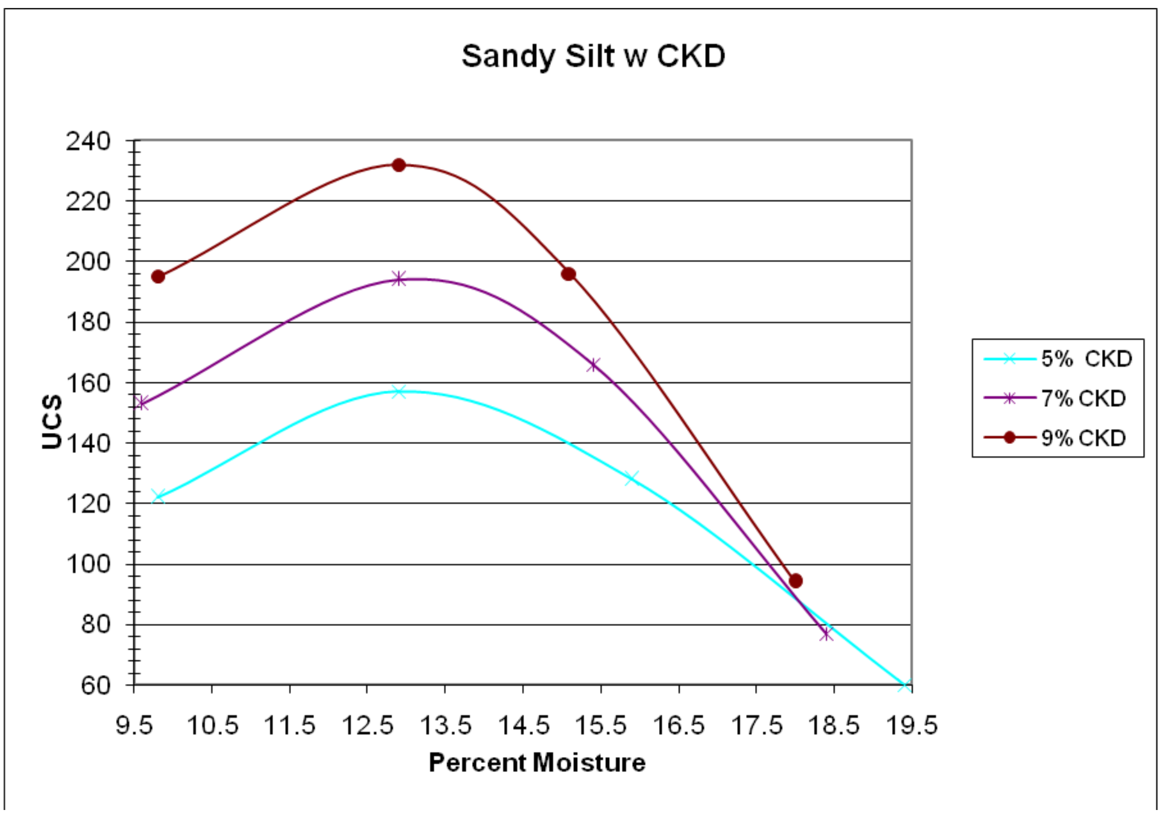


Figure 3: Unconfined Compressive Strength Curves for Sandy Silt w/CKD

Sandy-silt soil when mixed with fly ash had a 900% increase in strength with regard to native soil. Addition of fly ash to loess and loess/till increased strength 344% and 610% respectively. When mixed with fly ash, till and shale had increases of 522% and 250% respectively over the strength of native soil.

Addition of CKD to sandy-silt increased strength 1785% over that exhibited by the native soil. Loess and loess/till when mixed with CKD increased strength 569% and 606% respectively. Till and shale had increases of 914% and 471% respectively over native strength when mixed with CKD.

When mixed with hydrated lime, strength of sandy-silt increased 569% over the native value. Loess and loess/till when mixed with hydrated lime increased 244% and 284% over native strength. Till and shale had increases of 386% and 345% over native strength when mixed with hydrated lime.

4.5 Determination of Optimum Pozzolan Percentages

Figure 4 shows maximum unconfined compressive strength of each soil/pozzolan mixture on a chart with moisture content plotted against unconfined compressive strength (UCS). Maximum dry density (MDD) is plotted versus moisture content as a second vertical axis on the same chart. The soil type shown is sandy-silt mixed with 5, 7, or 9% CKD. Range of optimum moisture content is determined by creating an enclosure that ranges from ± 2% moisture content. Optimum pozzolan percentage is that percentage which maximizes unconfined compressive strength. Strength curves for each soil/pozzolan mixture are located in Appendix B. Once optimum pozzolan percentages were determined, freeze/ thaw, wet/dry, and swell testing were performed at optimum percentages of pozzolan. Optimum pozzolan percentages are summarized in Table 6.

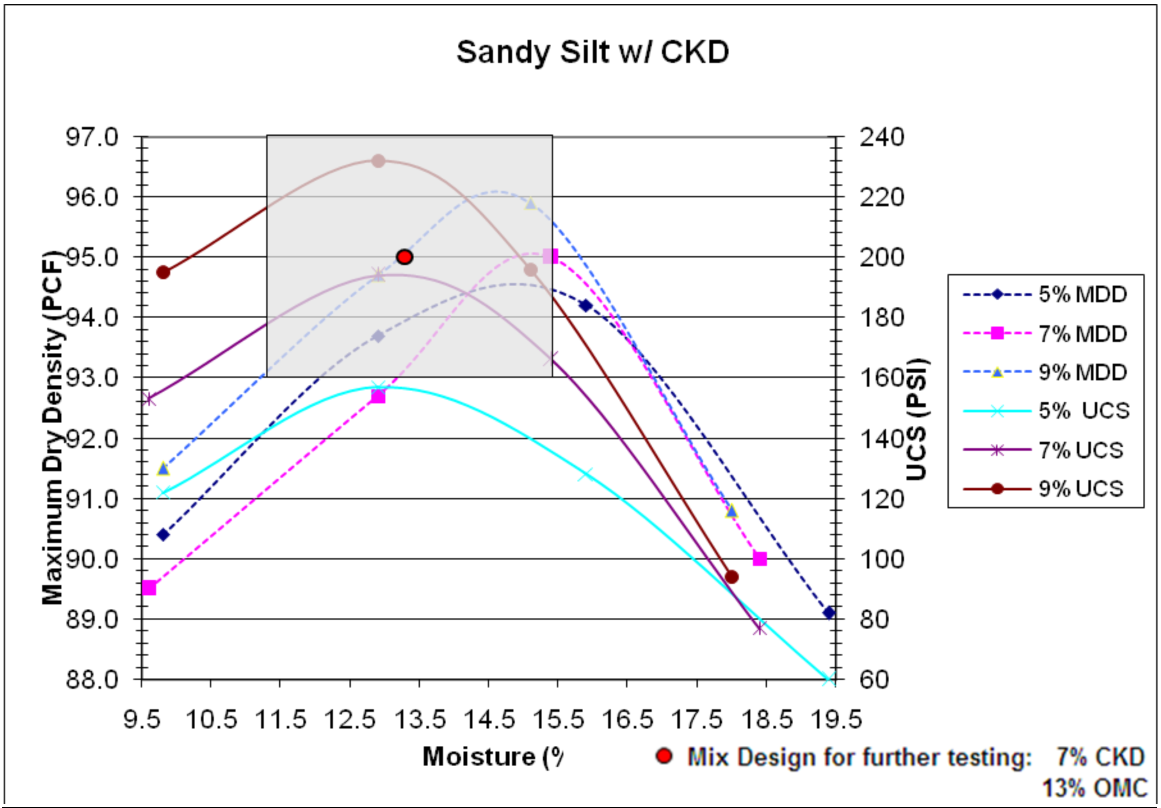


Figure 4: Moisture Content vs. Unconfined Compressive Strength

Table 6: Optimum Pozzolan Percentages for Various Soil Types

SOIL	Pozzolan Percentages		
	Fly Ash	CKD	Hydrated Lime
Gravel	10	5	2
Fine Sand	10	5	2
Sandy-Silt	14	7	4
Loess	12	7	5
Loess/Till	13	6	5
Till	12	7	5
Shale	14	6	6

4.6 Freeze-Thaw Testing

Freeze-thaw test results are shown in Figure 5. A soil shown with 100% loss indicates that those specimens did not complete the 12 cycle freeze-thaw test. Table 7 shows the number of freeze-thaw cycles that each soil completed. CKD performed best of all pozzolans in the freeze-thaw test, having the most loss in sandy-silt soil of 45% and the least loss in loess/till with 13%. Fly ash had a 100% loss in sandy-silt, loess, and shale soils. The hydrated lime had a 100% loss with sandy-silt and shale soils. Gravel and fine sands were not evaluated using freeze-thaw procedures because compaction instead of addition of pozzolan is the more common method of stabilizing these soils.

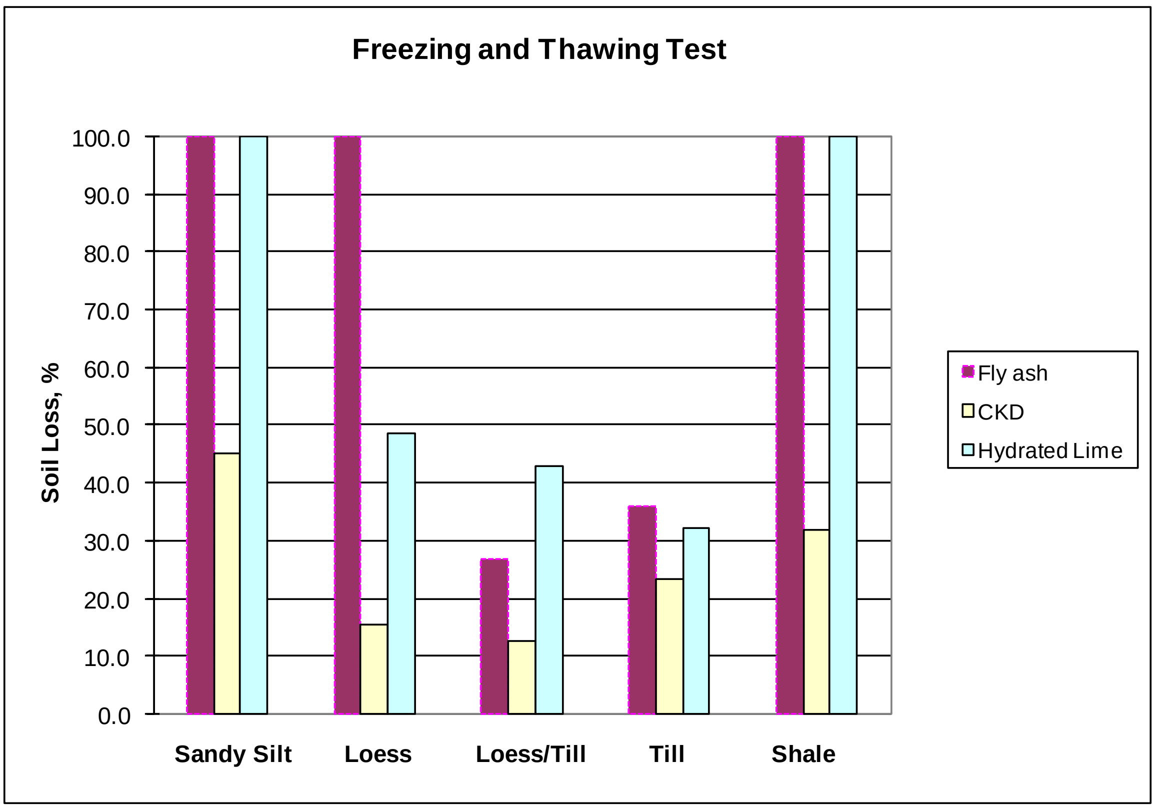


Figure 5: Freeze-Thaw Soil Loss after Twelve Cycles.

Table 7: Freeze-Thaw Cycles Completed

SOIL	Cycles Completed		
	Fly Ash	CKD	Hydrated Lime
Sandy-Silt	11	12	9
Loess	8	12	12
Loess/Till	12	12	12
Till	12	12	7
Shale	10	12	11

Figure 6: Freeze-Thaw Test Specimens

4.7 Wet-Dry Testing

Results of wet-dry testing are shown in Figure 7. In this aggressive testing procedure, 60% of the specimens disintegrated before completing twelve cycles specified. Specimens indicating 100% loss (Figure 7) did not complete a twelve cycle wet-dry test. Table 8 shows the number of cycles completed by each specimen. The gravel and fine sands (non-cohesive soils) were not evaluated using this test procedure.

Sandy-silt soil performed best of all soils, with each pozzolan completing the twelve cycle wet-dry test. Loess and shale with all three pozzolans failed prior to completing a 12 cycle wet-dry test, having losses of 33, 11 and 34% respectively for fly ash, CKD, and hydrated lime. Loess/till soil mixed with CKD and hydrated lime completed a 12 cycle wet-dry test with 27 and 22% loss. Till soil mixed with CKD was the only pozzolan to complete a 12 cycle wet-dry test with a loss 55%.

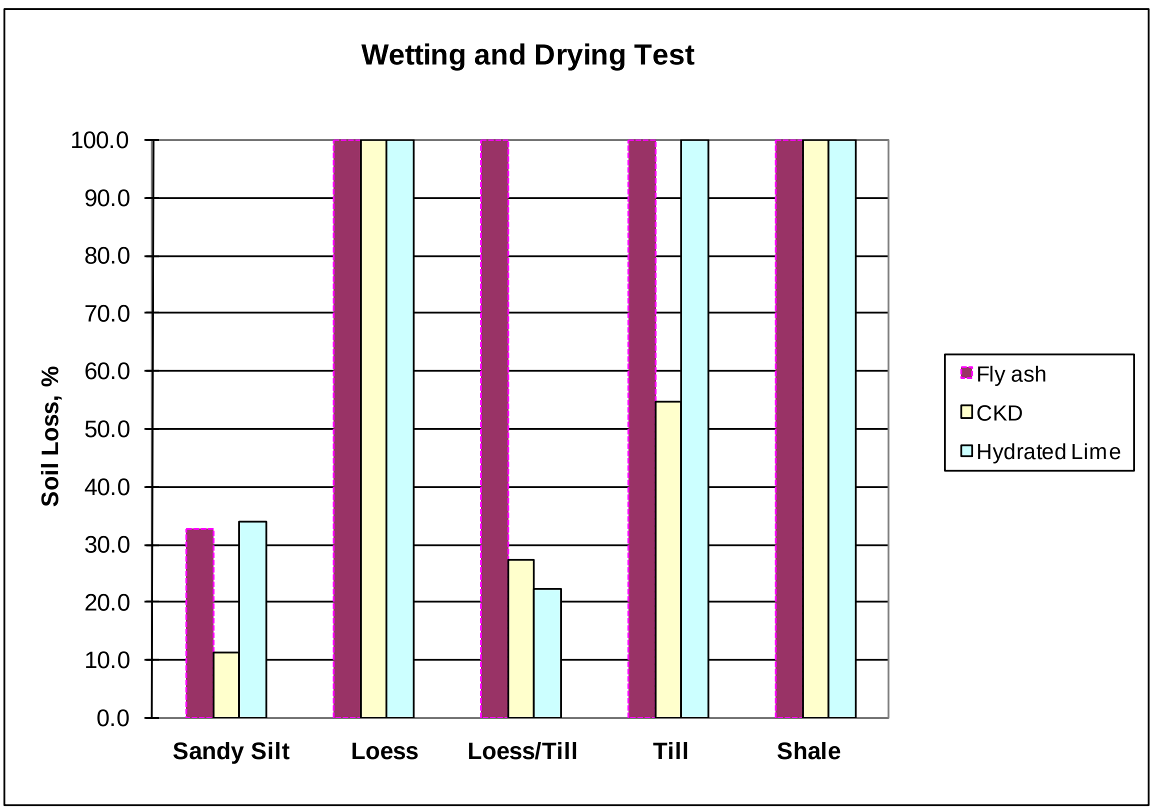


Figure 7: Wet-Dry Loss after 12 cycles

Table 8: Wet-Dry Cycles Completed

SOIL	Cycles Completed		
	Fly Ash	CKD	Hydrated Lime
Sandy-Silt	12	12	12
Loess	8	8	7
Loess/Till	6	12	12
Till	5	12	6
Shale	2	4	3

Figure 8: Wet-Dry Test Specimens

4.8 Swell Testing

Free swell test results are shown in Figure 9. This figure shows amount of free swell observed with native soils and soils mixed with optimum pozzolan percentages. Gravel and fine sand were not tested because these types of soil do not exhibit swell characteristics.

All soils exhibited a reduction in swelling when mixed with each pozzolan. Hydrated lime performed best, resulting in the greatest reduction in swelling with three different types of soil. Swell reduction from CKD was significant but when compared to hydrated lime resulted in more swell reduction only with shale. Fly ash reduced swell in all soils types but outperformed hydrated lime and CKD only in sandy silt.

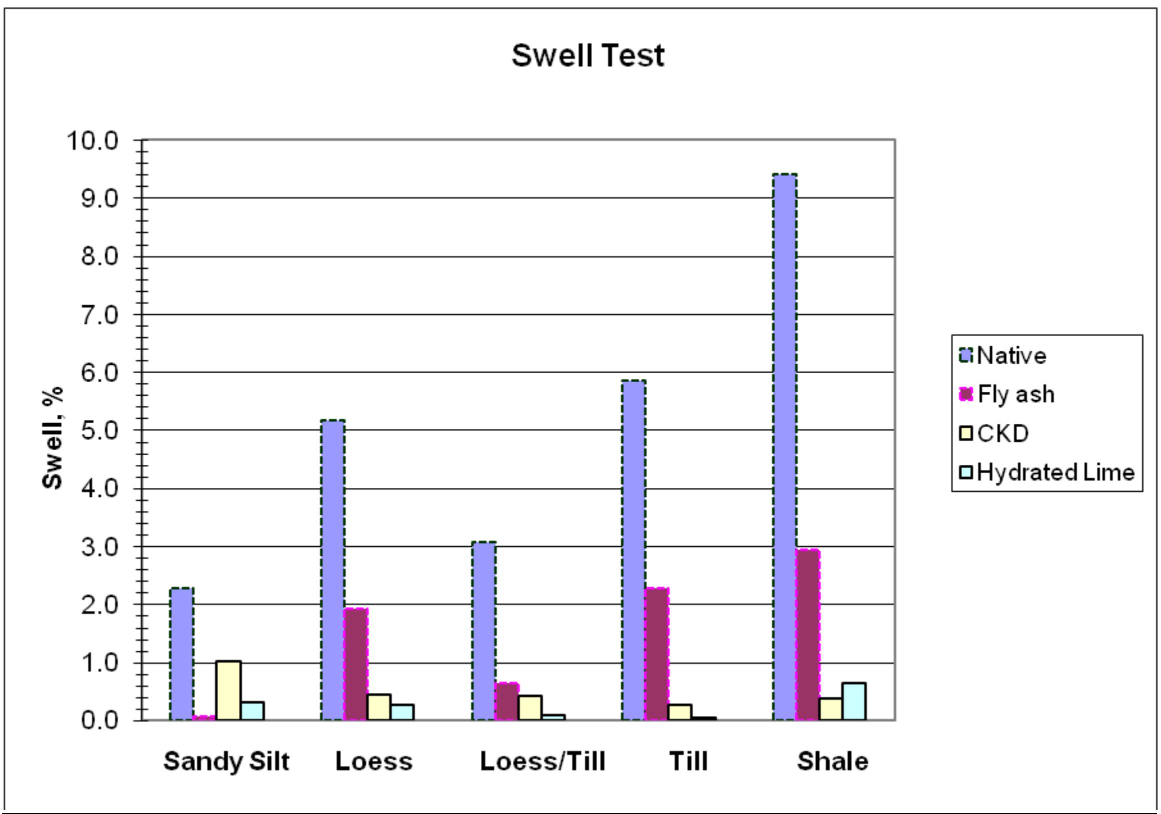


Figure 9: Swell Test Results

4.8 Resilient Modulus and GeoGauge Testing

Resilient modulus and GeoGauge results are listed in Table 9. Terracon Consultants, Inc. performed resilient modulus testing on loess, till, and shale. Readings were then taken with the GeoGauge on loess, till, and shale that were cured for 28 days.

Table 9: Resilient Modulus and GeoGauge Results

Pozzolan	Loess		Till		Shale	
	Resilient Modulus (psi)	GeoGauge (psi)	Resilient Modulus (psi)	GeoGauge (psi)	Resilient Modulus (psi)	GeoGauge (psi)
Fly ash	6,443	8,817	20,546	13,355	9,006	17,782
CKD	21,699	21,024	30,724	20,127	24,317	13,041
Hydrated Lime	9,033	15,120	25,265	19,958	20,183	21,026

Chapter 5

Cost Analysis Example

This section compares the cost of using each pozzolan to stabilize a section of subgrade a one mile in length by twelve feet in width. Costs for two pozzolans were calculated using average unit prices from the Nebraska Department of Roads for the 2006 construction season. Average unit cost for hydrated lime in Nebraska for the 2006 season was $132.11/ton while fly ash average unit cost in Nebraska for the 2006 season was $30.85/ton. A price was obtained for CKD delivered to Lincoln, NE of $75.00/ton. Lincoln represents the approximate center of the southeast corner of Nebraska, which is near the maximum economical delivery range from Ash Grove Cement in Chanute, KS. Table 9 was developed using these prices. An average percentage was used for each pozzolan i.e. fly ash evaluated at 10, 13, and 15% to determine optimum percentage, used 13% for cost comparison purposes.

Table 10: Cost Comparison of Pozzolans for One Mile Section of Roadway 12' Wide

Pozzolan Type	Percentage Pozzolan	Average Unit Wt. lb/ft³	Application lb/yd² @ 12" depth	Tons Per mile[1]	Average Cost Per Ton[2]	Cost Per mile[3]
Fly Ash	13	107	125.19	441	$ 30.85	$ 13,604.85
CKD	7	97	61.11	215	$ 74.75	$ 16,071.25
Hydrated Lime	5	94	42.30	149	$ 132.31	$ 19,714.19

1. One mile section 5280 ft long x 12 ft wide = 7040 yd²
2. CKD cost is based upon product delivery to Lincoln, NE (2006), while fly ash and hydrated lime are based on NDOR 2006 average unit prices across the State.
3. These are costs for material and transportation only. Costs of incorporating product into the subgrade are not included.

From Table 9, fly ash was found to be the most economical pozzolan followed by CKD and then hydrated lime. Two of these three costs are based upon average unit price, which would be generally applicable across the entire state. A project located much closer to a specific pozzolan source (CKD in southeast Nebraska) will significantly reduce transportation costs associated with that particular pozzolan, which in many instances will make it the most competitive.

Chapter 6
Application of Pozzolans

6.1 Mixing

One main concern when performing soil stabilization is achieving thorough and uniform mixing of the soil being stabilized. One of two approaches are generally used in construction: 1) mixing is performed off-site using a continuous or batch type mixer or 2) the mixing is performed on-site. The main advantage in using off-site mixing is more uniform mixtures can be created because quantities batched can be controlled with greater accuracy than with on-site mixing. The off-site mixing may not be an option depending upon the pozzolan specified or other project requirements.

On-site mixing is the most commonly used method. This method does not require a mixing plant and can take advantage of the rapid set time of specific pozzolans. Using this method, pozzolanic material is trucked to the site by belly dump or tanker trucks and then spread directly on the subgrade. The mixing can be accomplished by either a soil stabilizer or disc. An example of a soil stabilizer is shown in figure 10. Caterpillar, for example, has two sizes of soil stabilizers, SS-250B and RM-350B. The soil stabilizer is preferable over mixing with a towed disc because it mixes the materials much more thoroughly. Stabilizers are designed with a mixing chamber and rotors assuring a complete blending of materials. Discing of materials is not recommended unless it is the sole practical method of incorporating pozzolanic material. Discing fails to provide the compete blending needed to maximize the effects of a pozzolan.

6.2 Water

The most important step during the stabilization process is adding water and monitoring the water content of the soil. Maintaining near optimum moisture content is extremely important to maximize the total effectiveness of the pozzolan and also aids in achieving proper compaction. With the moisture too low, or too high, achieving the specified density may become almost impossible.

Water is sometimes added directly to the subgrade ahead of the stabilizer. This may cause problems, destabilizing the subgrade and creating difficult conditions for the soil stabilizer.   Another method calls for adding pozzolan to the subgrade and making one or more passes with the soil stabilizer, then adding water and making more passes with the soil stabilizer. While this process works well, the number of stabilizer passes required can add significant cost. The most effective procedure is utilizing the spray bar system provided on the soil stabilizer and apply water to the pozzolan-soil mixture during the mixing process.

<u>Figure 10: Soil Stabilizer SS-250 Caterpillar</u>

6.3 Field Calculation of Pozzolan

Table 10 illustrates a sample calculation for the quantity of pozzolan to be spread across a specific area in a field situation. Each project will have unique parameters based upon depth and width of subgrade stabilized, plus the soil unit weight and percentage of pozzolan used.

Table 11: Field Calculation of Pozzolan Amount

Specified Pozzolan Percentage	10% (by weight of subgrade)
Standard Proctor Dry Unit Weight of Soil	110 lb/ft^3
Depth of Stabilized Section	12 inches
Weight of Pozzolan	20 tons/truck load
Rate of Pozzolan Distribution	(110 lb/ft^3)(10%)(1 ft) = 11.00 lb/ft^2
Area to be Covered by Truck Load of Pozzolan	(20 tons x 2,000 lb)/11.00 lb/ft^2 = 3636 ft^2
Length of Spread for 12 ft Wide Section	3636 ft^2/12 ft = 303 ft

Chapter 7

Conclusions

1. Fly ash, CKD, and hydrated lime were all effective to a greater or lesser extent in improving Atterberg Limits for most soils in this study. Each soil had some improvement in the plasticity index with each pozzolan. Hydrated lime added at the percentages determined from Eades and Grim test made each soil type non-plastic. When CKD was evaluated, only the till and shale had PI values at 5% CKD. While fly ash did reduce the PI values of all soil types, the soils still retained some plasticity in loess, loess/till, and till at 10 and 13%, at 15% the PI was non-plastic. When added to shale even at 15% soil samples still retained PI values.
2. Unconfined compressive strength gains were realized with the addition of fly ash, CKD, or hydrated lime to most soils. CKD outperformed the other pozzolans with the highest strength for all soil types, fly ash performed next best (excluding shale), and the lowest strength gain by created by addition of hydrated lime (except with shale).
3. Native swell values lowered immensely with the addition of fly ash, CKD, or hydrated lime. Hydrated lime performed best overall followed by the CKD. While fly ash did reduce swelling in all soil types, it did not perform as well as hydrated lime and CKD for most soil types.
4. In freeze-thaw testing, CKD performed better than the others pozzolans, showing the least soil loss. Fly ash and hydrated lime had an intermediate amount of loss for most soils, the only difference being with loess where fly ash had a much higher soil loss.
5. Wet-dry testing had the best overall performance by CKD when evaluating both soil loss and number of cycles completed. All pozzolans had 100% soil loss on loess and shale. Fly ash had 100% soil loss on all soil types except for sandy silt, in which it performed better than hydrated lime, but not CKD. The CKD

outperformed the other pozzolans for sandy silt and till (only pozzolan making 12 cycles), while hydrated lime performed best for the loess/till soil.

Each soil type was evaluated for fly ash, CKD and hydrated lime, because any pozzolan could be theoretically be used to treat any type of soil . Which pozzolan would be ideal for a particular type of soil would depend on the location of the soil being treated, the degree of modification of natural properties desired, and the relative cost of the various pozzolans.

7.1 Recommendations

Gravel and Fine Sand

These two soil types will normally not be stabilized through addition of a pozzolan because of their granular nature. These soils are normally stabilized through compaction instead. Percentages of pozzolan and optimum moisture contents are shown in the Tables 11 and 12 below.

Table 12 - Optimum Moisture Content and Pozzolan Percentages for Gravel

Gravel						
Pozzolan	Optimum Native Moisture	Design				
		Pozzolan Percent	Pozzolan Moisture	Density (pcf)	UCS (psi)	Mr (psi)
Fly ash	10.0%	10.0%	8% ± 1.5	120 - 124	n/a	n/a
CKD	10.0%	5.0%	9% ± 1.5	114 - 117	n/a	n/a
Hydrated Lime	10.0%	2.0%	9% ± 1.5	114 - 116	n/a	n/a

Table 13 – Optimum Moisture Content and Pozzolan Percentages for Fine Sand

Fine Sand						
	Optimum	Design				
Pozzolan	Native Moisture	Pozzolan Percent	Pozzolan Moisture	Density (pcf)	UCS (psi)	Mr (psi)
Fly ash	11.5%	10.0%	9.5% ± 2	118 - 121	n/a	n/a
CKD	11.5%	5.0%	9.5% ± 2	112 - 116	n/a	n/a
Hydrated Lime	11.5%	2.0%	10.5% ± 2	112 - 116	n/a	n/a

Any of the three pozzolans could be used to improve the engineering properties of any of the five cohesive soils. The optimum moisture contents and recommended percentages of pozzolan for each soil type are outlined in Tables 13 to 17 which follow.

Table 14 – Optimum Moisture Content and Pozzolan Percentages for Sandy Silt

Sandy Silt						
	Optimum	Design				
Pozzolan	Native Moisture	Pozzolan Percent	Pozzolan Moisture	Density (pcf)	UCS (psi)	Mr (psi)
Fly ash	15.0%	14.0%	12% ± 2	112 - 116	90 - 120	n/a
CKD	15.0%	7.0%	13% ± 2	93 - 97	160 - 240	n/a
Hydrated Lime	15.0%	4.0%	14.5% ± 2	105 - 107	65 - 75	n/a

Table 15 - Optimum Moisture Content and Pozzolan Percentages for Loess

Loess						
Pozzolan	Optimum Native Moisture	Design				
		Pozzolan Percent	Pozzolan Moisture	Density (pcf)	UCS (psi)	Mr (psi)
Fly ash	20.0%	12.0%	19.5% ± 2	99 - 102	100 - 125	6,443
CKD	20.0%	7.0%	20% ± 2	94 - 96	170 - 210	21,699
Hydrated Lime	20.0%	5.0%	25% ± 2	86 - 88	60 - 75	9,033

Table 16 - Optimum Moisture Content and Pozzolan Percentages for Loess/Till

Loess-Till						
Pozzolan	Optimum Native Moisture	Design				
		Pozzolan Percent	Pozzolan Moisture	Density (pcf)	UCS (psi)	Mr (psi)
Fly ash	22.0%	13.0%	18% ± 2	100 - 104	140 - 190	n/a
CKD	22.0%	6.0%	20% ± 2	93 - 95	160 - 190	n/a
Hydrated Lime	22.0%	5.0%	27.5% ± 2	87 - 89	65 - 80	n/a

Table 17 - Optimum Moisture Content and Pozzolan Percentages for Till

Till						
	Optimum	Design				
Pozzolan	Native Moisture	Pozzolan Percent	Pozzolan Moisture	Density (pcf)	UCS (psi)	Mr (psi)
Fly ash	20.0%	12.0%	17% ± 2	106 - 110	145 - 195	20,546
CKD	20.0%	7.0%	18.5% ± 2	101 - 104	270 - 320	30,724
Hydrated Lime	20.0%	5.0%	18% ± 2	89.5 - 92.5	75 - 125	25,265

Table 18 - Optimum Moisture Content and Pozzolan Percentages for Shale

Shale						
	Optimum	Design				
Pozzolan	Native Moisture	Pozzolan Percent	Pozzolan Moisture	Density (pcf)	UCS (psi)	Mr (psi)
Fly ash	22.0%	14.0%	22% ± 2	94.5 - 97.0	80 - 100	9,006
CKD	22.0%	6.0%	27% ± 2	90.5 - 93.5	145 - 185	24,317
Hydrated Lime	22.0%	6.0%	25% ± 2	83.5 - 84.0	108 - 140	20,183

There are many variables to be considered when determining which pozzolan additive to use when stabilizing a specific subgrade. Factors will include the availability of and cost of various pozzolans, what type of equipment is available for application, the location of the project, and the transportation distance required for the each pozzolan, assuming they are not all from the same source. With all of these variables, it is impossible to determine a “best” pozzolan for each soil type.

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