Pozzolan Stabilized Subgrades

Nebraska Department of Roads
Research Project SPR-1 (06) 578

By

Construction Management Program
University of Nebraska
Lincoln, Nebraska 68588-0500

Timothy T. Hensley, M. Eng., P.E.
Wayne G. Jensen, Ph.D., P.E.
Charles W. Berryman, Ph.D., CPC

NDOR
Nebraska
Department of Roads

UNIVERSITY OF
Nebraska
Lincoln

Technical Report Documentation Page

1. Report No	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Pozzolan Stabilized Subgrades		5. Report Date June 2007 6. Performing Organization Code
7. Author/s Tim Hensley, Wayne Jensen and Charles Berryman		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Nebraska-Lincoln W-145 Nebraska Hall Lincoln, NE 68588-0500		10. Work Unit No. (TRAIS) 11. Contract or Grant No. SPR-1(06) 578
12. Sponsoring Organization Name and Address The Nebraska Department of Roads 1500 Highway 2 Lincoln, NE 68509-4759		13. Type of Report and Period Covered 14. Sponsoring Agency Code
15. Supplementary Notes		

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 wetting-drying test procedures. Each pozzolan was found to be effective in reducing the Atterberg Limits of all soils. 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. Laboratory testing of resilient modulus for nine pozzolan stabilized soil samples was completed by an outside agency. Values for elastic modulus based upon testing with a Geogauge were determined by the researchers for identical combinations of pozzolans and soils. Elastic modulus values from the Geogauge were subsequently compared to resilient moduli obtained from laboratory testing to compare results.

17. Key Words	18. Distribution Statement		
Pozzolan stabilized subgrade			
19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. Of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized

Acknowledgements

This study was funded by the Nebraska Department of Roads(NDOR) as a research project titled SPR-1(06) 578 "Pozzolan Stabilized Subgrades". The project was completed under the direction of Dr. Wayne Jensen and Dr. Charles Berryman at University of Nebraska-Lincoln. Tim Hensley was instrumental in completing this research as part of his graduate studies.

The authors wish to thank Robert Rea, formerly with the Materials and Research Division of the Nebraska Department of Roads, for suggesting this research project. Chris Dowding and Doug Churchwell from the Soils Section of the Materials and Research Division were instrumental in obtaining the original field samples. Many other individuals from the NDOR's Materials and Research Division also made significant contributions to this research.

TABLE OF CONTENTS

CHAPTER 1 Introduction **1**

CHAPTER 2 Literature Review **3**

2.1 Fly Ash 3

2.2 Cement Kiln Dust 4

2.3 Hydrated Lime 5

CHAPTER 3 Procedures and Methods **7**

3.1 Materials 7

3.1.1 Soil 7

3.1.2 Pozzolans 9

3.2 Laboratory Procedures 9

3.2.1 Soil Preparation 9

3.2.2 Moisture Density Testing 9

3.2.2.1 Hydrated Lime 9

3.2.2.2 Fly Ash 10

3.2.2.3 CKD 10

3.2.3 Atterberg Limits Testing 11

3.2.3.1 Hydrated Lime 11

3.2.3.2 Fly Ash 11

3.2.3.3 CKD 11

3.2.4 Swell Testing 11

3.2.4.1 Native Soils 11

3.2.4.2 Hydrated Lime 12

3.2.4.3 Fly Ash and CKD 12

3.2.5 Freezing and Thawing Tests 12

3.2.6 Wetting and Drying Tests 13

3.2.7 Unconfined Compressive Strength(UCS) 14

3.2.8 Soil Stiffness Testing 14

3.2.9 Resilient Modulus Testing 14

CHAPTER 4 Results 15

4.1 Native Soil Properties and Pozzolan Percentages 15

4.2 Atterberg Limits 15

4.3 Maximum Dry Density and Optimum Moisture Content 17

4.4 Unconfined Compressive Strength 19

4.5 Determination of Optimum Pozzolan Percentages 23

4.6 Freezing and Thawing Test Results 25

4.7 Wetting and Drying Test Results 27

4.8 Swell Testing 29

4.9 Resilient Modulus and GeoGauge Test Results 30

CHAPTER 5 Cost Analysis Example 31

CHAPTER 6 Application of Pozzolans 33

6.1 Mixing 33

6.2 Water 33

6.3 Curing and Compaction 34

6.4 Field Calculation of Pozzolan Distribution 35

CHAPTER 7 Conclusions and Recommendations 36

7.1 Conclusions 36

7.2 Recommendations 37

REFERENCES 41

APPENDIX A Using pH to Estimate Soil-Lime Percentage 44

APPENDIX B Moisture Density Relationship Curves 49

APPENDIX C Unconfined Compressive Strength Curves 61

APPENDIX D Optimum Pozzolan Percentages with Optimum Moisture Contents.....70

APPENDIX E Resilient Modulus Test Data.....79

APPENDIX F Field Manual for Soil Stabilization 107

LIST OF TABLES

Table 1: Soil Types 7

Table 2: ASTM Standard Test Methods 8

Table 3: Properties of Native Soils 15

Table 4: Atterberg Limits Results 16

Table 5: Maximum Dry Density and Optimum Moisture Content 17

Table 6: Optimum Pozzolan Percentages for Various Soil Types 24

Table 7: Freezing and Thawing Cycles Completed 26

Table 8: Wetting and Drying Cycles Completed 28

Table 9: Resilient Modulus and GeoGauge Test Results 30

Table 10: Cost Comparison of Pozzolans for One Mile Section of Roadway 12' Wide 31

Table 11: Field Calculation for Pozzolan Distribution 35

Table 12: Optimum Moisture Content and Pozzolan Percentages for Gravel 37

Table 13: Optimum Moisture Content and Pozzolan Percentages for Fine Sand 38

Table 14: Optimum Moisture Content and Pozzolan Percentages for Sandy Silt 38

Table 15: Optimum Moisture Content and Pozzolan Percentages for Loess 39

Table 16: Optimum Moisture Content and Pozzolan Percentages for Loess/Till 39

Table 17: Optimum Moisture Content and Pozzolan Percentages for Till 40

Table 18: Optimum Moisture Content and Pozzolan Percentages for Shale 40

LIST OF FIGURES

Figure 1: Maximum Dry Density Curve 19

Figure 2: Maximum Unconfined Compressive Strength for Each Soil Type 20

Figure 3: Unconfined Compressive Strength Curves for Sandy Silt 22

Figure 4: Moisture Content vs. Unconfined Compressive Strength 24

Figure 5: Freezing and Thawing Test Results 25

Figure 6: Freezing and Thawing Test Specimens 26

Figure 7: Wetting and Drying Test Results 27

Figure 8: Wetting and Drying Test Specimens 28

Figure 9: Swell Test Results 29

Figure 10: Soil Stabilizer SS-250 Caterpillar 34

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 must currently 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.

This research investigated the performance of lime, cement kiln dust and fly ash for use as stabilization agents with a variety of Nebraska soils. It provides 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.

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 if the recommendations in this report are incorporated into NDOR procedures. 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 several 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 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. Placing shoulders without a base course will result in significant savings in time, labor and materials.

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, 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 Ash 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 microns. 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 Ash Association 2003).

A study by Lin, Lin, and Luo (2007) showed the effects of both sludge ash and fly ash. Their research indicated that both sludge ash and fly ash reduce the plasticity index (PI) and swelling characteristics of many soils. The addition of 8% fly ash increased the California Bearing Ratio (CBR) value from 2 (native) to 15; 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 value for 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.

2.2 Cement Kiln Dust

While manufacturing Portland cement, lime, silica, alumina, are iron are blended together before entering 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 1400° C to 1650° C, which transforms the materials into a cement clinker. During this process a small percentage of dust, referred to as cement kiln dust, is captured as waste. CKD has become a major concern as it poses significant disposal problem; roughly 3.85 million tons of CKD are created annually in the United States (Todres 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. CKD from the same kiln producing the same cement can be relatively consistent with regard to chemical and physical properties (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 and hot mix asphalt and used for a pavement base, Fatani and Khan (1990) reported stability improvements approximately ten times that of native soil. Zaman et al. (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 Pra-Chic 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 subgrade stabilization, which lowered the PI from 28 to 15. The CBR increased from slightly less than ten without CKD to around fifty when ten percent 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 et al. 2001).

Lime should generally 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 et al.

(1976), 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 have 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, the PI was reduced from 47 to 15. Hydrated lime reduces 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 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 and swell while improving 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 as part of this study. Native soils types were selected based upon Nebraska Group Index (NGI), a soil classification system similar to the AASHTO Group Index. One of the seven native soils tested falls within each NGI range shown in Table 1.

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
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

The ASTM standards shown above were retrieved from one of the following:

ASTM Cement; Lime; Gypsum (2005). Standard Test Methods. Annual Book of ASTM Standards, Vol. 04.01, ASTM, Philadelphia, PA.

ASTM Soil and Rock D 420 – D 5611 (2005). Standard Test Methods. Annual Book of ASTM Standards, Vol. 04.08, ASTM, Philadelphia, PA.

ASTM Soil and Rock D 5714 - latest (2005). Standard Test Methods. Annual Book of ASTM Standards, Vol. 04.09, ASTM, Philadelphia, PA

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 Company in Chanute, KS. The additives were mixed with each of the soil types in various percentages and each soil's engineering properties were subsequently evaluated.

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%. Percentages of each pozzolan 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 (ASTM D 421). Samples of soil were dried at 75° 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. Results for each soil type are included in Appendix A. 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 75° F near 100% humidity for six days. At the end of the six days, the specimens were cured in the open atmosphere at 75° 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 the specified 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 75° F near 100% humidity for six days. Specimens were then cured in the open atmosphere at 75° 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 the specified 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 75° F near 100% humidity for six days. Next each was cured for 24 hours in open atmosphere at 75° 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.

3.2.3.3 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. Water needed to reach the optimum moisture content was added to each of the soils, mixed 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, similar to testing procedures used with 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 Freezing and Thawing Tests

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 –10° F for 24 hours. The specimens are then placed in a moist room at 70° 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 Wetting and Drying Tests

Wetting and drying testing of compacted soil-cement mixtures was conducted in accordance with ASTM D 559 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 160° 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 (UCS)

Specimens were prepared and compacted at each of the points shown on the moisture-density curves and cured at 75° F near 100% humidity for 6 days, then at 75° F for 24 hours, totaling seven days of curing (NDOR 2006). Specimens were then tested using ASTM D 1633 or D 5102 procedures to determine their unconfined compressive strength. The procedures used differ from ASTM standards only in cure time. ASTM 5102 procedures require the samples to 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 samples of loess, till, and shale stabilized with lime, fly ash and CKD. The GeoGauge readings were taken for pozzolan stabilized mixtures at intervals up to 28 days.

The GeoGauge is a hand-portable instrument that provides a simple, rapid and precise means of directly measuring layer stiffness and elastic modulus of compacted soils. A GeoGauge applies cyclic loadings which simulating traffic loading and then measures deflection, displaying the layer's structural stiffness and elastic modulus.

3.2.9 Resilient Modulus Testing

Samples of loess, till, and shale stabilized with lime, fly ash and CKD were sent to Terracon Consultants, Incorporated in Oklahoma City, OK for evaluation of resilient modulus under laboratory conditions using AASHTO T 307-99 procedures. The results of resilient modulus testing are included in this report as Appendix E.

Chapter 4

Results

Tests were performed on seven different soils stabilized using three different pozzolans, lime, fly ash and CKD. This chapter includes native soil properties and engineering 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, and 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 had a liquid limit (LL) of 25 and a plasticity index (PI) of 5. 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 a LL of 31 and a PI of 9. When 5% hydrated lime was added, the PI was NP. The PI 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 became NP for all percentages.

The native loess/till had a LL of 42 and a PI of 21. 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 of 44 and a PI of 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 till became 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 became NP.

Native shale had a LL of 65 and PI of 43. The addition of hydrated lime at 6% reduced the PI to NP. Addition of fly ash at 10%, 13%, and 15% created a PI range from 32 to 29. When 5% CKD was added the PI value was 20, when 7% and 9% were added the shale became 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 percentage tested are included as Appendix B.

Table 5: Maximum Dry Density and Optimum Moisture Content

	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 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 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 while optimum moisture contents were slightly lower. When mixed with hydrated lime, both loess and loess/till densities were lower while 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.

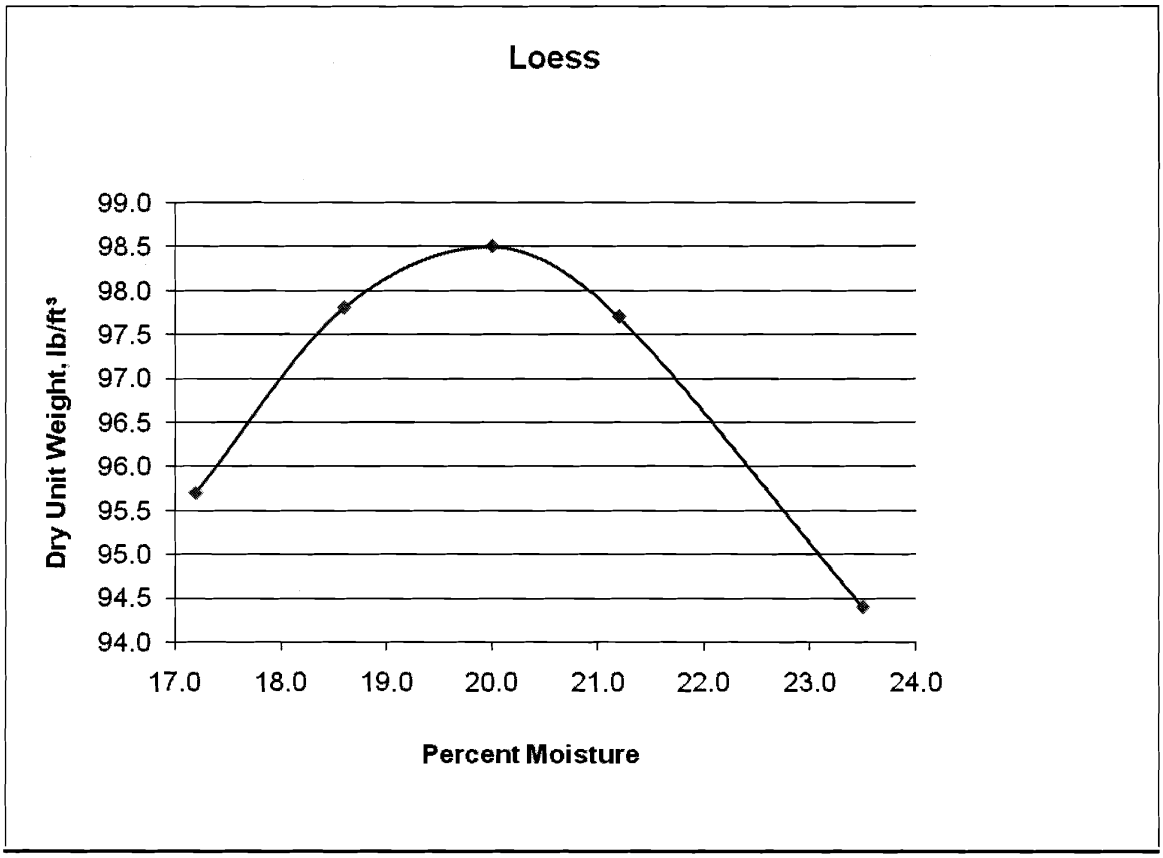
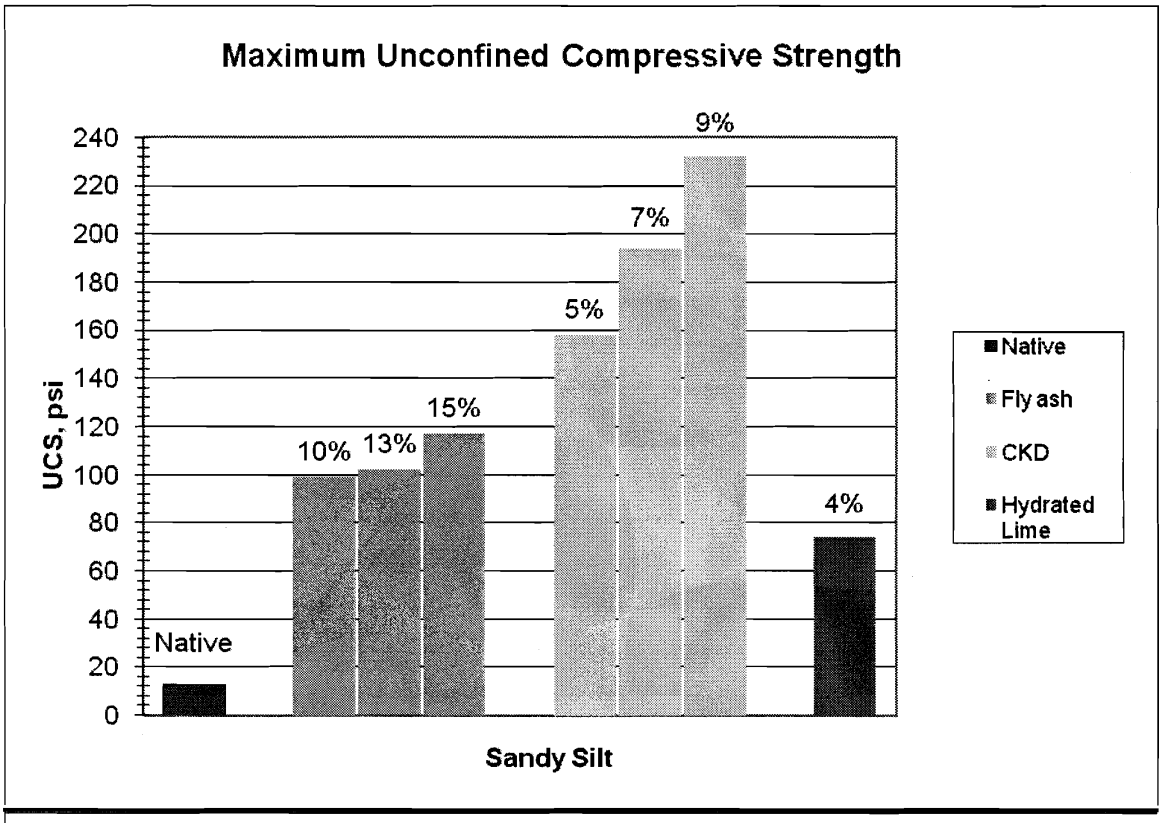


Figure 1: Maximum Dry Density Curve

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, and then cured in air for one day (NDOR 2006 procedure). Unconfined compressive strength was determined in accordance with ASTM D 5102 or ASTM D 1633. An example of the unconfined compressive strength curve used to determine maximum strength is shown in Figure 3.



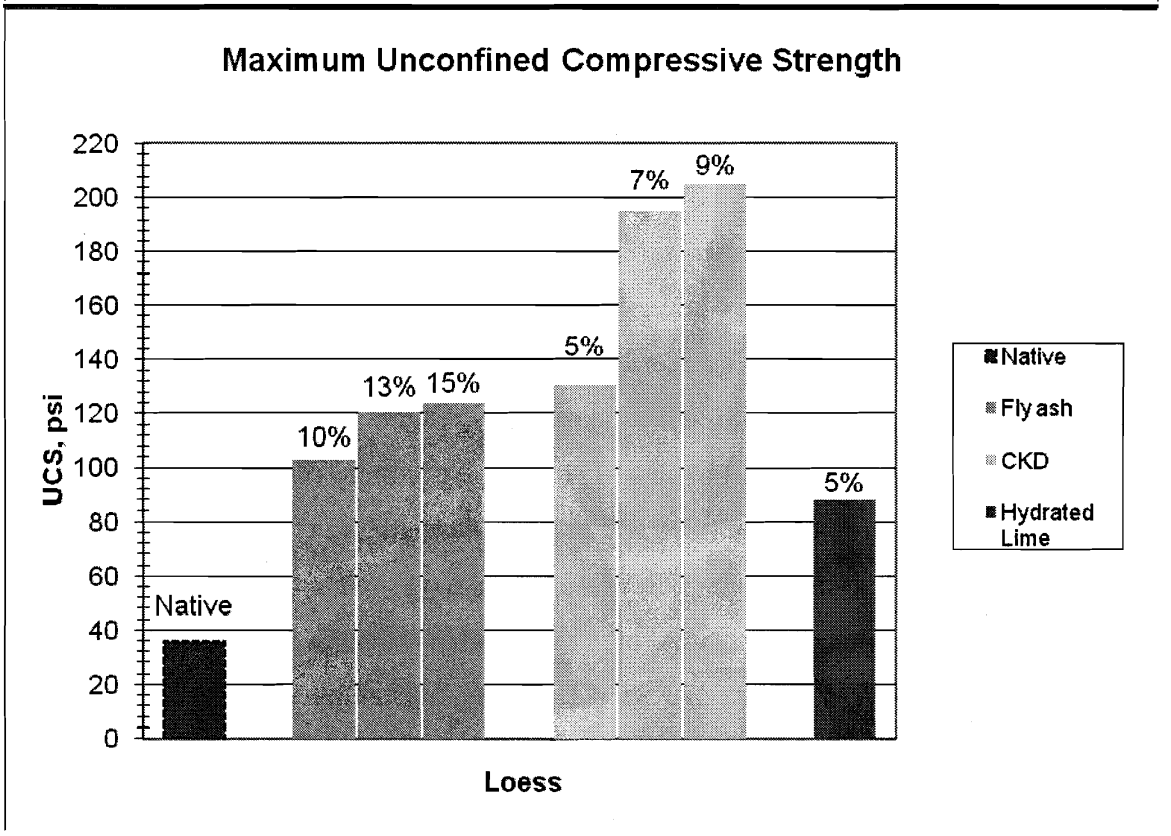
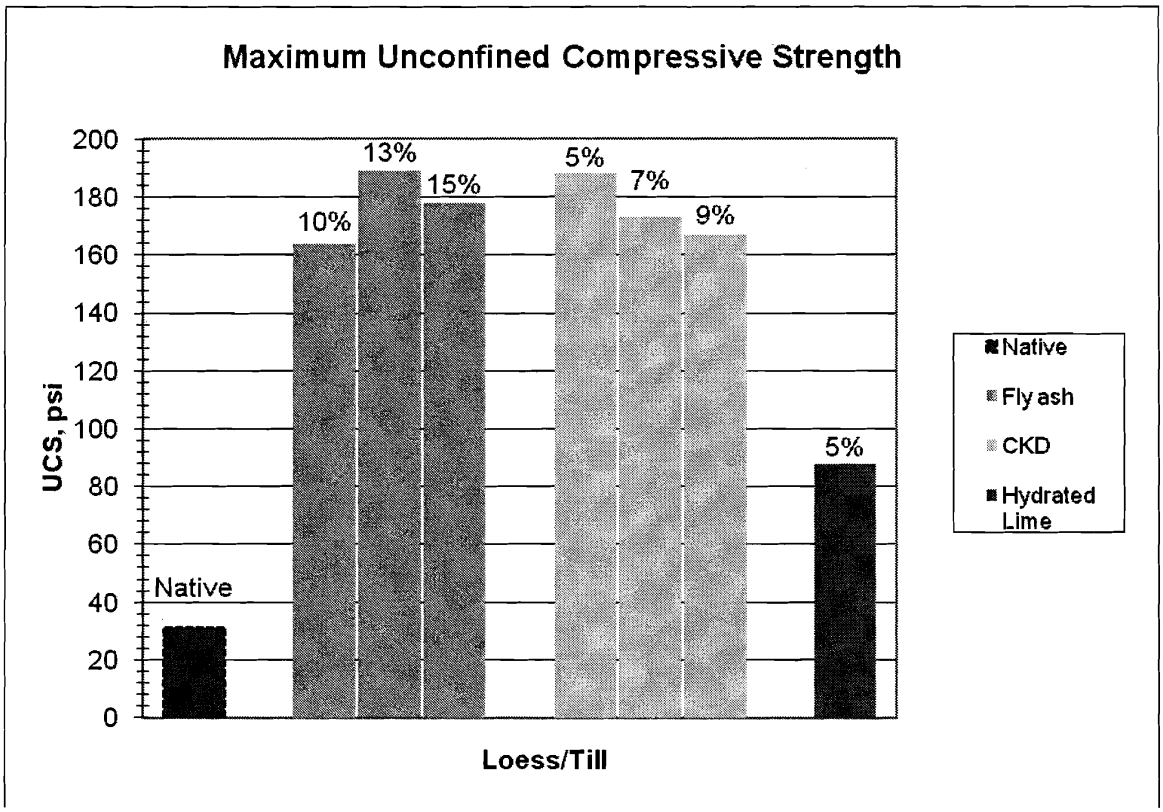


Figure 2: Maximum Unconfined Compressive Strength for Each Soil Type



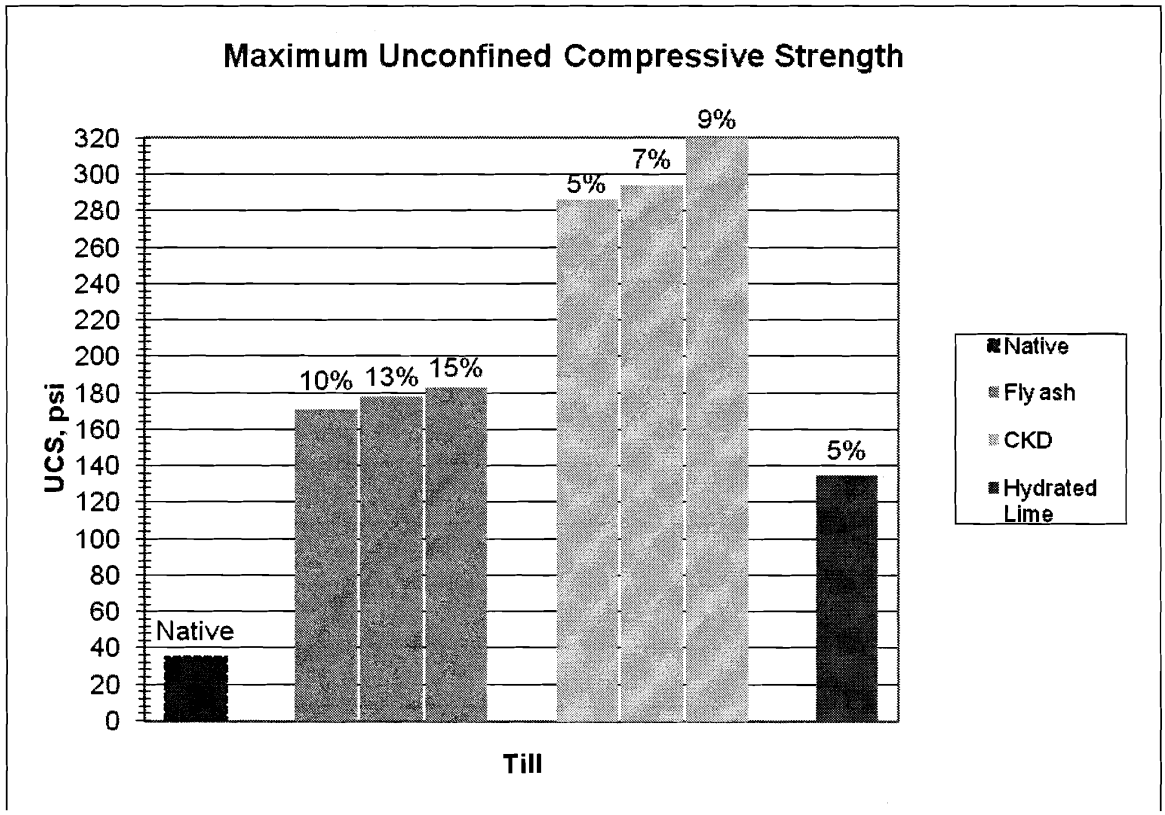


Figure 2 (continued): Maximum UCS for Each Soil Type

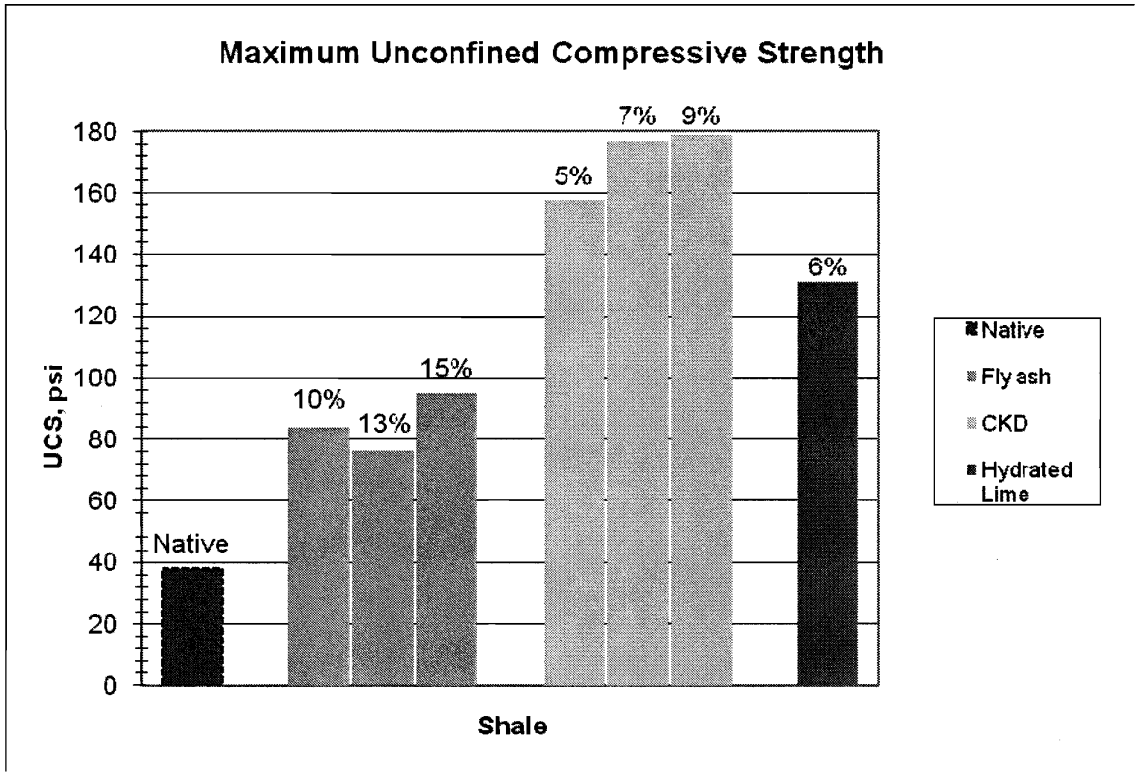


Figure 2 (continued): Maximum UCS for Each Soil Type

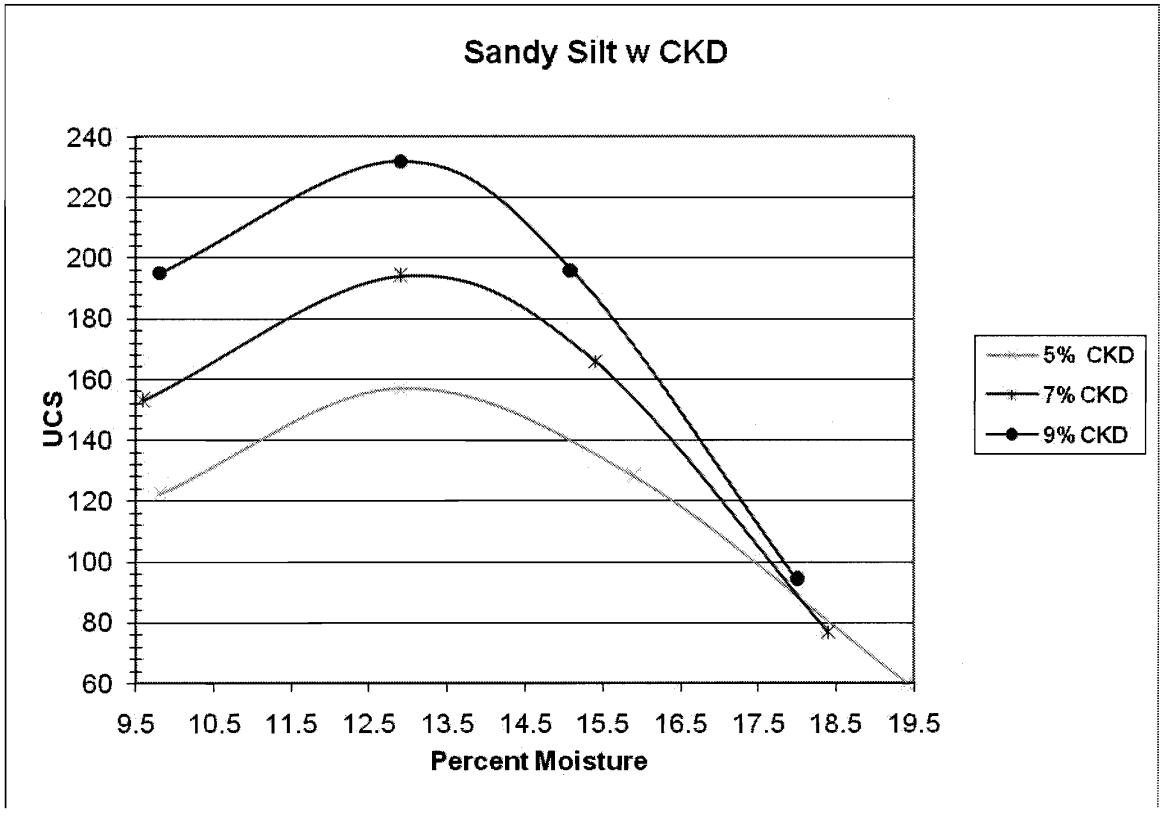


Figure 3: Unconfined Compressive Strength Curves for Sandy Silt

Unconfined compressive strength curves for each soil/pozzolan combination are included in this report as Appendix C. Sandy-silt, 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 the native soils.

Addition of CKD to sandy-silt increased strength 1785% over that exhibited by the native soil. Loess and loess/till when mixed with CKD showed strength increases of 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 showed increases of 386% and 345% respectively over native strength when mixed with hydrated lime.

4.5 Determination of Optimum Pozzolan Percentages

Figure 4 shows an example where moisture content (on the x-axis) has been plotted against unconfined compressive strength (on the y-axis) for a specific soil type. Maximum dry density (MDD) has been plotted versus moisture content as a second vertical axis on the same chart. The soil type shown is sandy-silt stabilized with 5%, 7%, or 9% CKD shown by the curves. Range of optimum moisture content was determined by creating an enclosure with limits of ± 2% moisture content from maximum value for UCS. Optimum pozzolan percentage is that percentage of pozzolan which maximized unconfined compressive strength for a specific soil type. Optimum pozzolan percentage and optimum moisture contents for each soil/pozzolan combination are included in this report as Appendix D. Once optimum percentages of each pozzolan were determined for the various soil types, freeze/thaw, wet/dry, and swell tests were performed at optimum pozzolan percentages. Optimum percentages of pozzolan for the various soil types are summarized in Table 6.

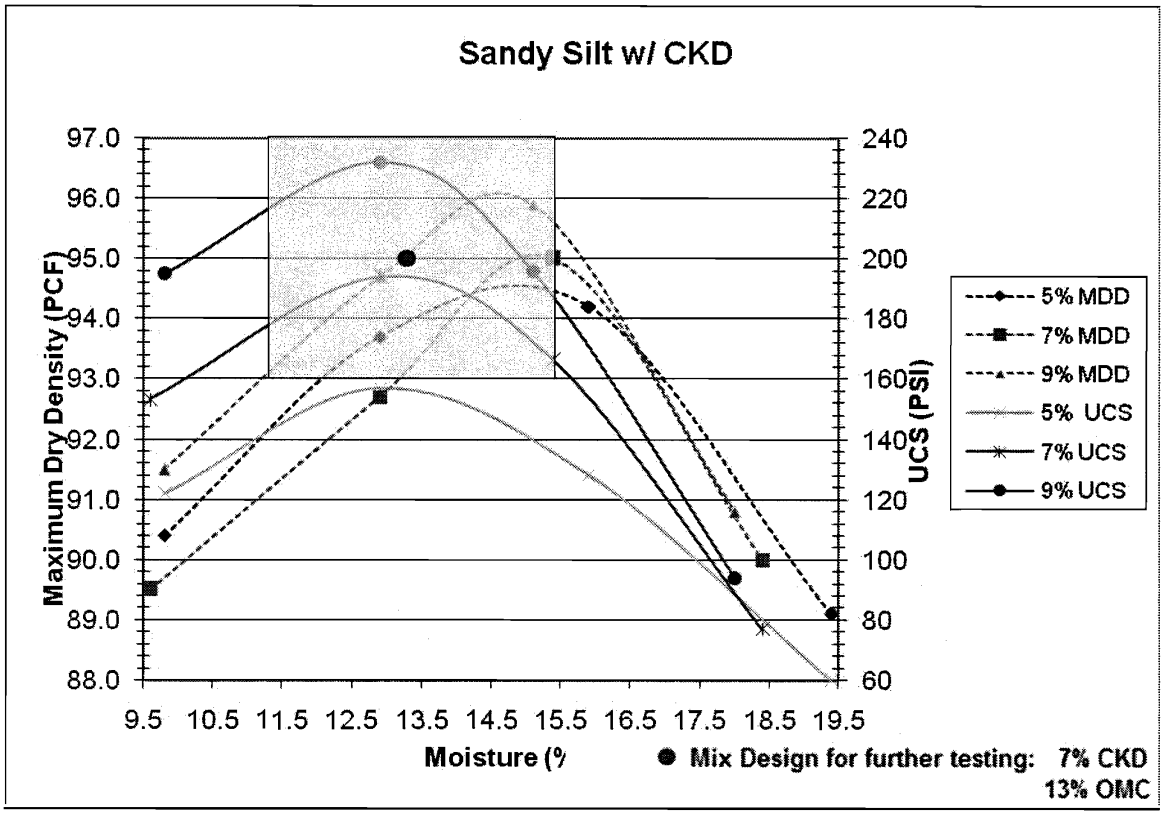


Figure 4: Moisture Content vs. Unconfined Compressive Strength

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 Freezing and Thawing Test Results

Freezing and thawing 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 greatest 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.

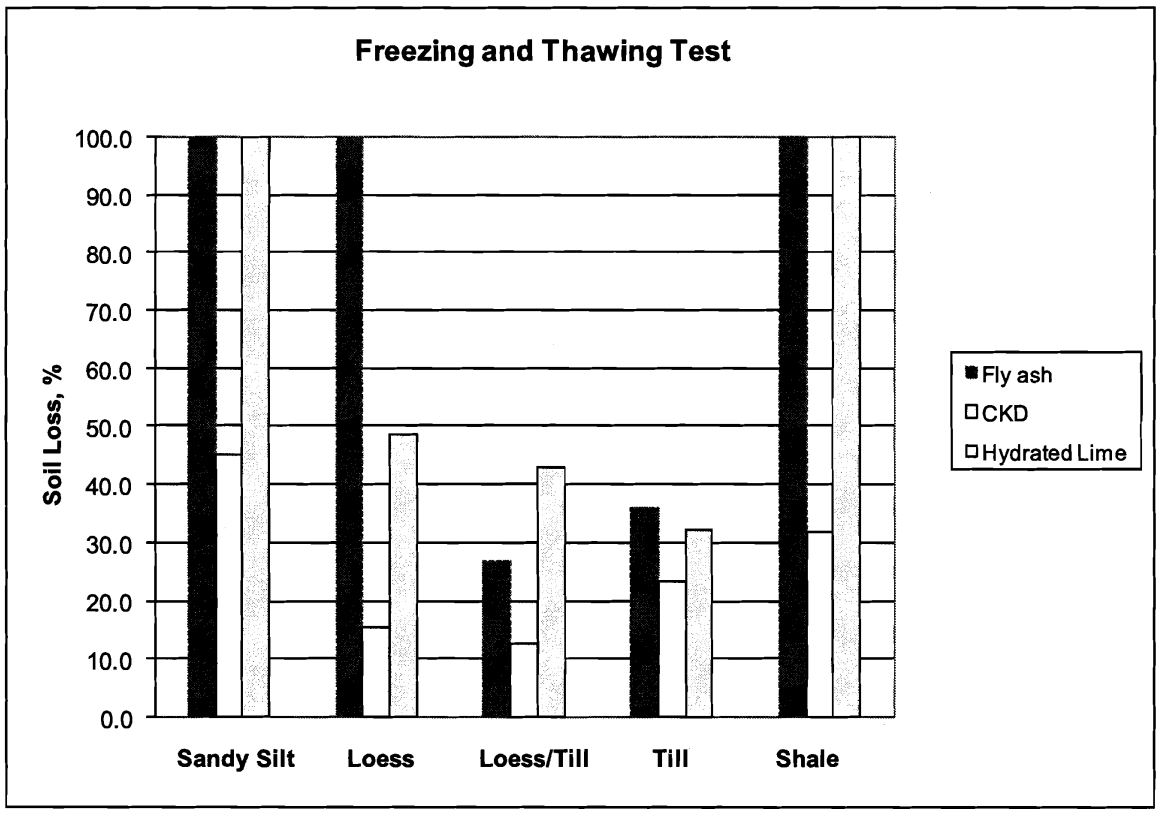


Figure 5: Freezing and Thawing Test Results

Table 7: Freezing and Thawing 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: Freezing and Thawing Test Specimens

4.7 Wetting and Drying Test Results

Results of wetting and drying tests are shown in Figure 7. In this aggressive testing procedure, 60% of the specimens disintegrated before completing the twelve cycles specified. Specimens indicating 100% loss (Figure 7) did not complete the 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, completing the twelve cycle wet-dry test with each pozzolan. Loess and shale failed prior to completing a 12 cycle wet-dry test with all three pozzolans, 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 respectively. Till soil mixed completed a 12 cycle wet-dry test only with CKD, experiencing a loss 55% .

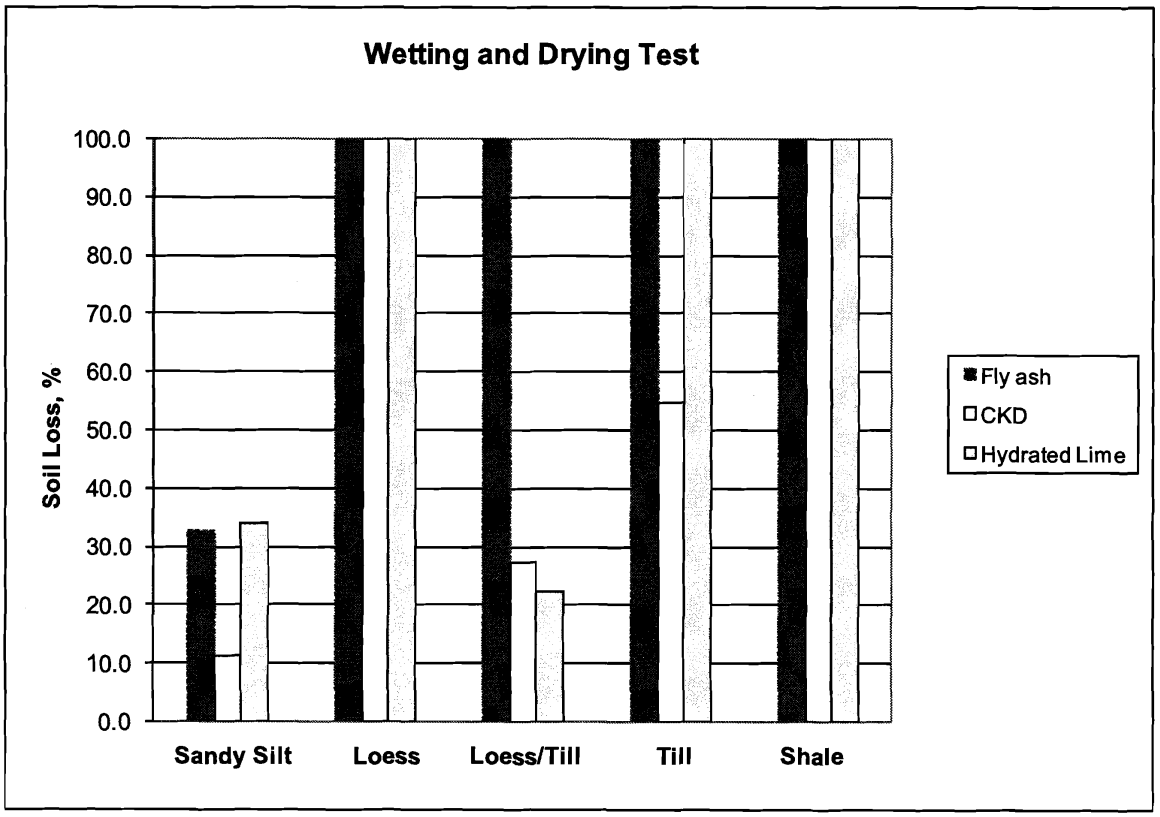


Figure 7: Wetting and Drying Test Results

Table 8: Wetting and Drying 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: Wetting and Drying 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 significant swell reduction only with shale. Fly ash reduced swell in all soils types but outperformed hydrated lime and CKD only in sandy silt.

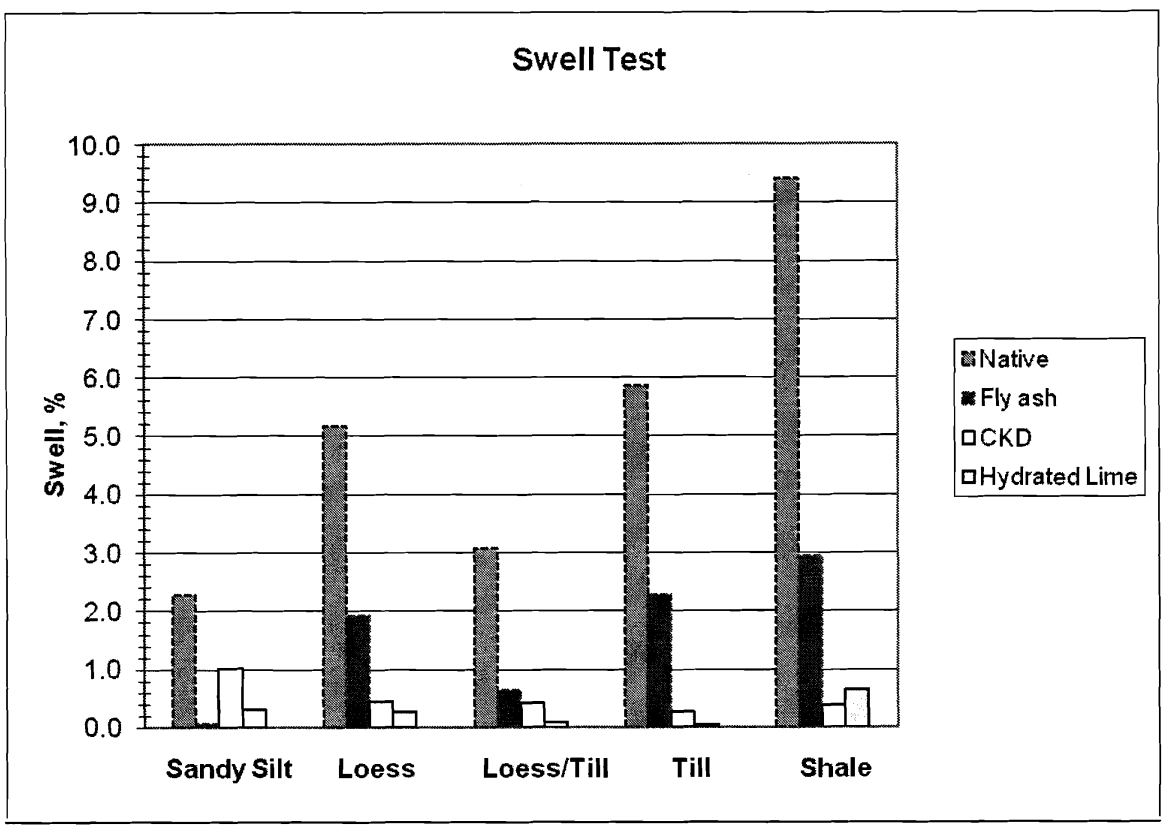


Figure 9: Swell Test Results

4.9 Resilient Modulus and GeoGauge Test Results

Terracon Consultants, Incorporated performed resilient modulus testing on loess, till, and shale with fly ash, CKD and lime added at optimum pozzolan percentages. Resilient modulus test data from Terracon is included in this report as Appendix E. A GeoGauge was used by the researchers to measure the elastic modulus of loess, till, and shale with fly ash, CKD and lime added at optimum percentages. Laboratory resilient modulus and elastic modulus (as measured by a GeoGauge) are compared in Table 9.

All GeoGauge samples were allowed to cure for 28 days before measurements were taken. While the results were not expected to be identical, both test procedures apply dynamic loads and then measure deflection, so the results were expected to be somewhat similar. The difference between values obtained for shale with fly ash and CKD and till with CKD suggest further research will be required.

Table 9: Resilient Modulus and GeoGauge Test 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/ft^3	Application lb/yd^2 @ 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 yd^2
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. Off-site mixing may not be feasible 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, manufacturers two sizes of soil stabilizers, SS-250B and RM-350B. A soil stabilizer is preferable over mixing with a towed disc because it mixes the materials much more thoroughly. Stabilizers are designed with a continuous mixing chamber and shaped rotors assuring a complete blending of materials. Disking of materials is not recommended unless it is the sole practical method of incorporating pozzolanic material. Disking fails to provide the compete blending needed to maximize the effects of most pozzolans.

6.2 Water

The most important step during the stabilization process is adding (or subtracting) 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, plus it aids in achieving proper compaction. With the moisture too low or too high, achieving a specified density becomes almost impossible.

Water is sometimes added to the subgrade directly ahead of the stabilizer. This may cause problems, by 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 additional passes with the soil stabilizer. While this process works well, the increased 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.

6.3 Curing and Compaction

Lime stabilized subgrades should be allowed to cure a minimum of 48 hours before initial compaction. Subgrades stabilized with CKD or fly ash should be compacted as soon as practical after incorporation of the pozzolan.

Figure 10: Soil Stabilizer SS-250 Caterpillar

6.4 Field Calculation for Pozzolan Distribution

Table 11 illustrates a sample calculation for the quantity of pozzolan to be distributed 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 for Pozzolan Distribution

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

An abbreviated field manual summarizing information concerning optimum percentages of each pozzolan and optimum moisture contents for all seven soil types is included as Appendix F to this report.

Chapter 7

Conclusions & Recommendations

7.1 Conclusions

1. Fly ash, CKD, and hydrated lime were all effective for 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 ASTM D 6276 procedures made most soil types non-plastic. While others were NP, only the till and shale retained PI values with 5% CKD. While fly ash did reduce the PI values of all soil types, the soil still retained some plasticity in loess, loess/till, and till at 10% and 13%, while at 15% the all three were non-plastic. When 15% CKd was added to shale, 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 was created by addition of hydrated lime (in all soils 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 freezing and thawing tests, 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 exceptionn being with loess where fly ash had a much higher loss.
5. Wetting and drying tests showed that CKD had the best overall performance when evaluating both soil loss and number of cycles completed. All pozzolans had 100% soil loss with loess and shale. Fly ash had 100% soil loss on all soil types except sandy silt, where it performed better than hydrated lime, but not

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

Each soil type was evaluated with 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.

7.2 Recommendations

Gravel and Fine Sand

These two soil types will normally not be stabilized by addition of a pozzolan because of their granular nature. These soils are normally stabilized through vibratory compaction instead. Optimum 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						
Pozzolan	Optimum Native Moisture	Design				
		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 14 to 18 which follow.

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

Sandy Silt						
Pozzolan	Optimum Native Moisture	Design				
		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						
Pozzolan	Optimum Native Moisture	Design				
		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						
Pozzolan	Optimum Native Moisture	Design				
		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. Variables include the availability of and cost of each pozzolan, what type of equipment is available for application and mixing, the location of the project, and the transportation distance required for the each pozzolan, assuming they are all procured from the same location. Because of these many variables, NDOR or contractor representatives still must determine which pozzolan can be used to achieve the desired modifications in the most expeditious and economical manner.

REFERENCES

American Coal Ash Association (2003). Fly Ash Facts for Highway Engineers. Sponsoring Agency Federal Highway Administration Report No. FHWA-IF-03-019.

Azad, S. (1998). Soil Stabilization of Three Different Soils Using Cement Kiln Dust, Master's Thesis, University of Oklahoma, Norman, OK.

Baghdadi, Z.A. (1990). Utilization of Kiln Dust in Clay Stabilization, Journal of King Abdulaziz University.; Engineering and Science, Jeddah, Saudi Arabia, Vol 2, pp. 153-163.

Baghdadi, Z.A., Fantini, M.N., and Sabban, N.A. (1995). Soil modification by Cement Kiln Dust, Journal of Materials in Civil Engineering, Vol. 7, No. 4, pp. 218-222.

Çokça, E. (2001). Use of Class C Fly Ashes for the Stabilization of an Expansive Soil, Journal of Geotechnical and Geoenvironmental Engineering, 127(7), 568-273.

Currin, D. D., Allen, J. J., & Little, D. N. (1976). Validation of Soil Stabilization Index System with Manual Development. United States Air Force Academy, CO: Frank J. Seiler Research Laboratory.

Dempsey, B. J., and Thompson, M. R., (1968), Durability Properties of Lime-Soil Mixtures, Highway Research Record 235, National Research Council, Washington, D. C., pp. 61 -75.

Department of Energy (DOE) (2004). U.S. Coal Supply and Demand; 2002 review. DOE website: http://www.eia.doe.gov/cneaf/coal/page/special/feature.html.

Eoery, J.E. (1972). Stabilization of Sludges and Sediments for Fill Apllications, Hamilton, Ontario, pp. 341-345.

Epps, J. A., Dunlap, W.A., Gallaway, B. M., and Currin D. D. (1971). Soil Stabilization: A Mission Oriented Approach, Highway Research Record 351, TRB, National Research Council, Washington, D.C., pp. 1-20.

Fatani, M.N., and Khan, A.M. (1990). Improvement of Dune Sand Asphalt Mixes for Pavement Bases, Journal of King Abdulaziz University.; Engineering and Science, Jeddah, Saudi Arabia, Vol 2, pp. 39-47.

Ferguson, G. (1993). Use of Self-Cementing Fly Ashes as a Soil Stabilization Agent, ASCE Geotechnical Special Publication No. 36, ASCE, New York.

Ferguson, G., and Leverson, S.M. (1999). Soil and Pavement Base Stabilization with Self-Cementing Coal Fly Ash, American Coal Ash Association, Alexandria, VA.

Jan, M. A. and R. D. Walker. (1963). "Effect of Lime, Moisture, and Compaction on a Clay Soil, Highway Research Record 29, TRB, National Research Council, Washington, D.C.

Kennedy, T.W., R. Smith, R.J. Holmgreen, and M. Tahmoressi. (1987). An Evaluation of Lime and Cement Stabilization, Transportation Research Record 1119, TRB, National Research Council, Washington, D.C. pp.11-25.

Laguros, J. G. (1965). Lime-Stabilized Soil Properties and the Beam Action Hypothesis, Highway Research Record 92, TRB, National Research Council, Washington, D.C., pp. 12-20.

Lin, D., Lin, K., and Luo, H. (2007). A Comparison Between Sludge Ash and Fly Ash on the Improvement in Soft Soil. Journal of the Air & Waste Management Association (2007) Vol. 57, pp. 59-64.

Little, D. N. (1995). Handbook for Stabilization of Pavement Subgrades and Base Courses with Lime. Dubuque, Iowa: Kendall/Hunt Pub. Co.

Little, D. N. (1998). Evaluation of Structural Properties of Lime Stabilized Soils and Aggregates. Arlington, Va: National Lime Association.

Marquez, H.R. (1997). Evaluation of Cement Kiln Dust Soil Stabilization for Oklahoma Pra-Chic 12(1) Guy Sandy Area Chickasaw National Recreation Area, Federal Highway Administration Central Federal Lands Highway Division Materials Branch.

Milburn, J.P., and Parsons, R.L. (2004). Performance of Soil Stabilization Agents. Research Report No. K-TRAN: KU-01-8, University of Kansas.

Morgan, D.S., and Halff, A.H. (1984). Oil Sludge Solidification Using Cement Kiln Dust, Journal of Environmental Engineering, Vol. 110, No. 5, pp. 935-948.

NDOR (2006). Testing and sample preparation for stabilized subgrades. Personal conversion with M. Syslo, NDOR Flexible Pavement Engineer on November 6, 2006.

Parsons, R.L., Johnson, C.P., and Cross, S.A. (2001) Evaluation of Soil Modification Mixing Procedures, Research Report No. K-TRAN: KU-00-6, University of Kansas.

Perry, J., Snowdon, R.A., and Wilson, P.E. (1995). Site Investigation for Lime Stabilisation in the United Kingdom, Cement Lime and Gravel, Vol. 42, No. 9, pp. 277-280.

Petry, T. M., and McCallister, L. D. (1990), Property Changes in Lime Treated Expansive Clays Under Continuous Leaching, Technical Report GL-90-17, U. S. Army Corps of Engineers, Vicksburg, Mississippi.

Thompson, M. R., (1970), "Soil Stabilization of Pavement Systems - State of the Art," Technical Report - Department of the Army, Construction Engineering Research Laboratory, Champaign, Illinois.

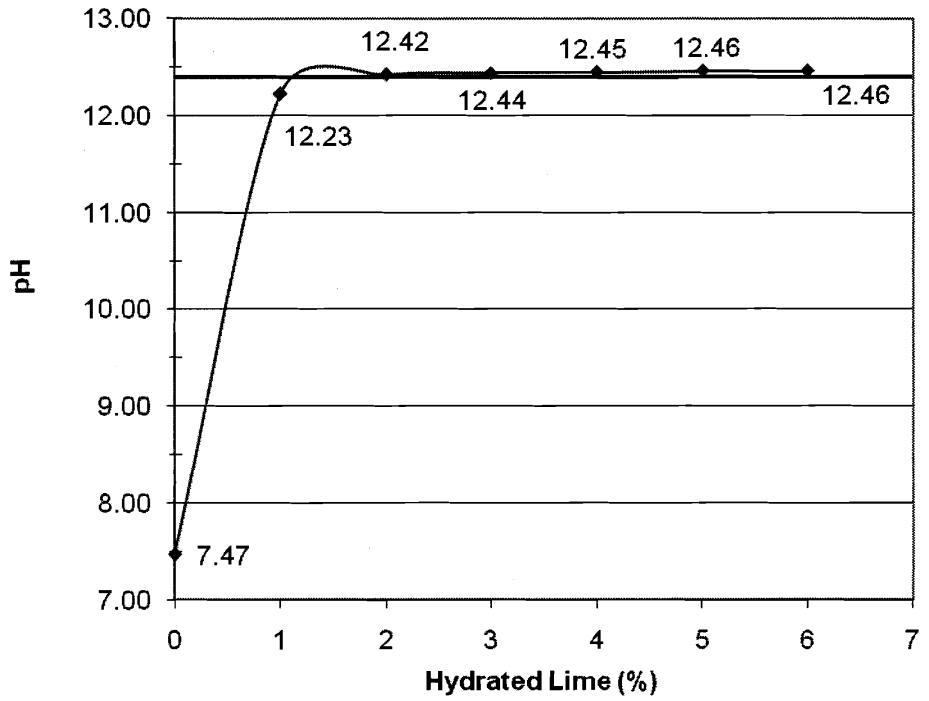
Thompson, M. R., and Robnett, Q. L., (1976), Effect of Lime Treatment on the Resilient Behavior of Fine-Grained Soils, Transportation Research Record No. 560, pp. 11-20.

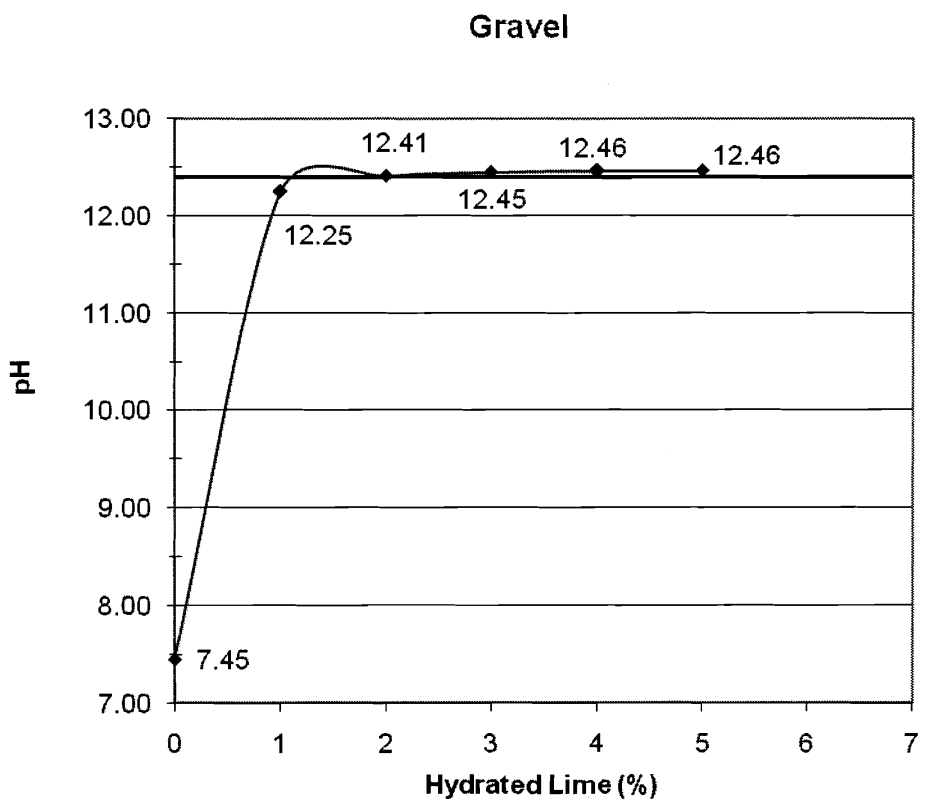
Todres, H. A. (1992). Cement Kiln Dust: Field Compaction and Resulting Permeability. Research and Development Bulletin, RD106T. Skokie, Ill: Portland Cement Association.

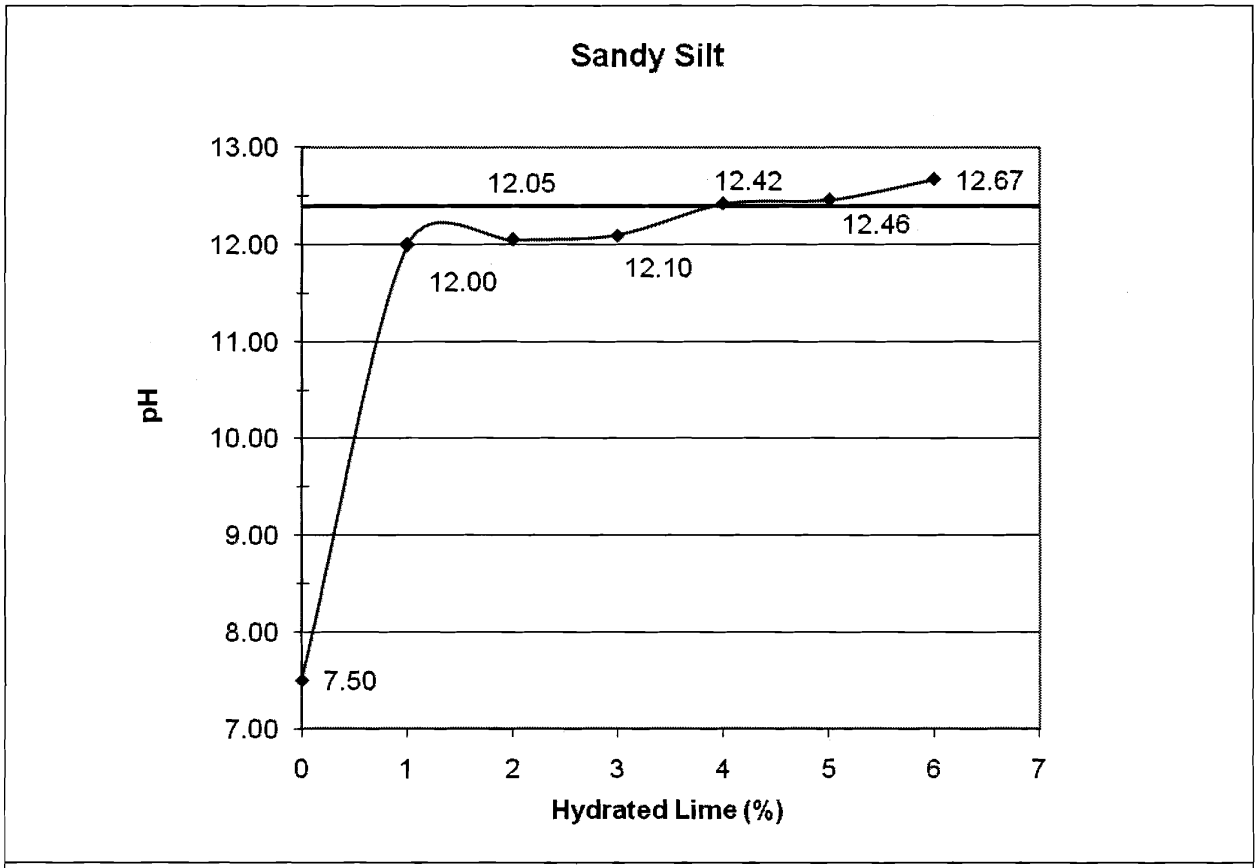
Zaman, M., Lagurous, J.G., and Sayah, A. (1992). Soil Stabilization Using Cement Kiln Dust, Proceedings of the 7th International Conference on Expansive Soils, Dallas, Texas, pp. 347-351.

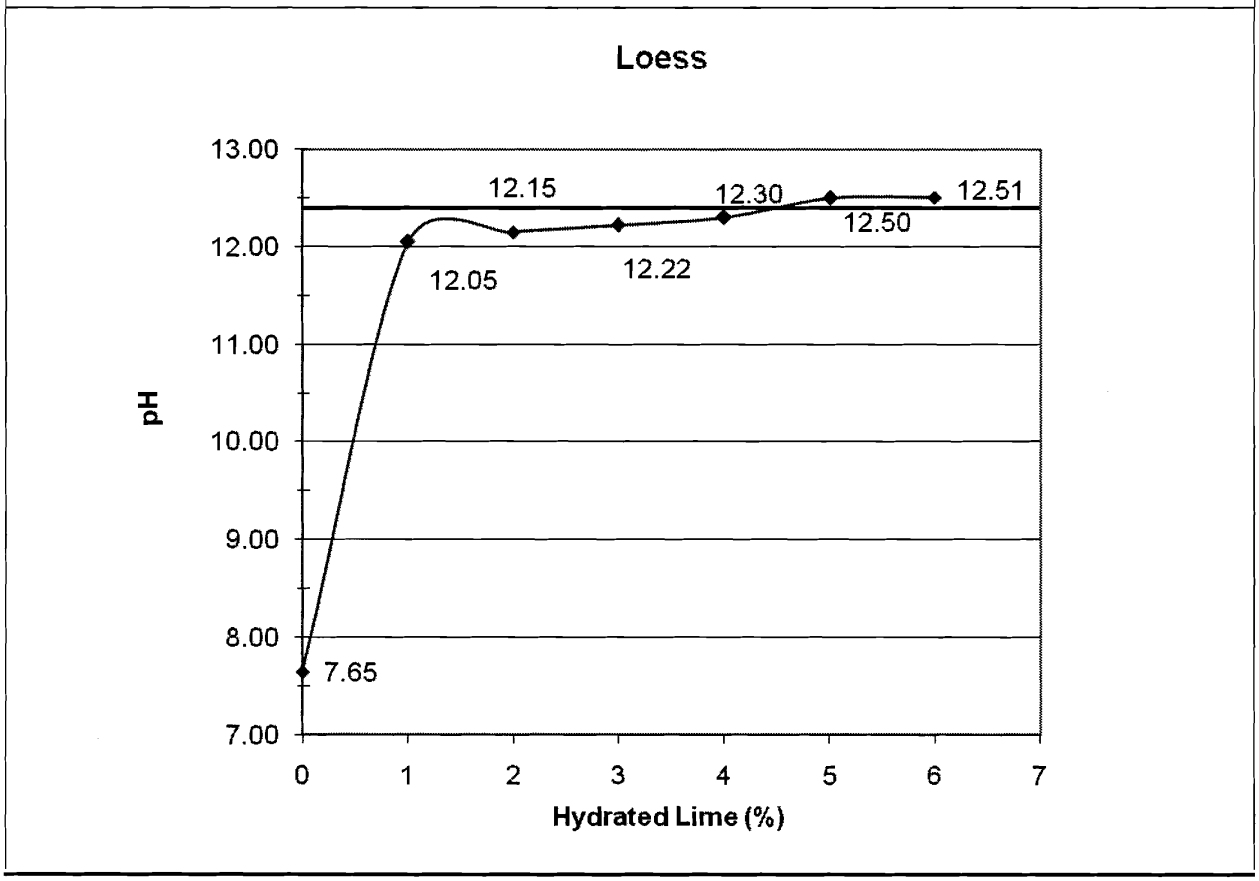
APPENDIX A

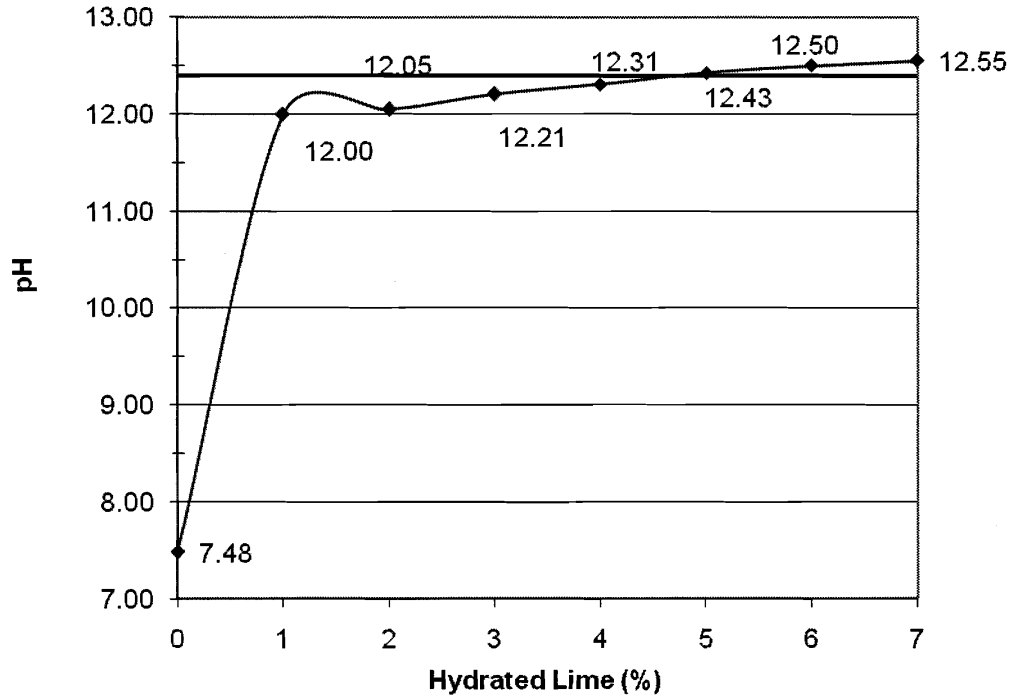
Using pH to Estimate Soil Lime Percentage

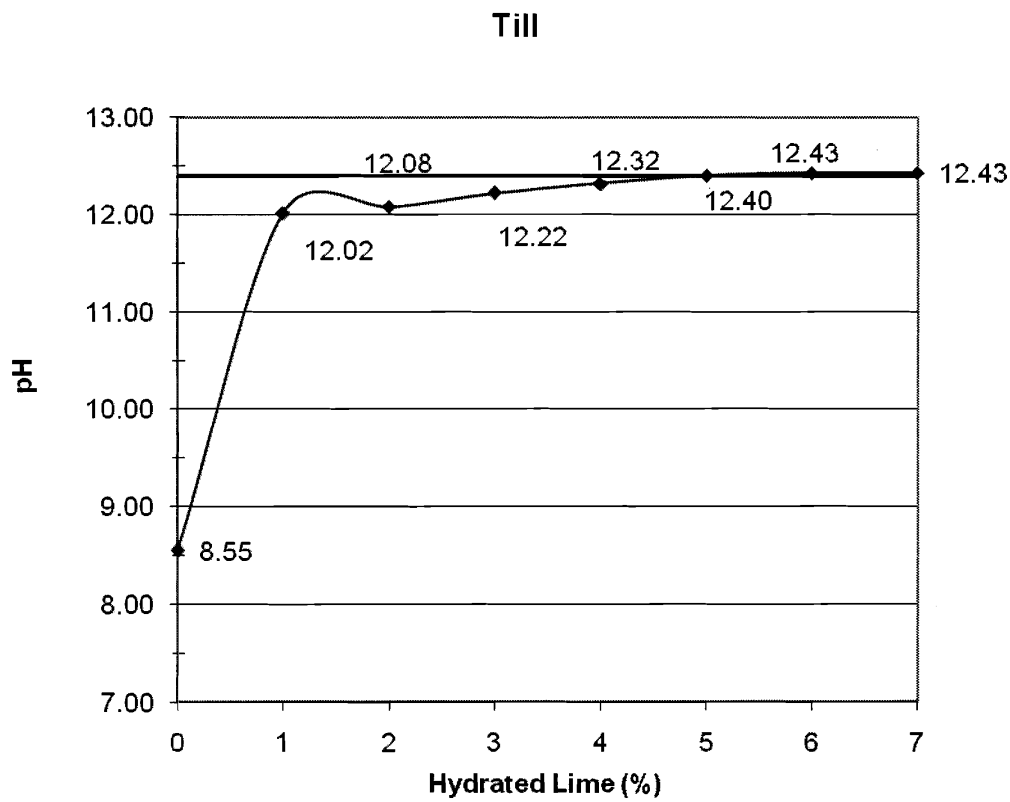

Fine Sand
13.00
12.00
11.00
10.00
9.00
8.00
7.00
pH
12.42
12.45
12.46
12.44
12.46
12.23
7.47
0
1
2
3
4
5
6
7
Hydrated Lime (%)

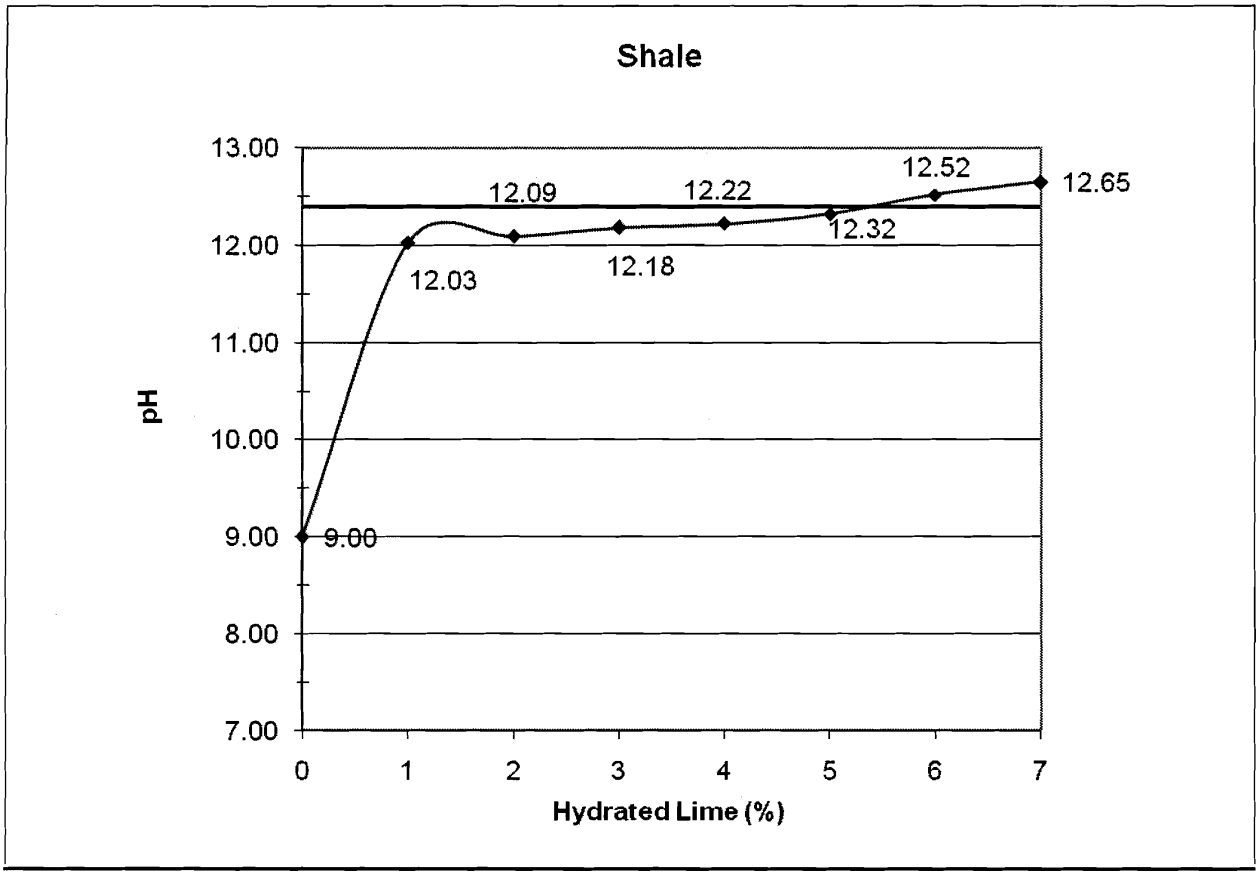

Gravel
13.00
12.00
11.00
10.00
9.00
8.00
7.00
pH
12.41
12.46
12.46
12.45
12.25
7.45
0
1
2
3
4
5
6
7
Hydrated Lime (%)


Sandy Silt
13.00
12.00
11.00
10.00
9.00
8.00
7.00
pH
12.05
12.42
12.67
12.46
12.00
12.10
7.50
0
1
2
3
4
5
6
7
Hydrated Lime (%)


Loess
13.00
12.00
11.00
10.00
9.00
8.00
7.00
pH
12.15
12.30
12.51
12.50
12.05
12.22
7.65
0
1
2
3
4
5
6
7
Hydrated Lime (%)

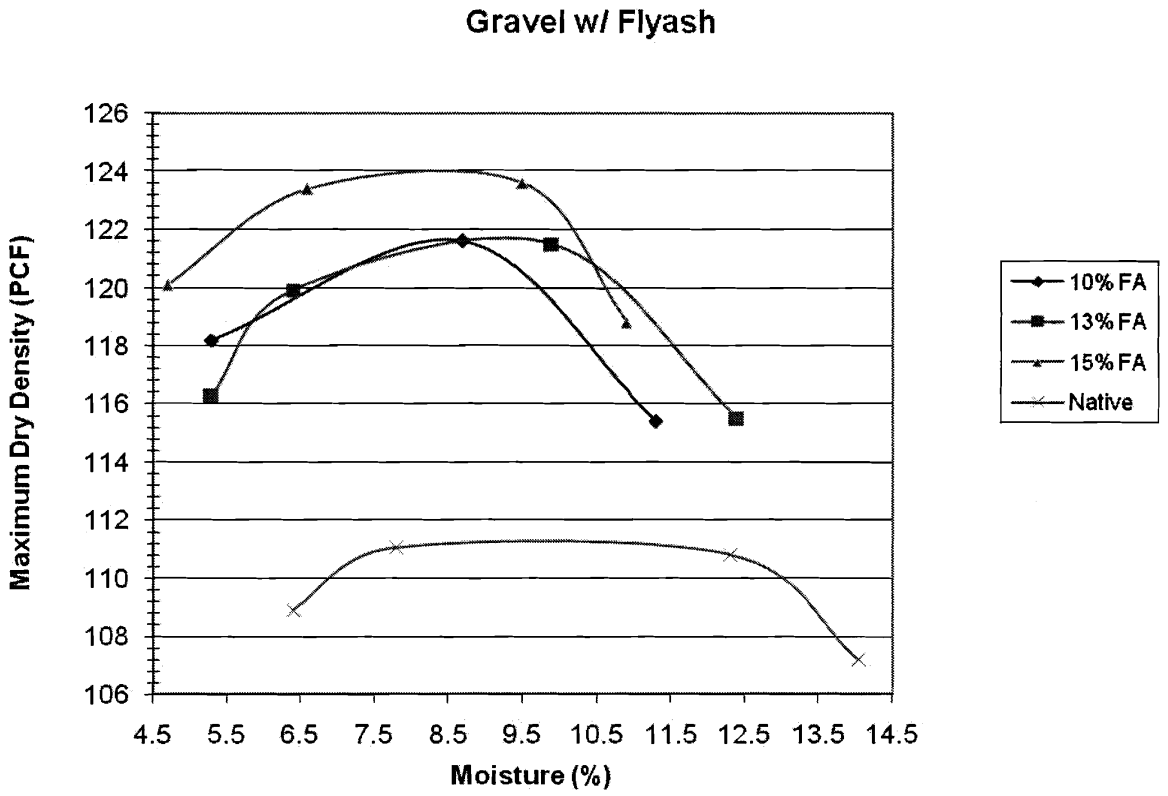

Loess/Till
13.00
12.00
11.00
10.00
9.00
8.00
7.00
pH
0
1
2
3
4
5
6
7
Hydrated Lime (%)
7.48
12.00
12.05
12.21
12.31
12.43
12.50
12.55

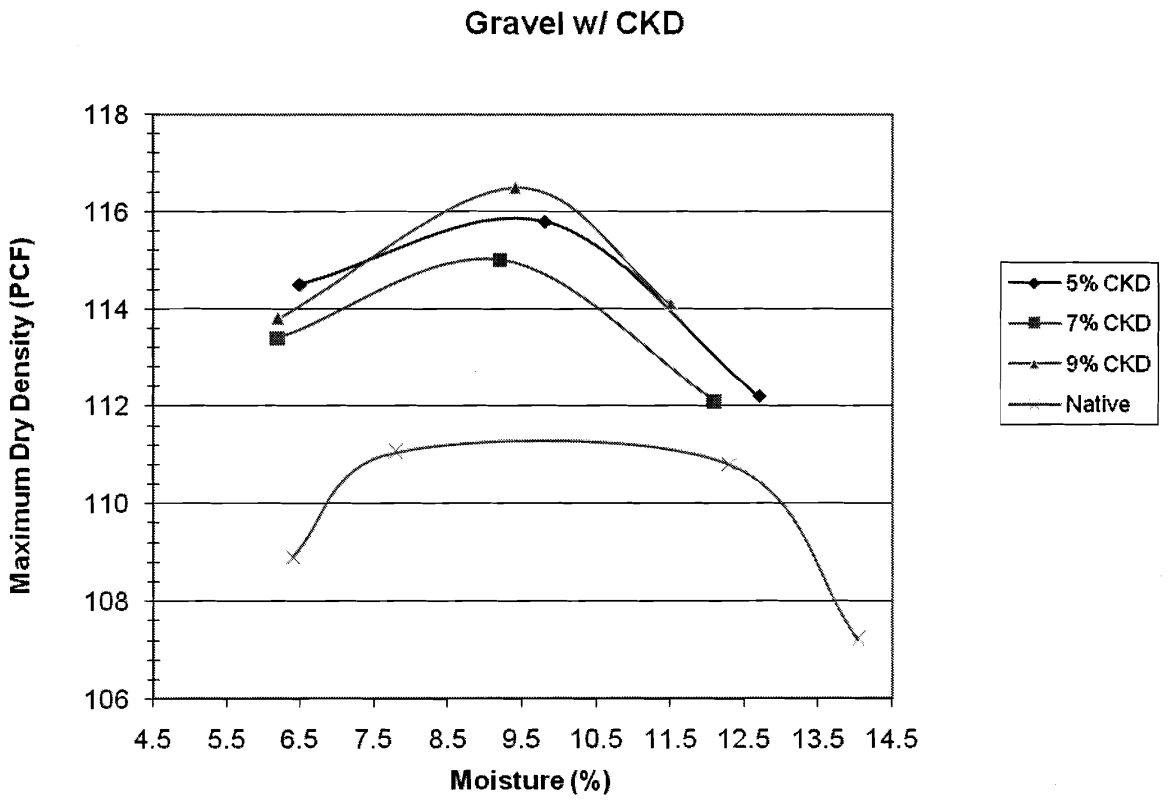

Till
13.00
12.00
11.00
10.00
9.00
8.00
7.00
pH
0
1
2
3
4
5
6
7
Hydrated Lime (%)
8.55
12.02
12.08
12.22
12.32
12.40
12.43
12.43

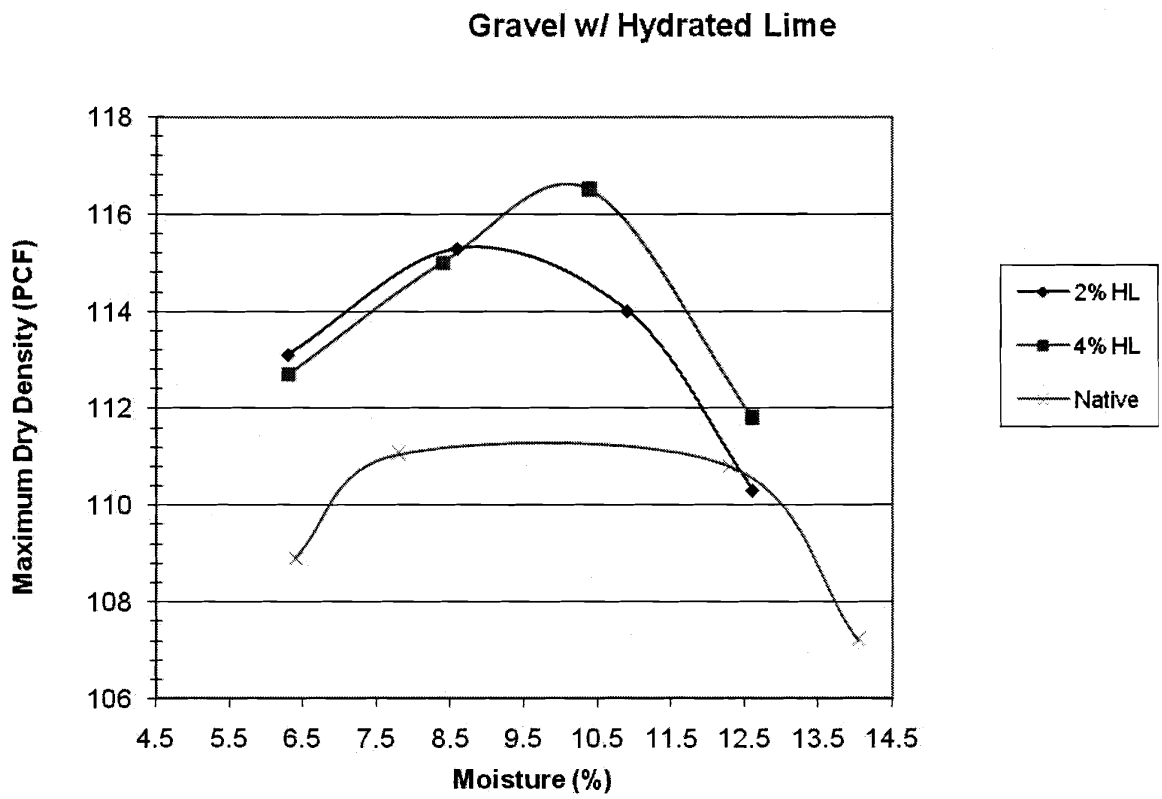

Shale
13.00
12.00
11.00
10.00
9.00
8.00
7.00
pH
0
1
2
3
4
5
6
7
Hydrated Lime (%)
9.00
12.03
12.09
12.18
12.22
12.32
12.52
12.65

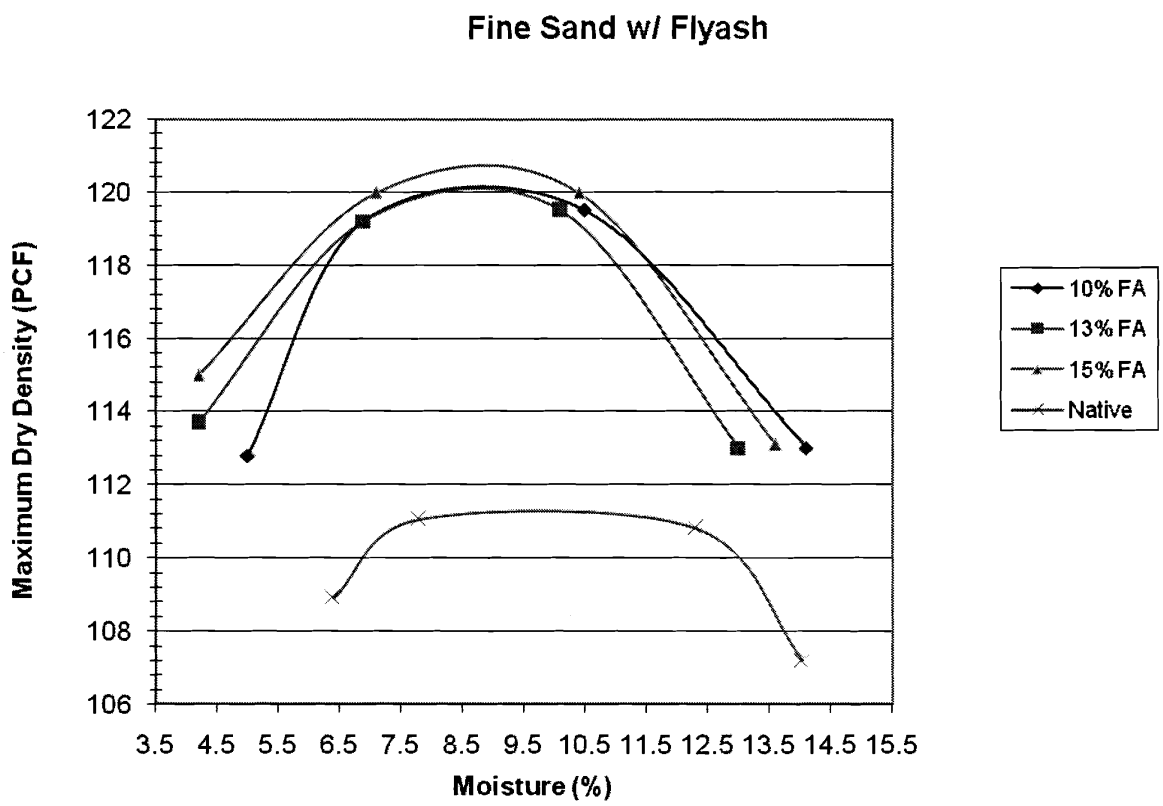
APPENDIX B

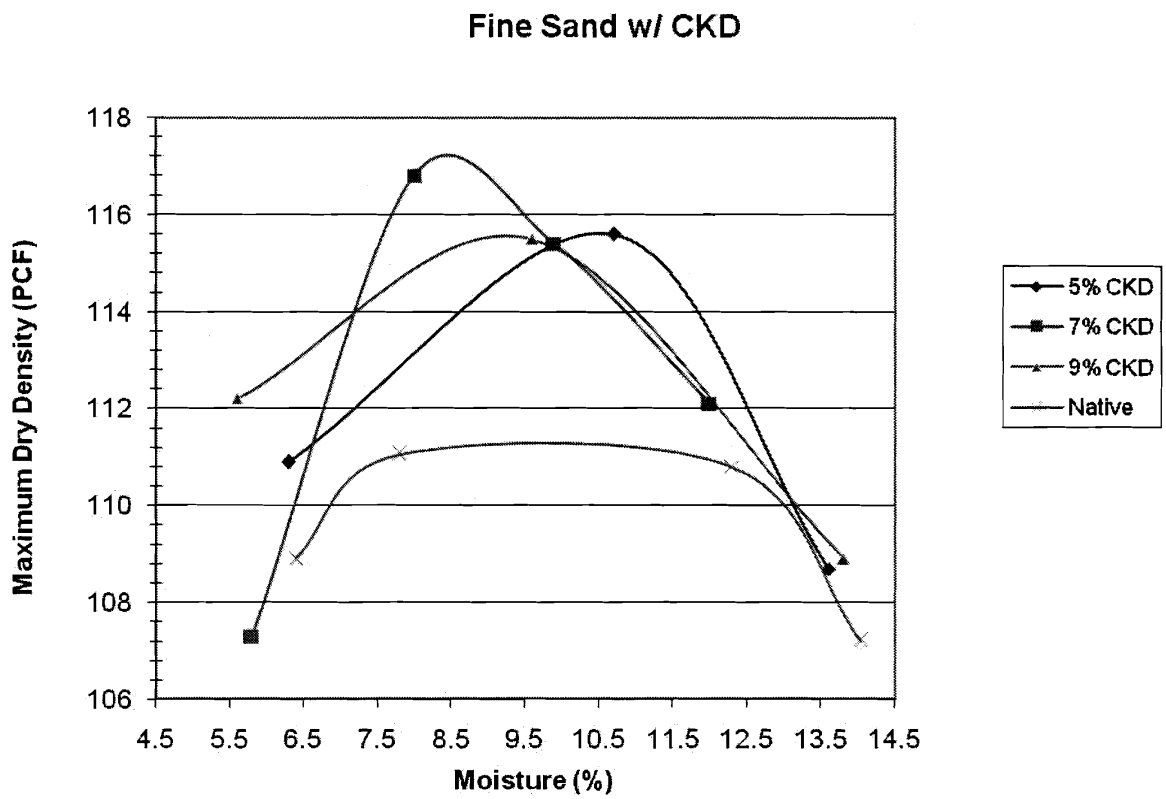
Moisture Density Relationship Curves

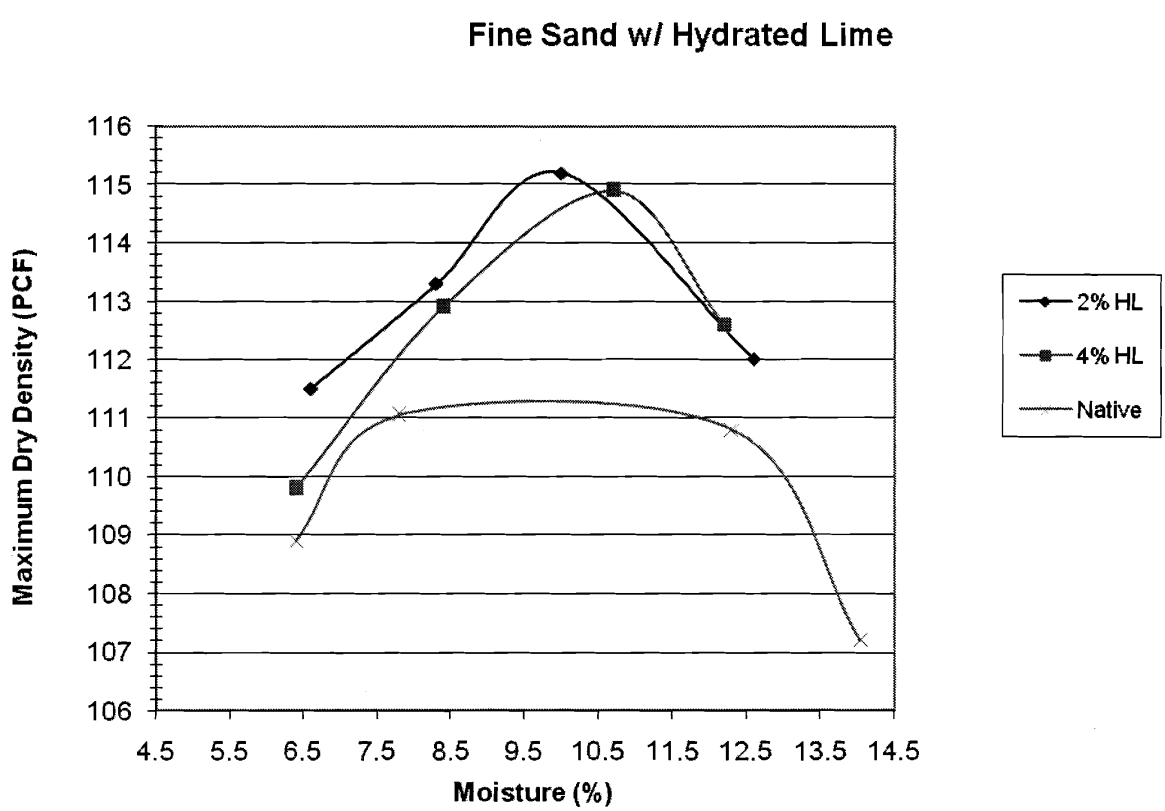

Gravel w/ Flyash
Maximum Dry Density (PCF)
126
124
122
120
118
116
114
112
110
108
106
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
Moisture (%)
10% FA
13% FA
15% FA
Native

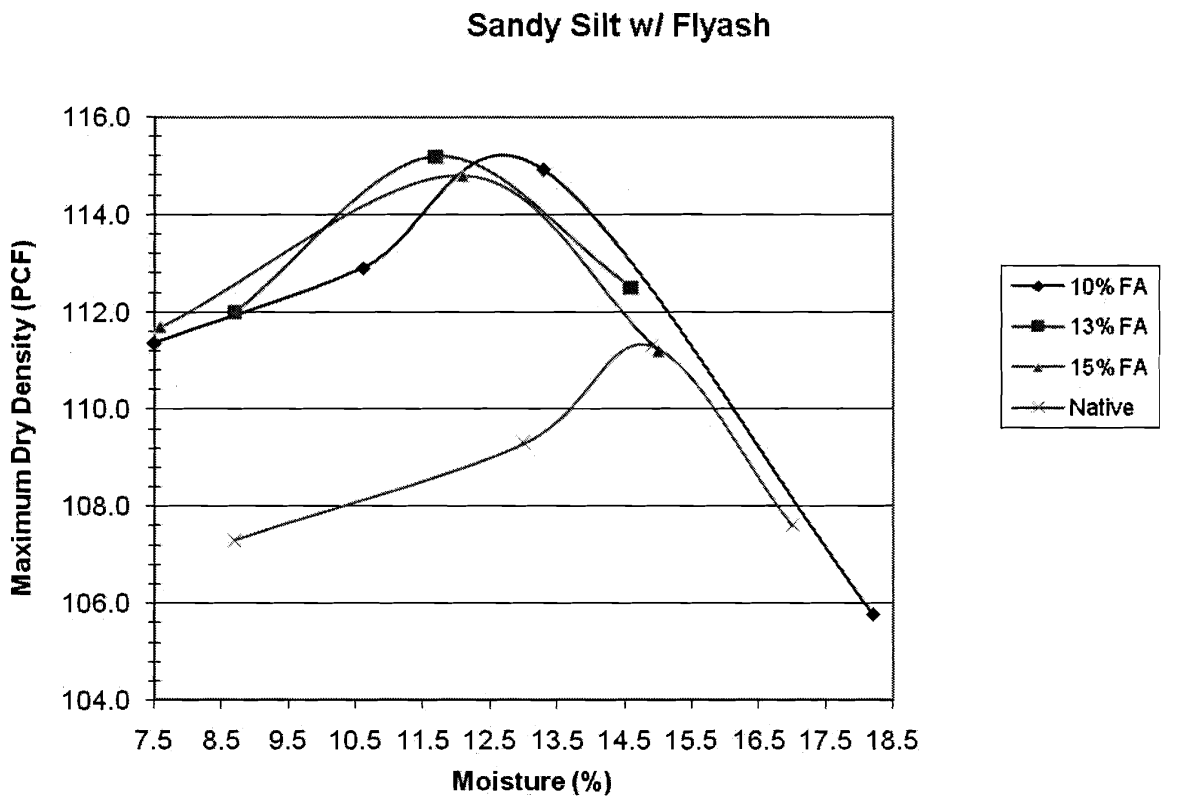

Gravel w/ CKD
Maximum Dry Density (PCF)
118
116
114
112
110
108
106
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
Moisture (%)
5% CKD
7% CKD
9% CKD
Native

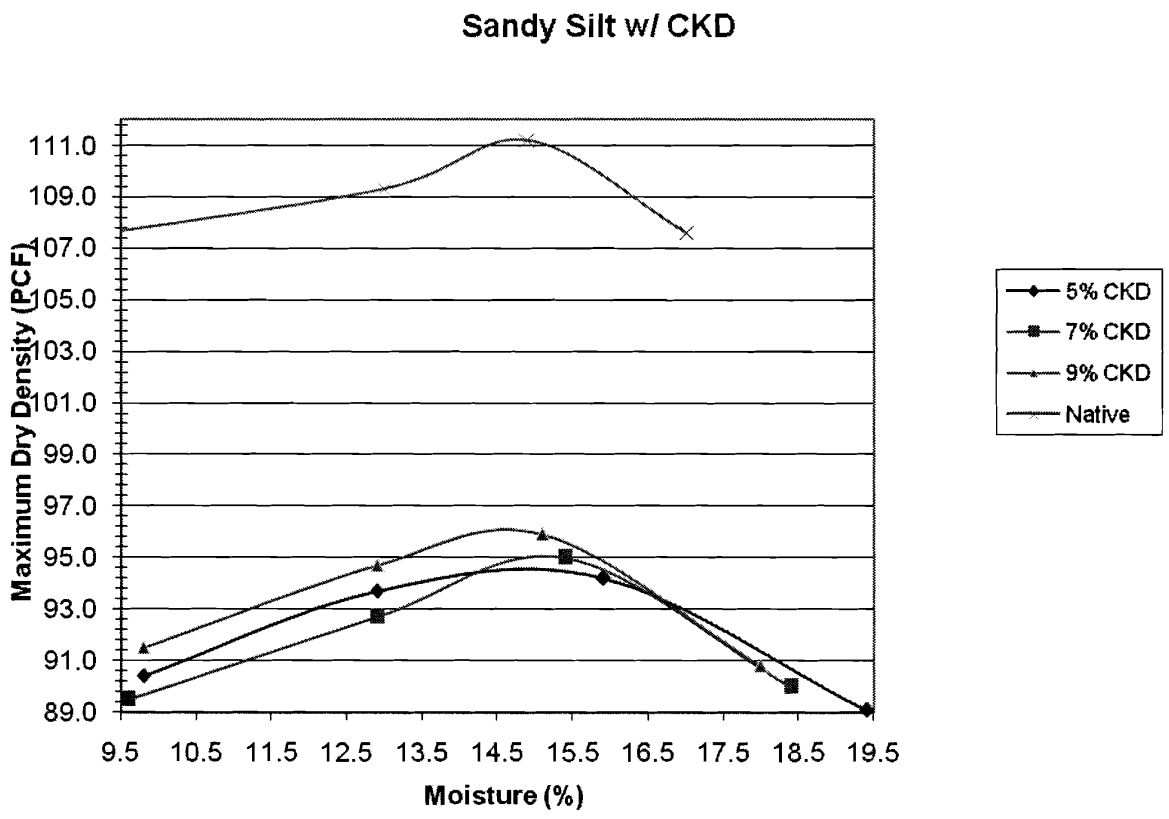

Gravel w/ Hydrated Lime
Maximum Dry Density (PCF)
118
116
114
112
110
108
106
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
Moisture (%)
2% HL
4% HL
Native

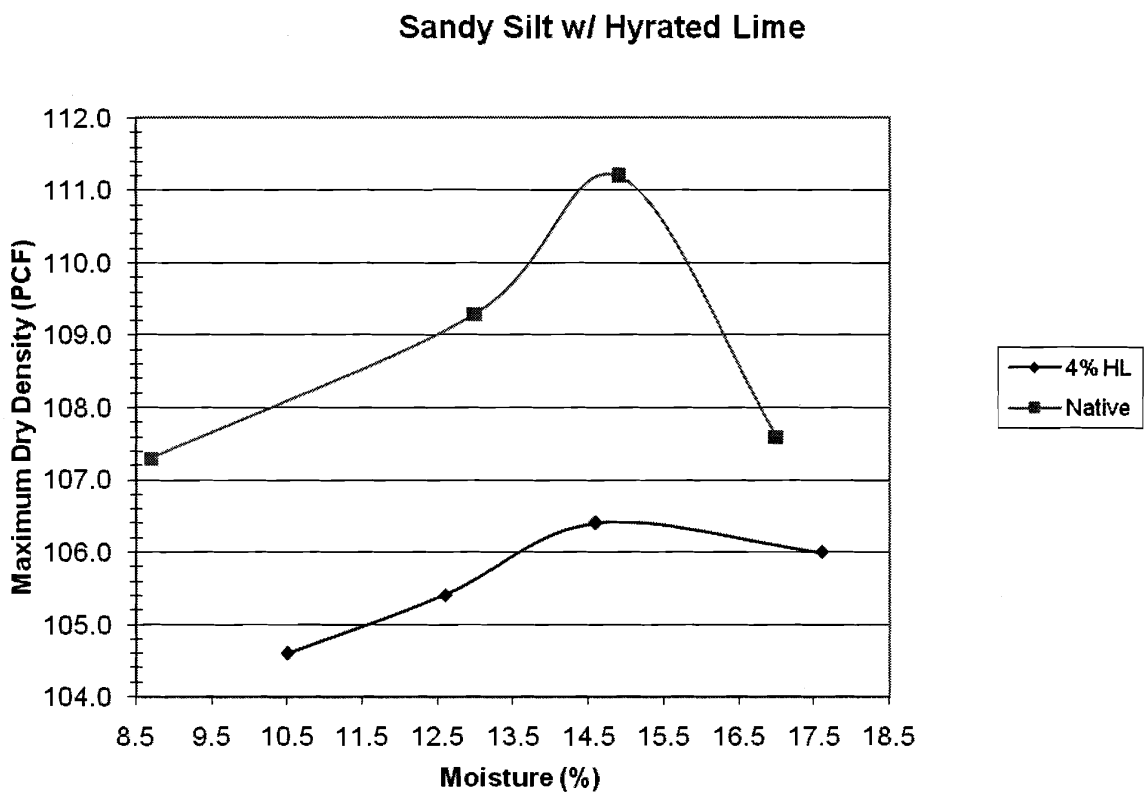

Fine Sand w/ Flyash
Maximum Dry Density (PCF)
122
120
118
116
114
112
110
108
106
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
15.5
Moisture (%)
10% FA
13% FA
15% FA
Native

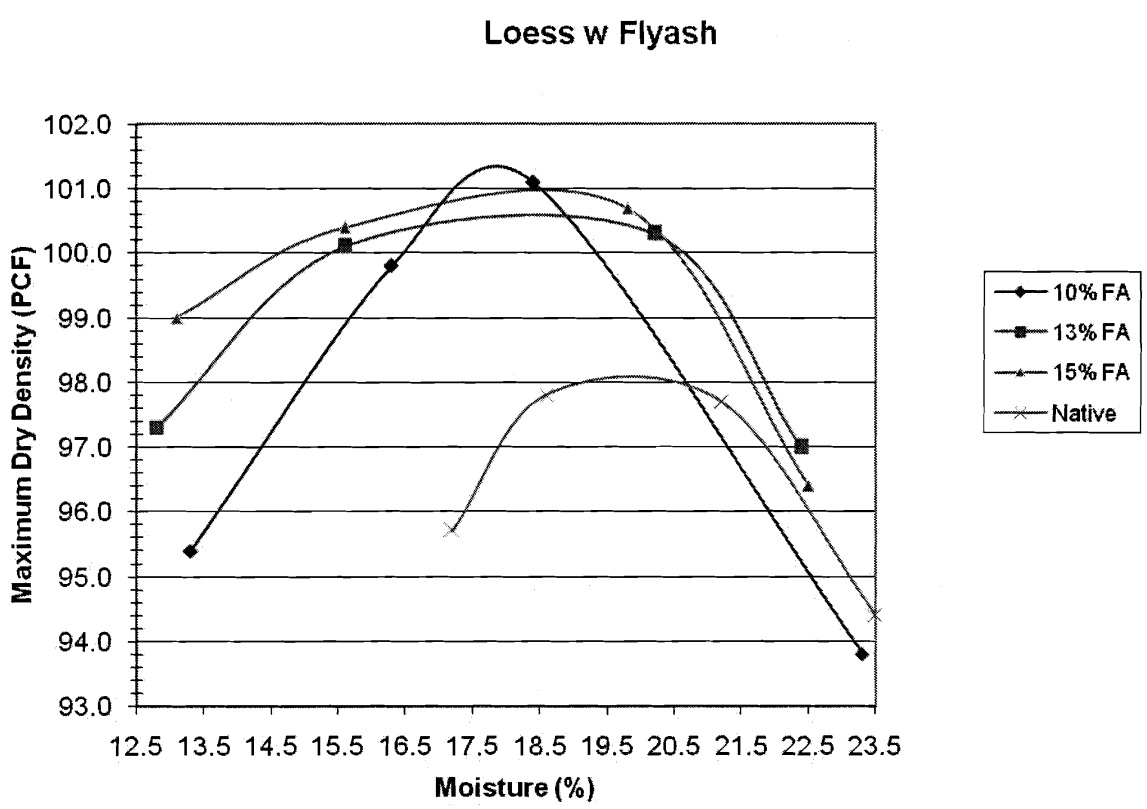

Fine Sand w/ CKD
Maximum Dry Density (PCF)
118
116
114
112
110
108
106
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
Moisture (%)
5% CKD
7% CKD
9% CKD
Native

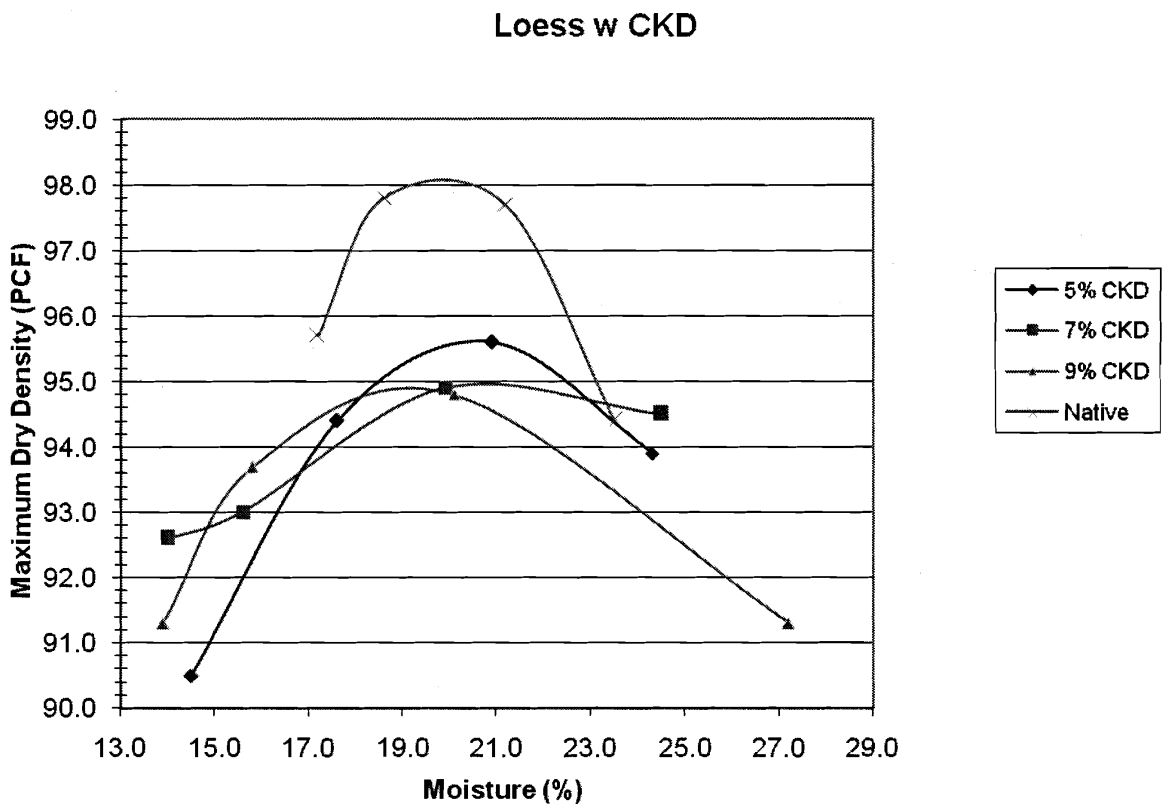

Fine Sand w/ Hydrated Lime
Maximum Dry Density (PCF)
116
115
114
113
112
111
110
109
108
107
106
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
Moisture (%)
2% HL
4% HL
Native

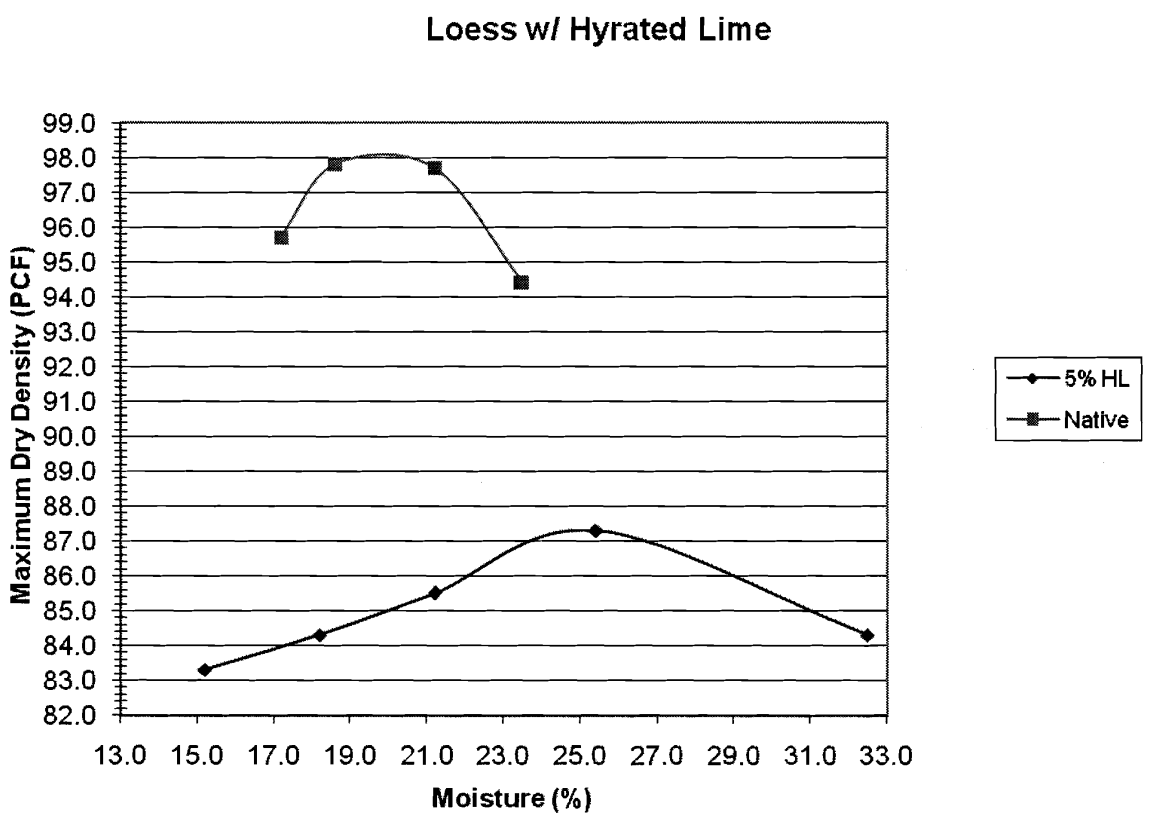

Sandy Silt w/ Flyash
116.0
114.0
112.0
110.0
108.0
106.0
104.0
Maximum Dry Density (PCF)
7.5 8.5 9.5 10.5 11.5 12.5 13.5 14.5 15.5 16.5 17.5 18.5
Moisture (%)
10% FA
13% FA
15% FA
Native

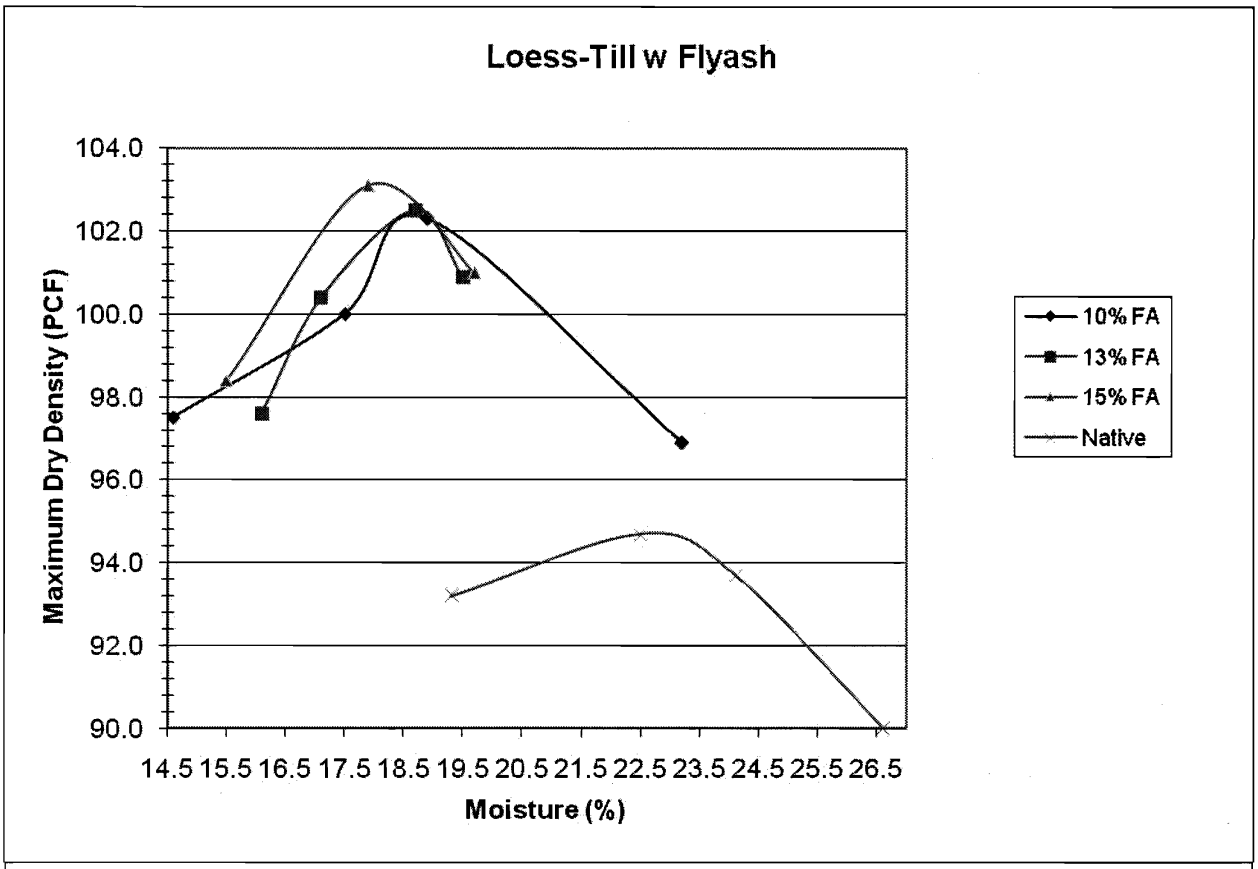

Sandy Silt w/ CKD
111.0
109.0
107.0
105.0
103.0
101.0
99.0
97.0
95.0
93.0
91.0
89.0
Maximum Dry Density (PCF)
9.5 10.5 11.5 12.5 13.5 14.5 15.5 16.5 17.5 18.5 19.5
Moisture (%)
5% CKD
7% CKD
9% CKD
Native

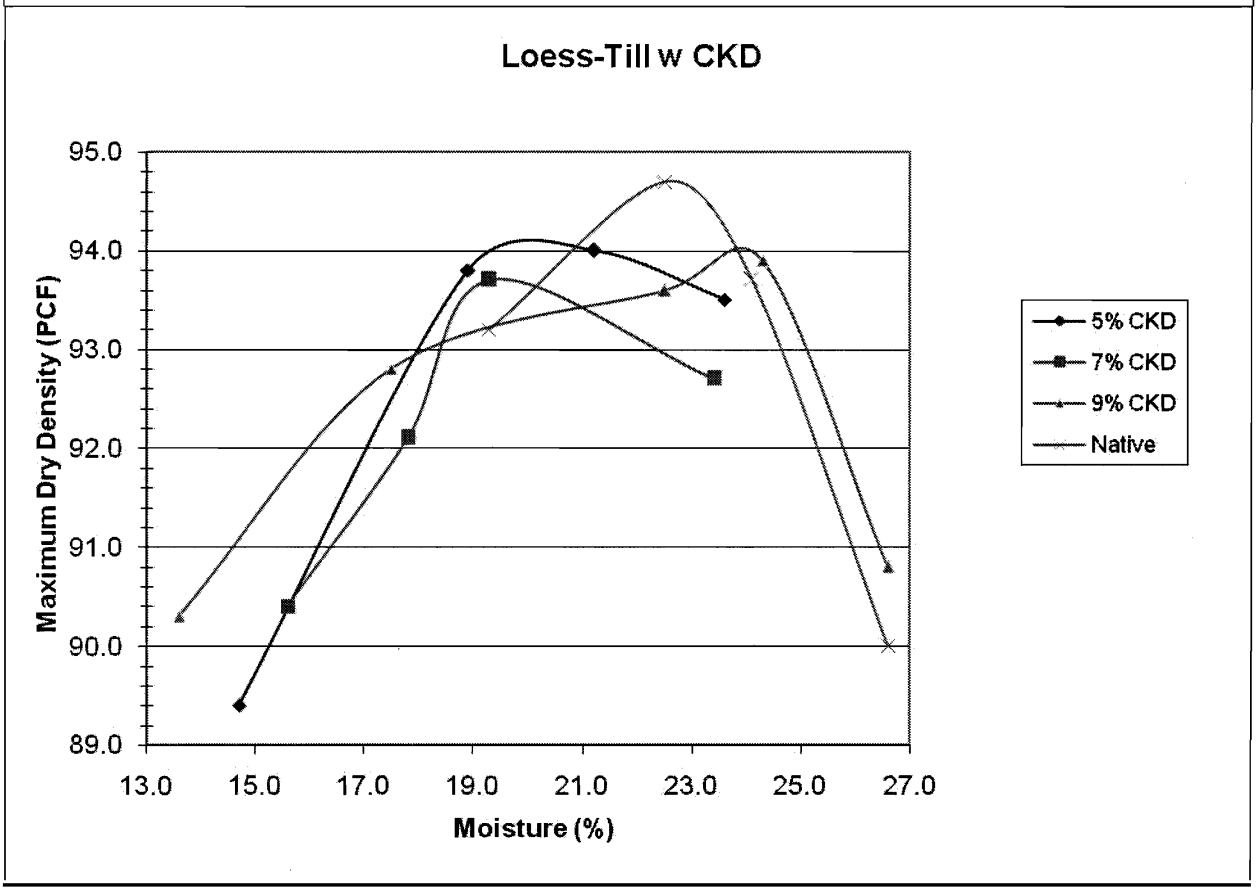

Sandy Silt w/ Hyrated Lime
112.0
111.0
110.0
109.0
108.0
107.0
106.0
105.0
104.0
Maximum Dry Density (PCF)
8.5
9.5
10.5
11.5
12.5
13.5
14.5
15.5
16.5
17.5
18.5
Moisture (%)
4% HL
Native

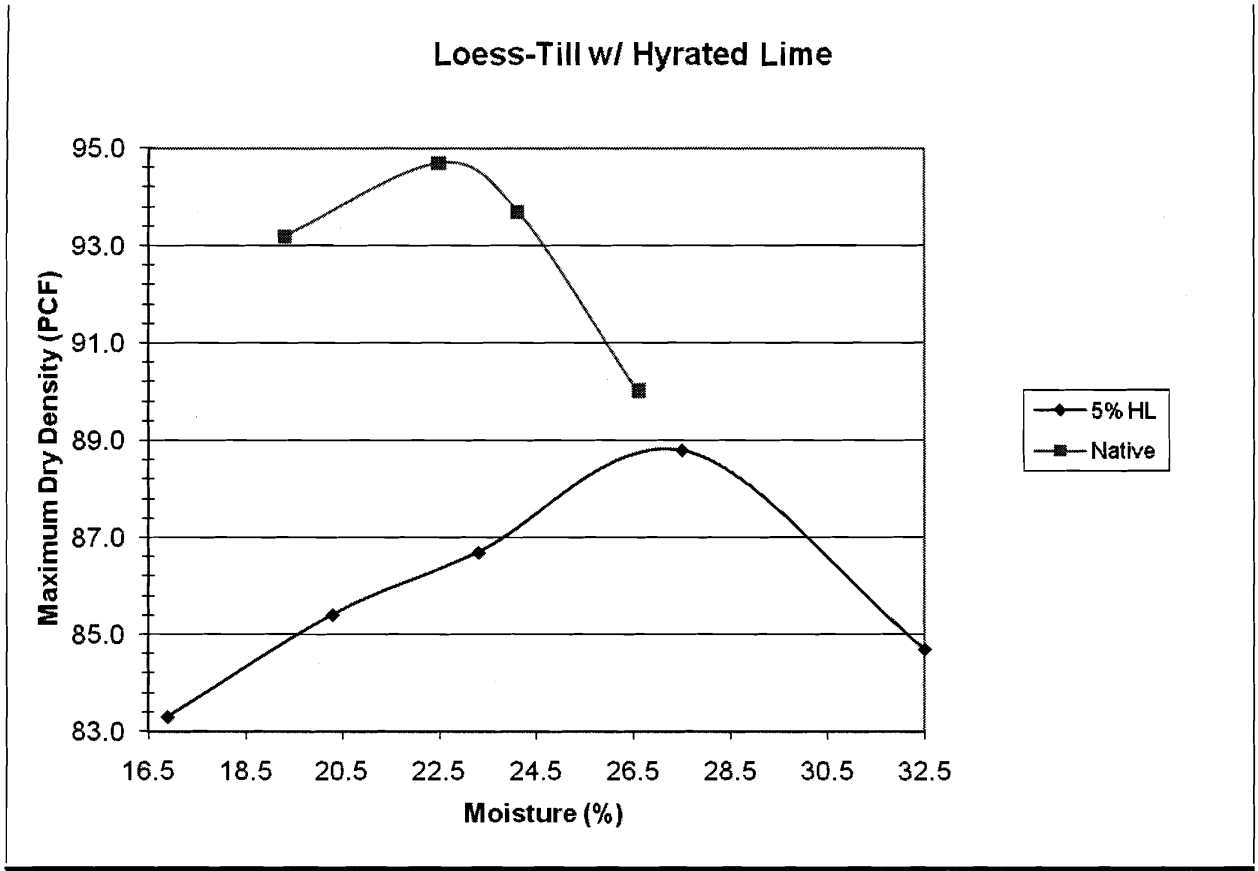

Loess w Flyash
102.0
101.0
100.0
99.0
98.0
97.0
96.0
95.0
94.0
93.0
Maximum Dry Density (PCF)
12.5
13.5
14.5
15.5
16.5
17.5
18.5
19.5
20.5
21.5
22.5
23.5
Moisture (%)
10% FA
13% FA
15% FA
Native

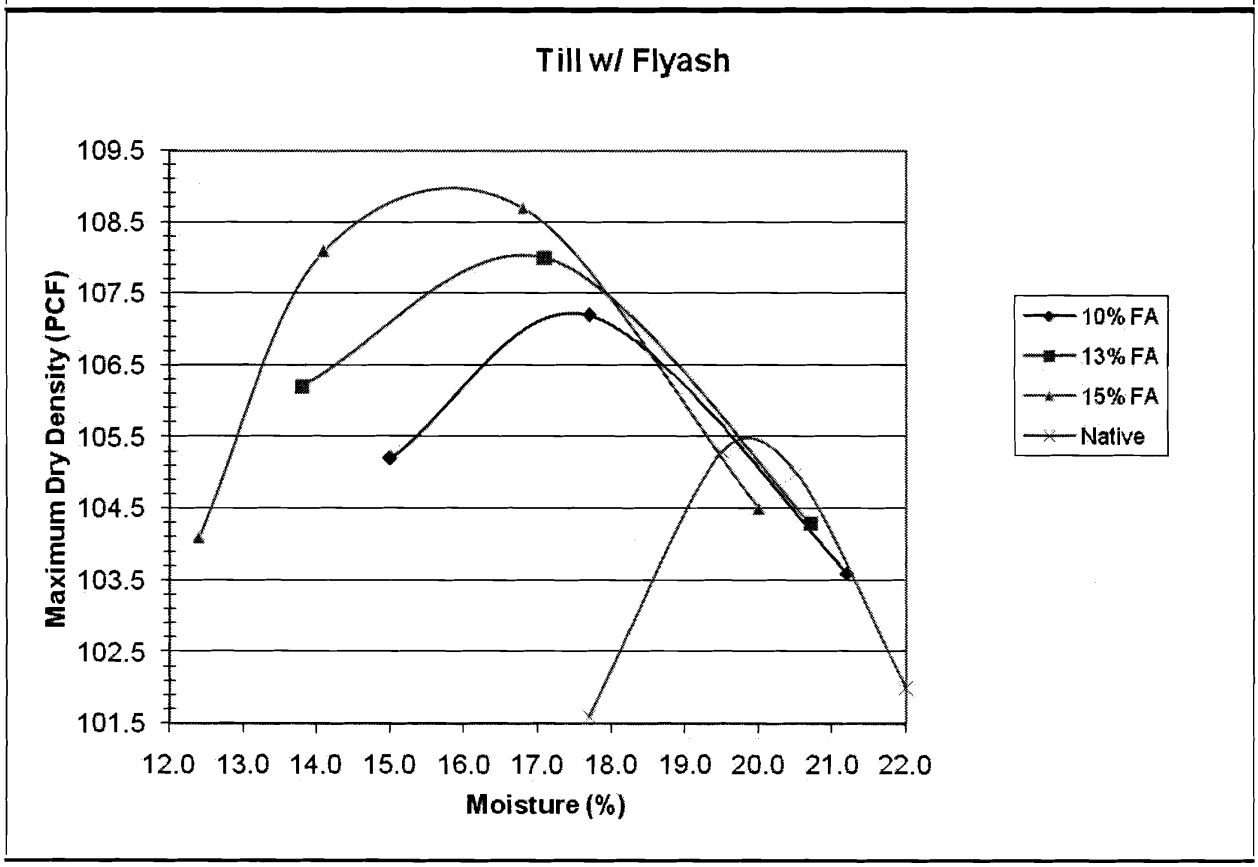

Loess w CKD
Maximum Dry Density (PCF)
99.0
98.0
97.0
96.0
95.0
94.0
93.0
92.0
91.0
90.0
13.0
15.0
17.0
19.0
21.0
23.0
25.0
27.0
29.0
Moisture (%)
5% CKD
7% CKD
9% CKD
Native

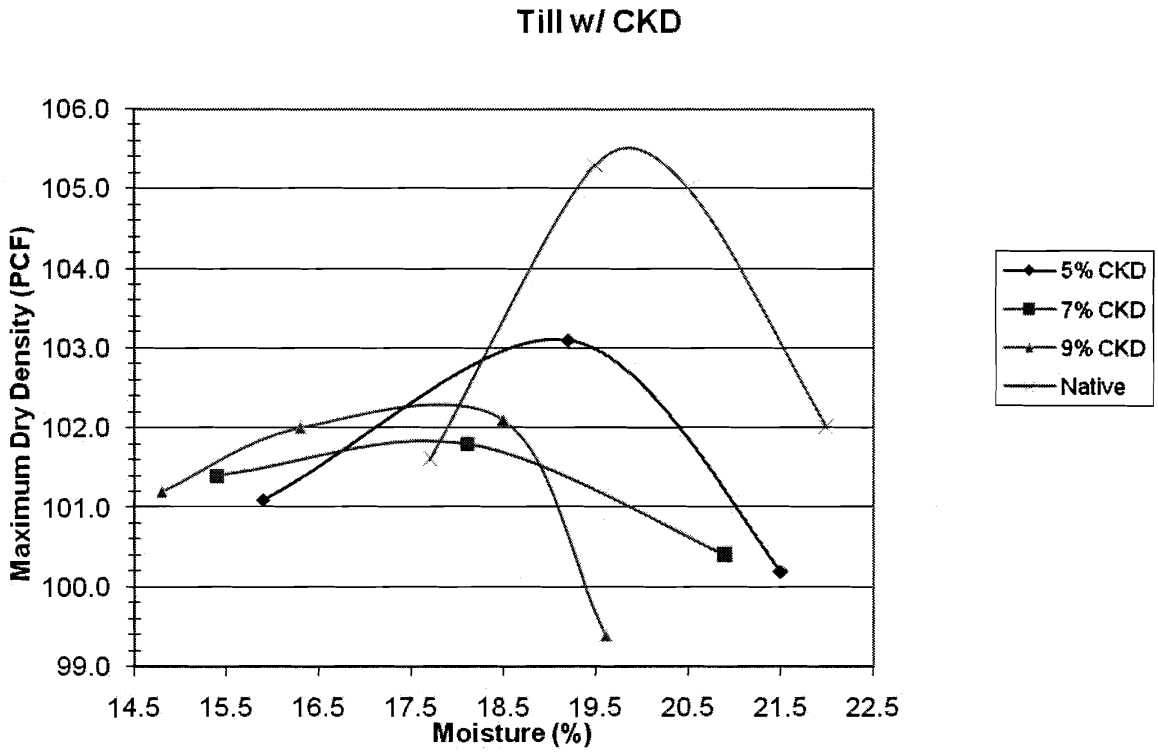

Loess w/ Hyrated Lime
Maximum Dry Density (PCF)
99.0
98.0
97.0
96.0
95.0
94.0
93.0
92.0
91.0
90.0
89.0
88.0
87.0
86.0
85.0
84.0
83.0
82.0
13.0
15.0
17.0
19.0
21.0
23.0
25.0
27.0
29.0
31.0
33.0
Moisture (%)
5% HL
Native

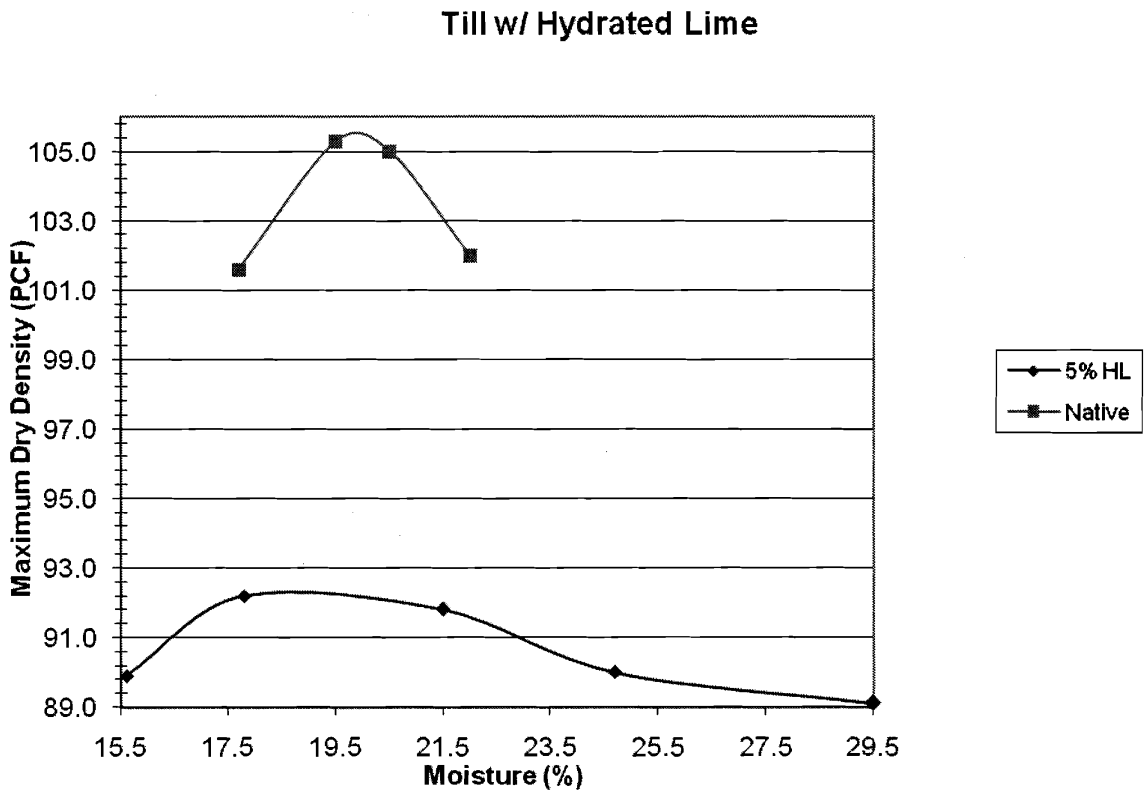

Loess-Till w Flyash
Maximum Dry Density (PCF)
104.0
102.0
100.0
98.0
96.0
94.0
92.0
90.0
14.5 15.5 16.5 17.5 18.5 19.5 20.5 21.5 22.5 23.5 24.5 25.5 26.5
Moisture (%)
10% FA
13% FA
15% FA
Native

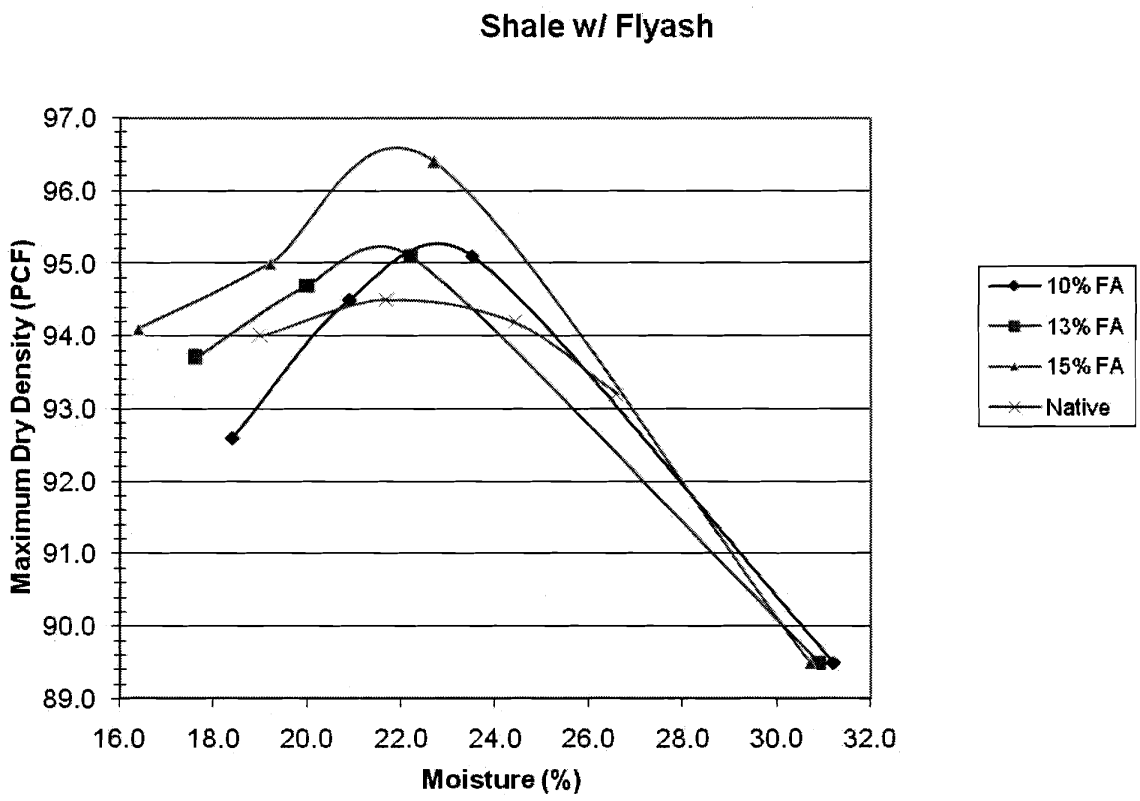

Loess-Till w CKD
Maximum Dry Density (PCF)
95.0
94.0
93.0
92.0
91.0
90.0
89.0
13.0 15.0 17.0 19.0 21.0 23.0 25.0 27.0
Moisture (%)
5% CKD
7% CKD
9% CKD
Native

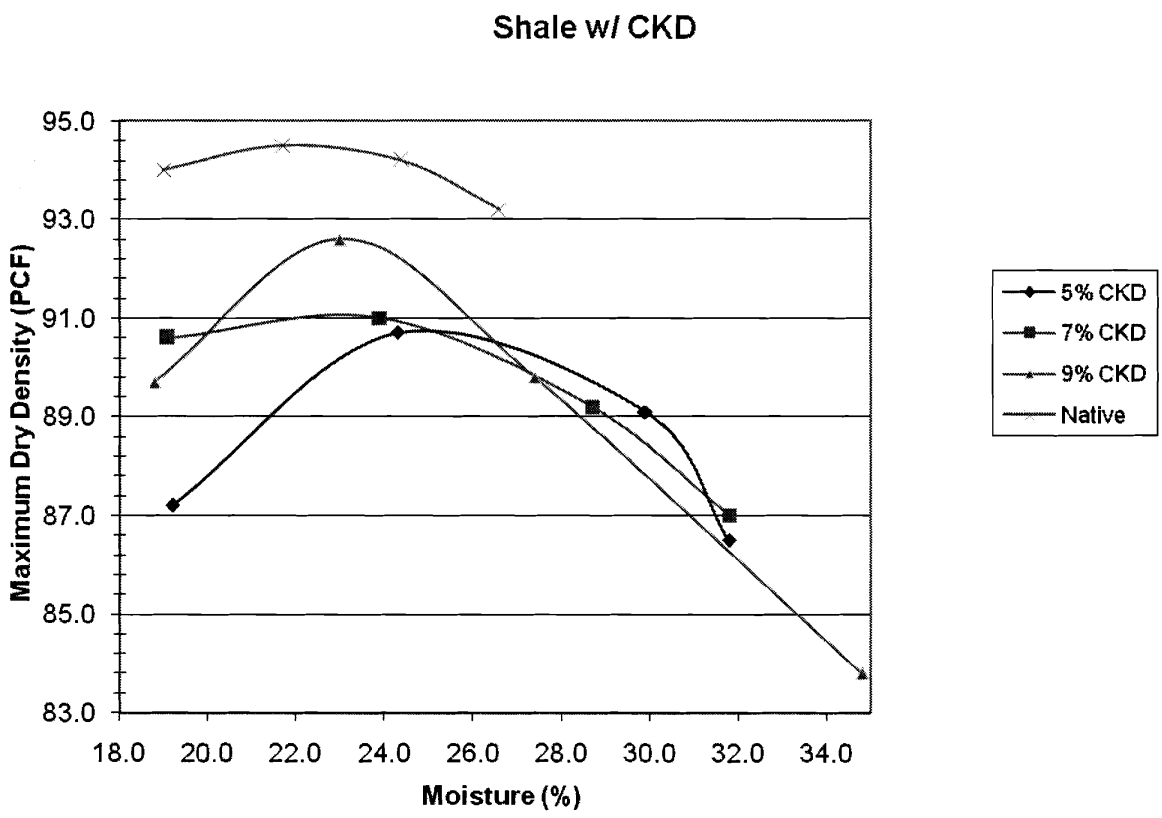

Loess-Till w/ Hyrated Lime
Maximum Dry Density (PCF)
95.0
93.0
91.0
89.0
87.0
85.0
83.0
16.5
18.5
20.5
22.5
24.5
26.5
28.5
30.5
32.5
Moisture (%)
5% HL
Native

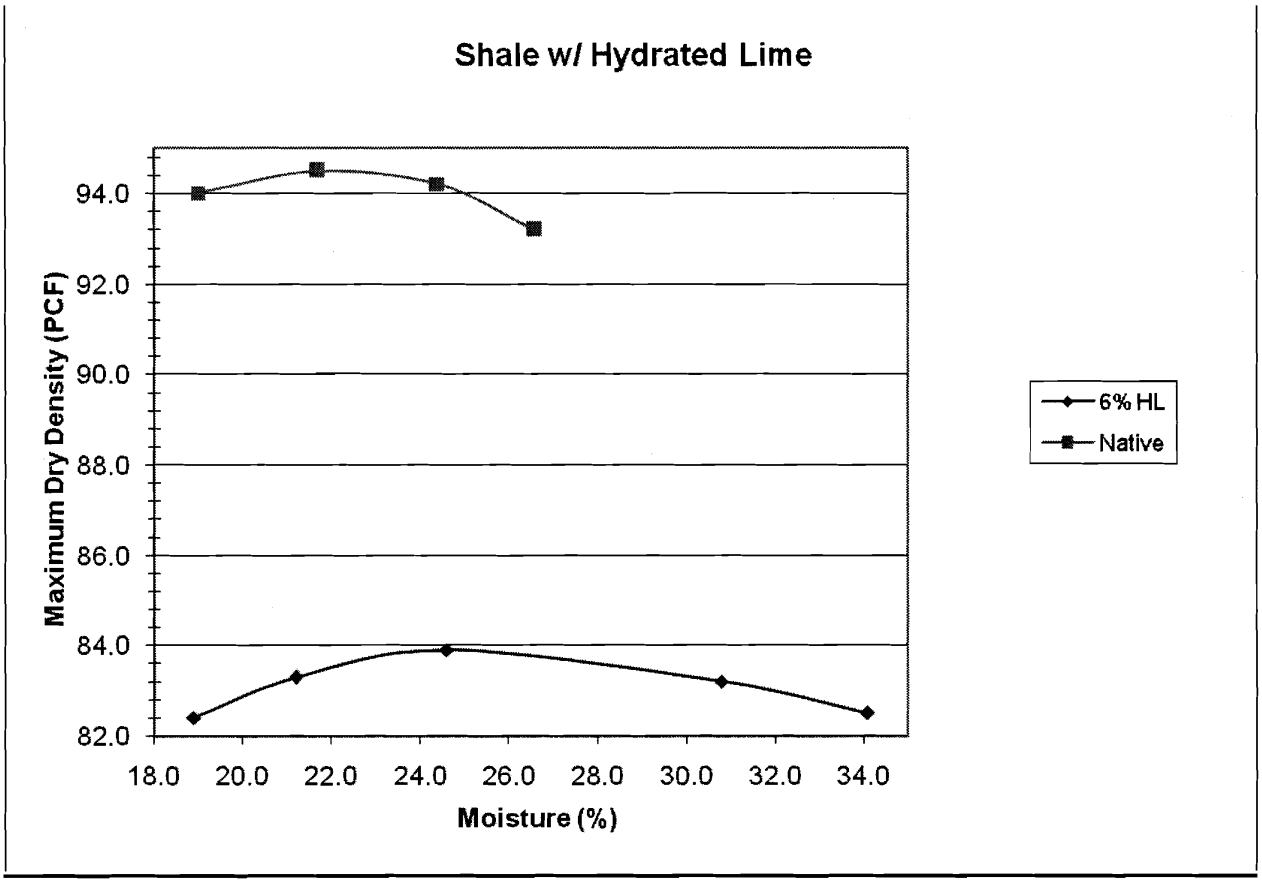

Till w/ Flyash
Maximum Dry Density (PCF)
109.5
108.5
107.5
106.5
105.5
104.5
103.5
102.5
101.5
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0
20.0
21.0
22.0
Moisture (%)
10% FA
13% FA
15% FA
Native


Till w/ CKD
Maximum Dry Density (PCF)
106.0
105.0
104.0
103.0
102.0
101.0
100.0
99.0
14.5
15.5
16.5
17.5
18.5
19.5
20.5
21.5
22.5
Moisture (%)
5% CKD
7% CKD
9% CKD
Native


Till w/ Hydrated Lime
Maximum Dry Density (PCF)
105.0
103.0
101.0
99.0
97.0
95.0
93.0
91.0
89.0
15.5
17.5
19.5
21.5
23.5
25.5
27.5
29.5
Moisture (%)
5% HL
Native

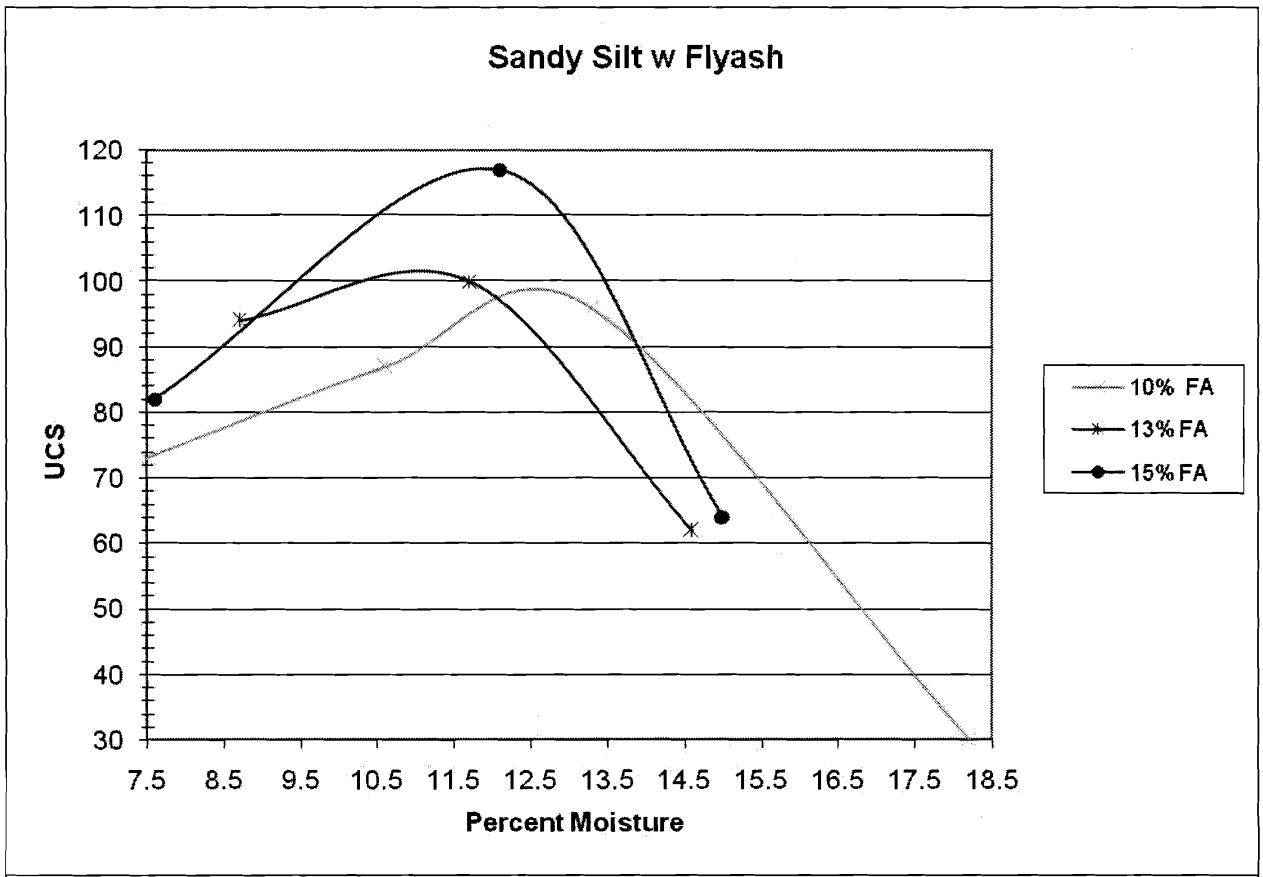

Shale w/ Flyash
Maximum Dry Density (PCF)
97.0
96.0
95.0
94.0
93.0
92.0
91.0
90.0
89.0
16.0
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
Moisture (%)
10% FA
13% FA
15% FA
Native

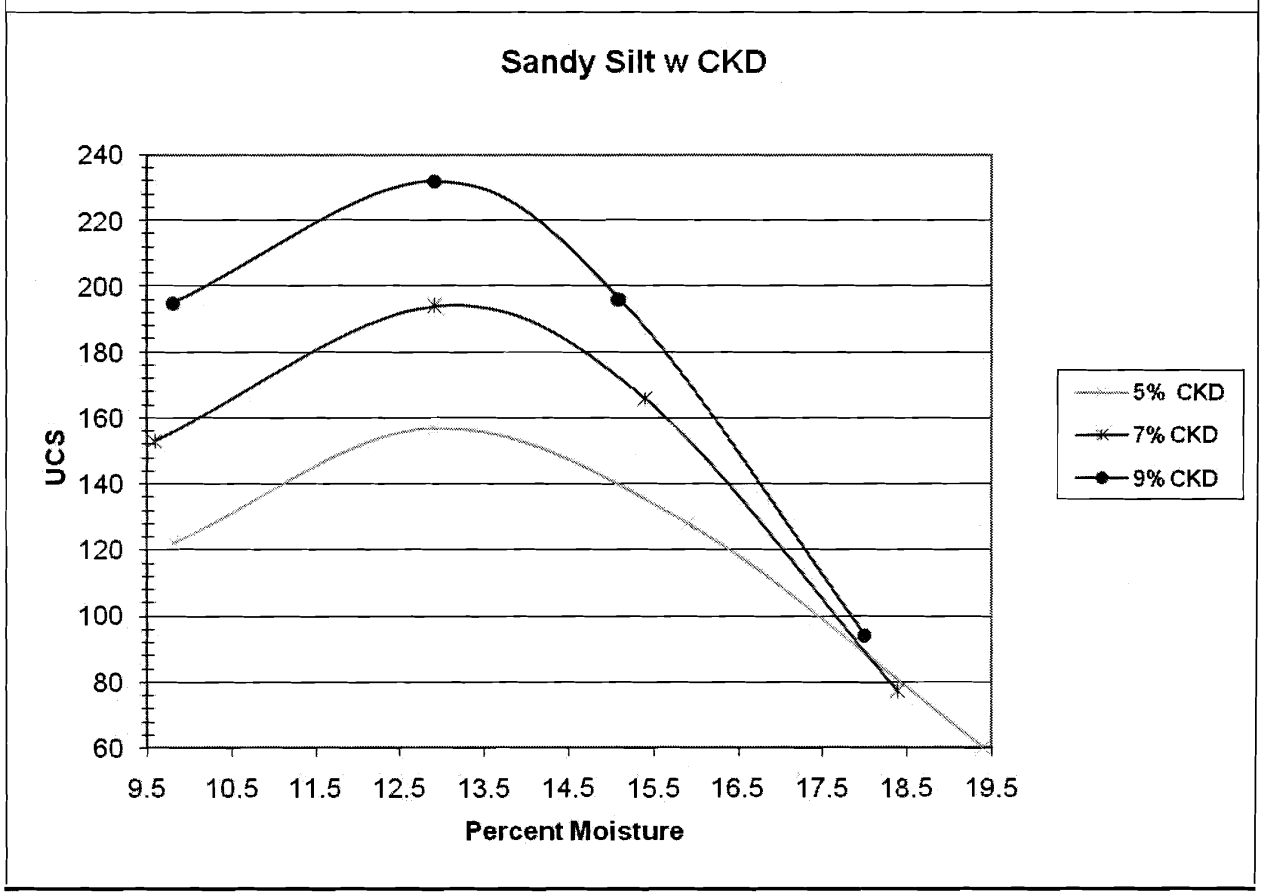

Shale w/ CKD
Maximum Dry Density (PCF)
95.0
93.0
91.0
89.0
87.0
85.0
83.0
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
Moisture (%)
5% CKD
7% CKD
9% CKD
Native

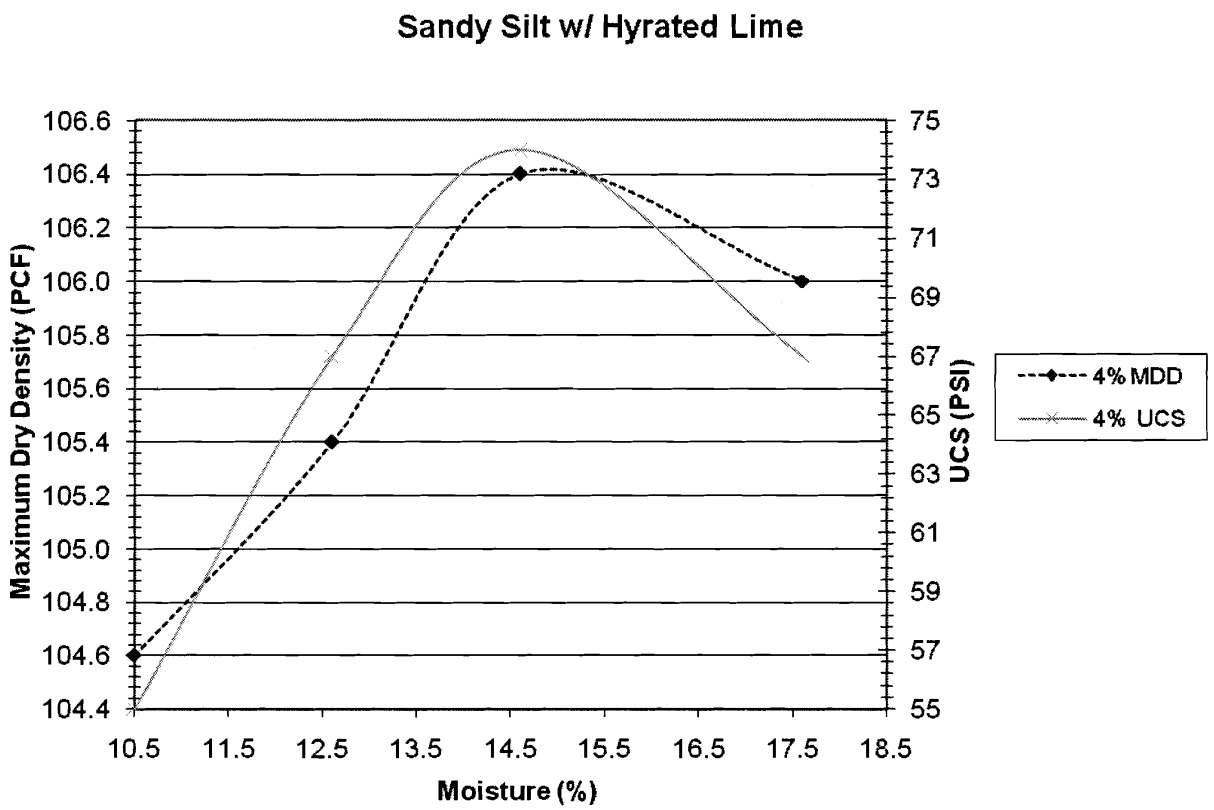

Shale w/ Hydrated Lime
Maximum Dry Density (PCF)
94.0
92.0
90.0
88.0
86.0
84.0
82.0
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
Moisture (%)
6% HL
Native

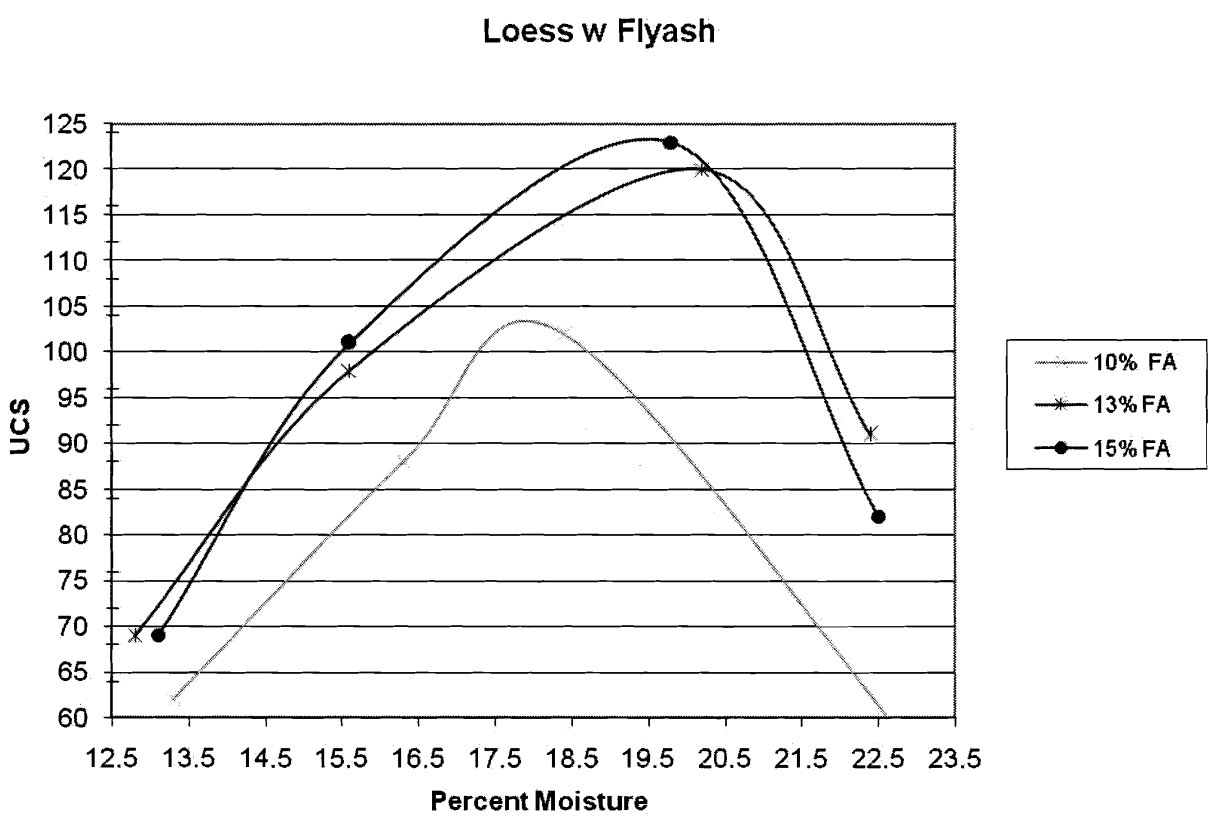
APPENDIX C

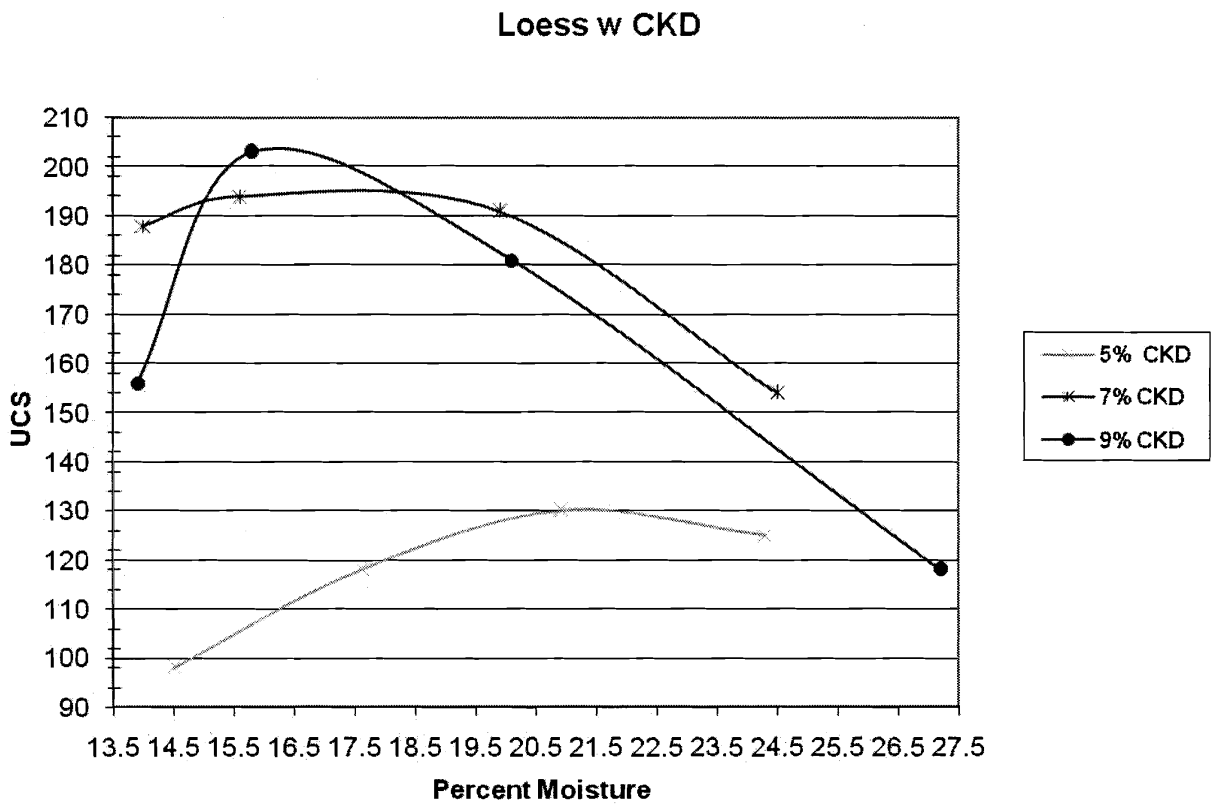
Unconfined Compressive Strength Curves

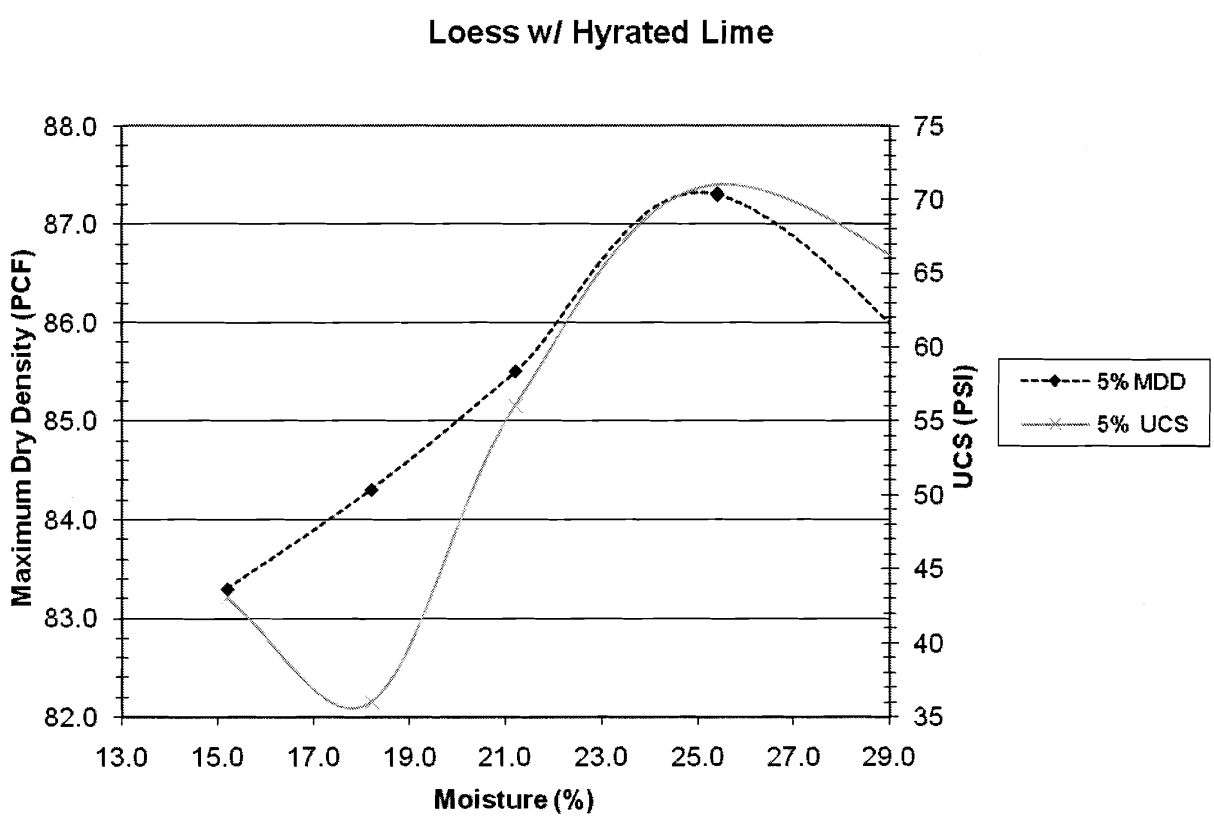

Sandy Silt w Flyash
UCS
120
110
100
90
80
70
60
50
40
30
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
15.5
16.5
17.5
18.5
Percent Moisture
10% FA
13% FA
15% FA

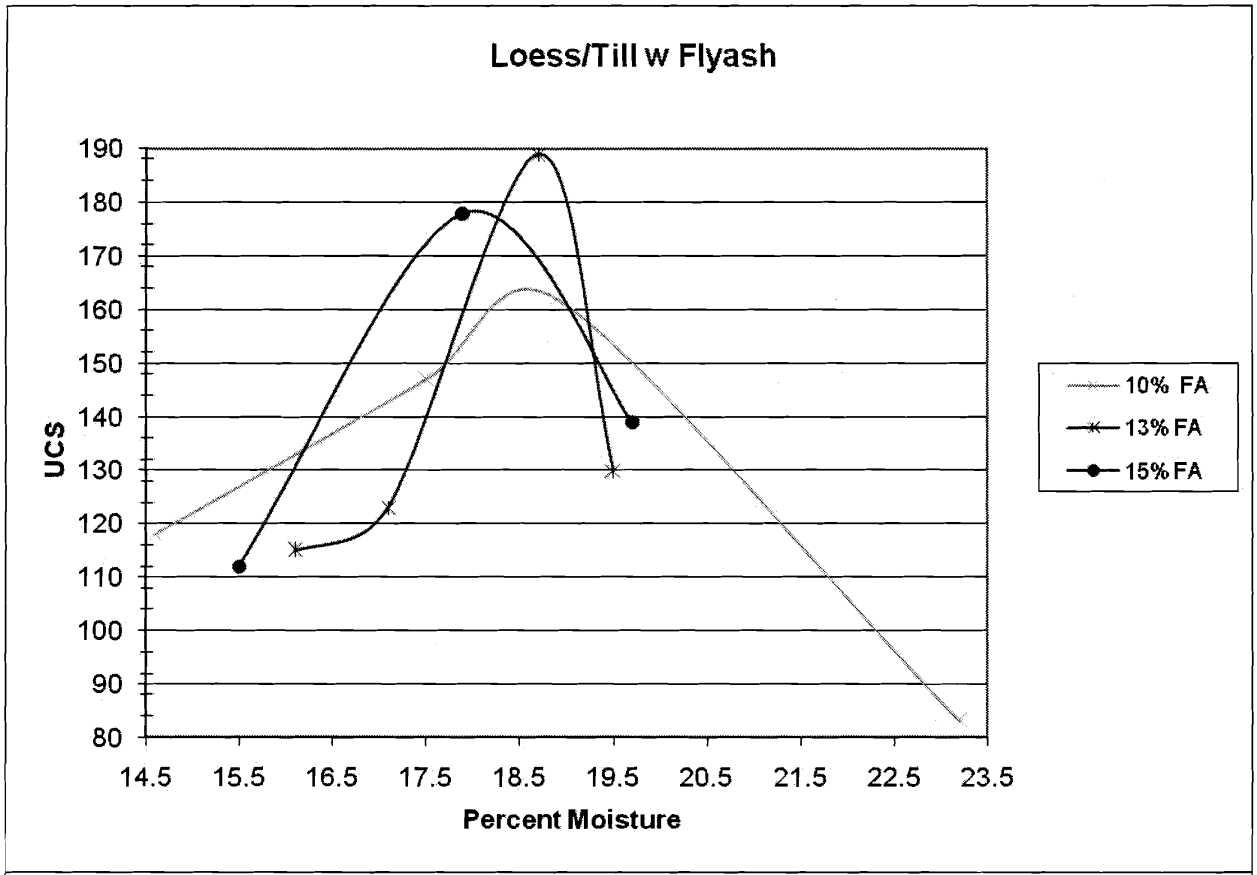

Sandy Silt w CKD
UCS
240
220
200
180
160
140
120
100
80
60
9.5
10.5
11.5
12.5
13.5
14.5
15.5
16.5
17.5
18.5
19.5
Percent Moisture
5% CKD
7% CKD
9% CKD

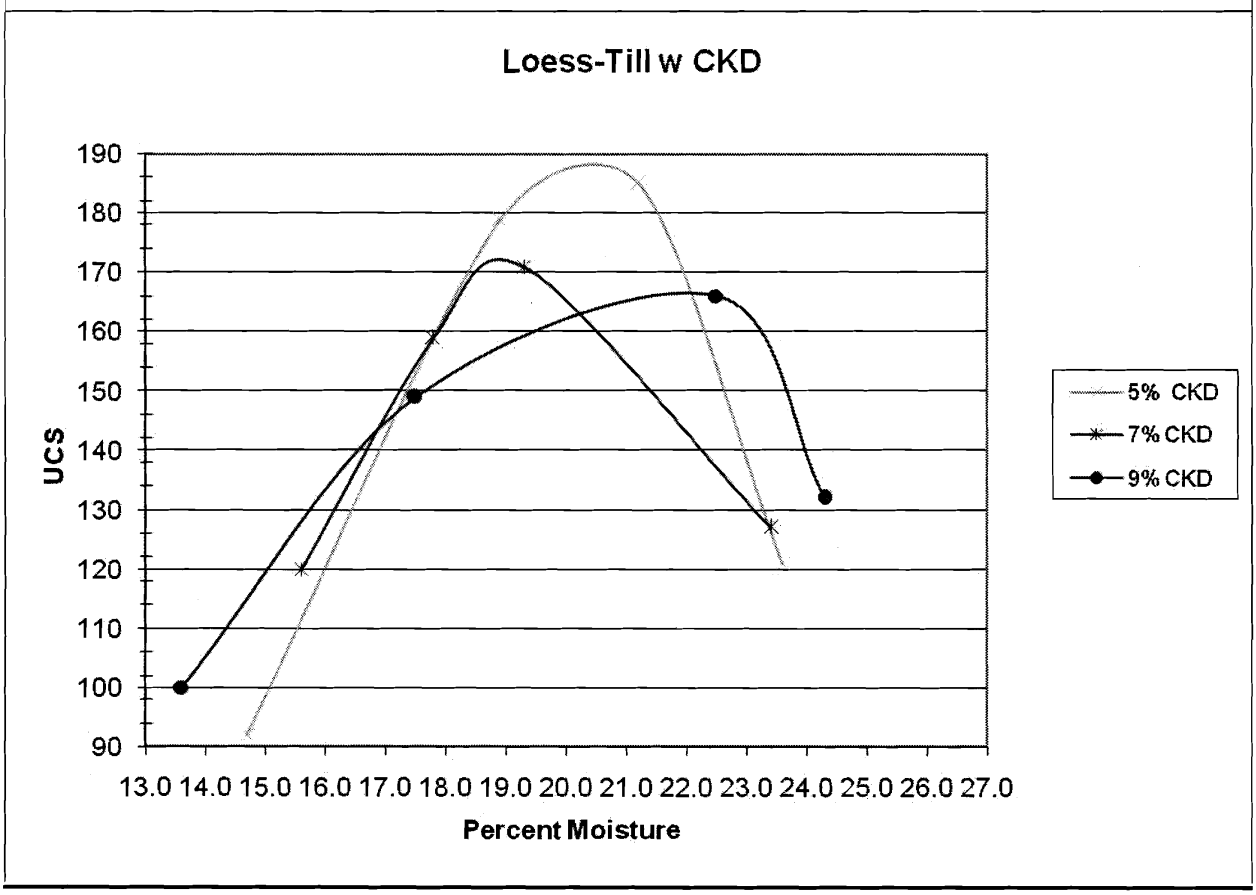

Sandy Silt w/ Hyrated Lime
Maximum Dry Density (PCF)
106.6
106.4
106.2
106.0
105.8
105.6
105.4
105.2
105.0
104.8
104.6
104.4
UCS (PSI)
75
73
71
69
67
65
63
61
59
57
55
10.5
11.5
12.5
13.5
14.5
15.5
16.5
17.5
18.5
Moisture (%)
4% MDD
4% UCS

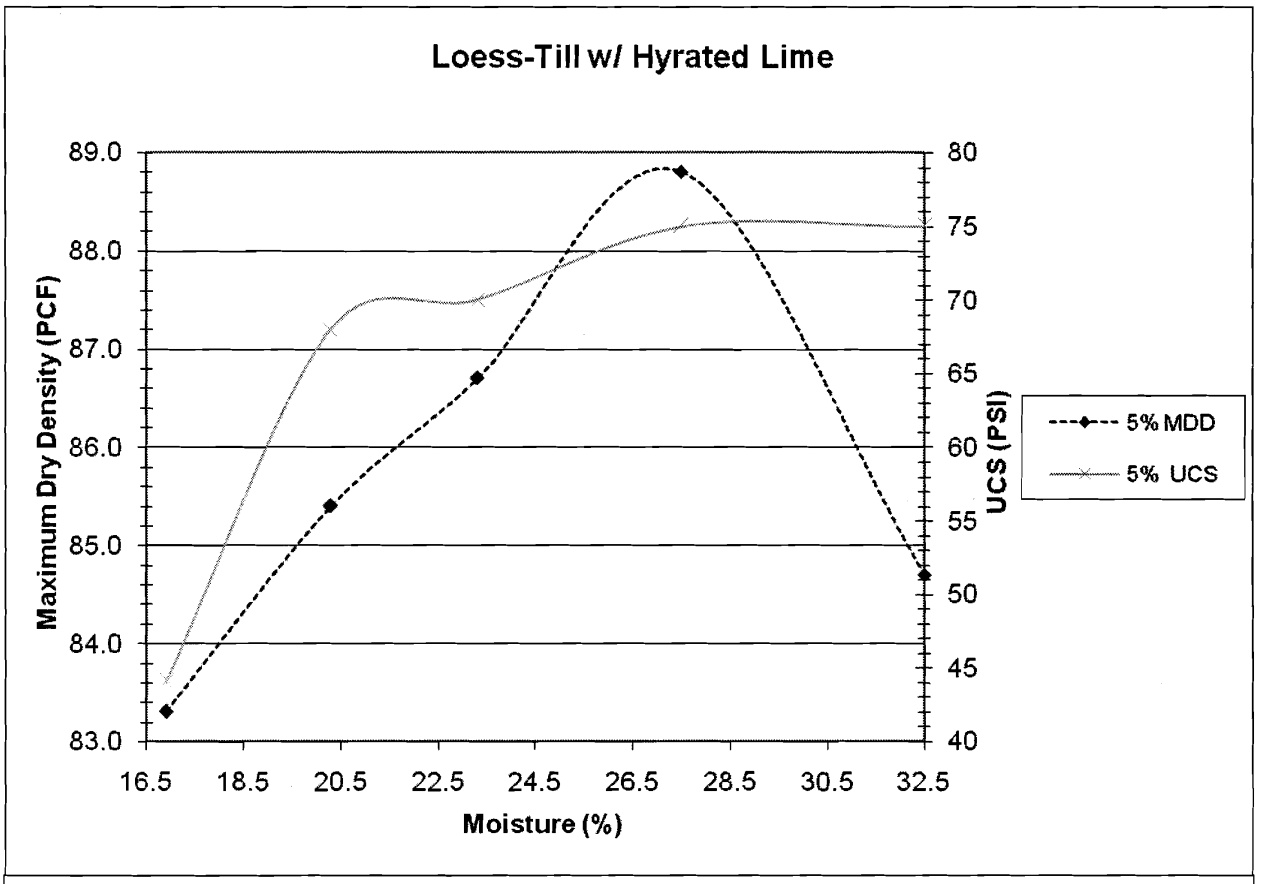

Loess w Flyash
UCS
125
120
115
110
105
100
95
90
85
80
75
70
65
60
12.5
13.5
14.5
15.5
16.5
17.5
18.5
19.5
20.5
21.5
22.5
23.5
Percent Moisture
10% FA
13% FA
15% FA

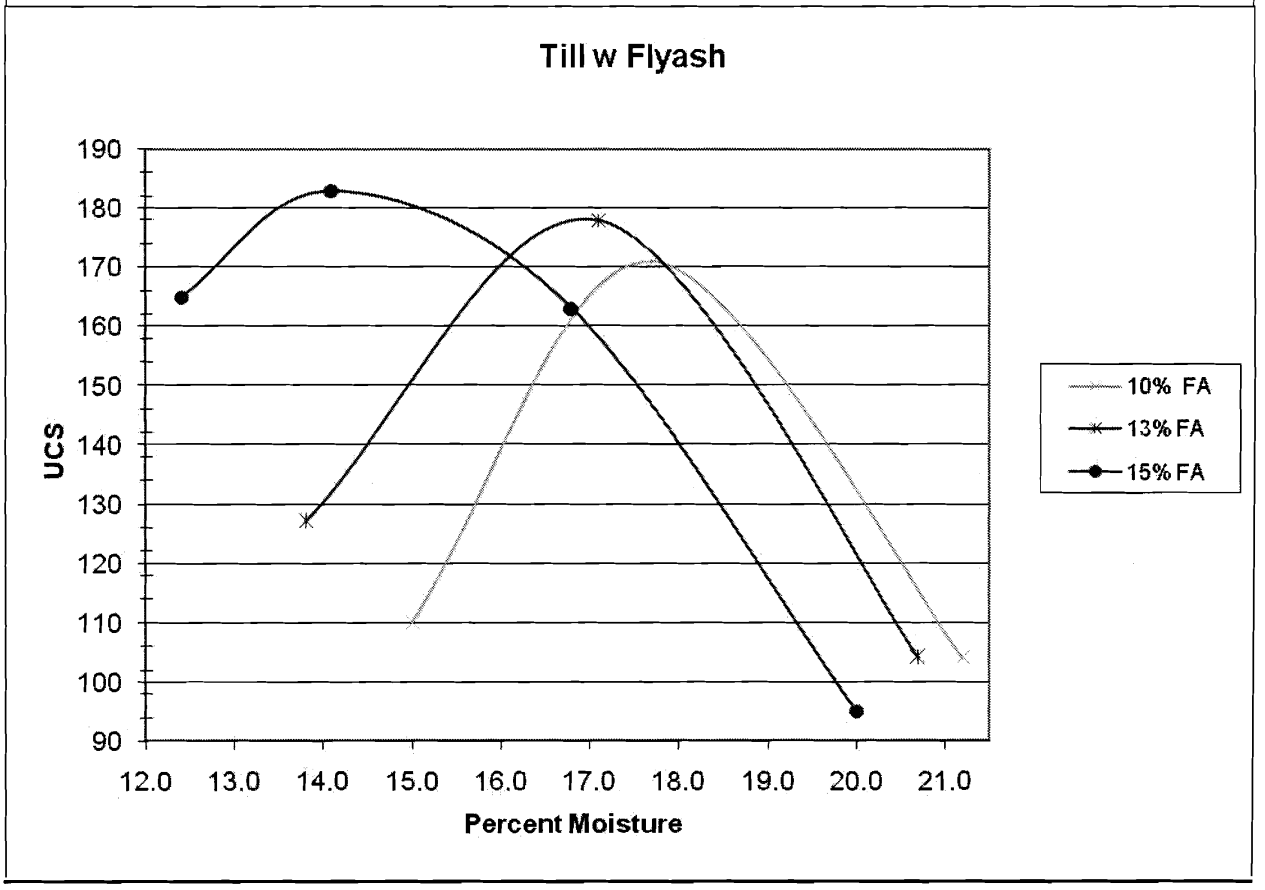

Loess w CKD
UCS
210
200
190
180
170
160
150
140
130
120
110
100
90
13.5 14.5 15.5 16.5 17.5 18.5 19.5 20.5 21.5 22.5 23.5 24.5 25.5 26.5 27.5
Percent Moisture
5% CKD
7% CKD
9% CKD

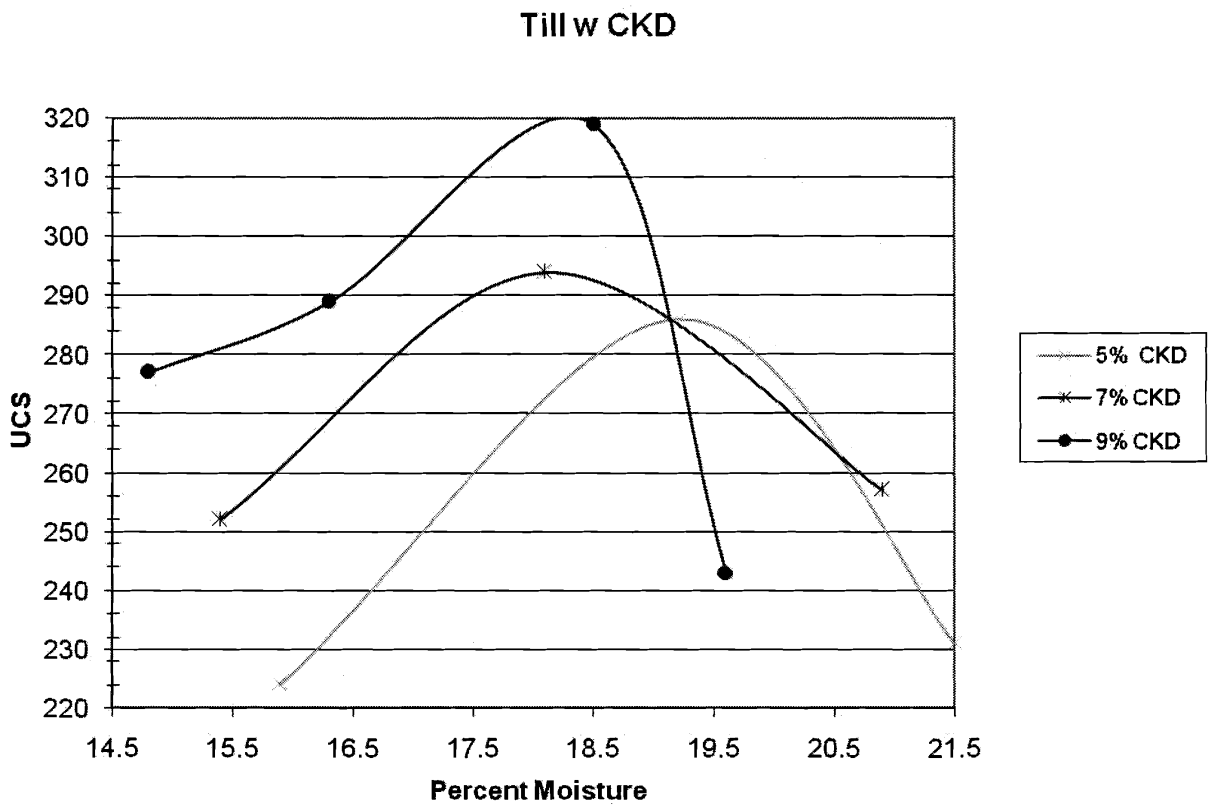

Loess w/ Hyrated Lime
Maximum Dry Density (PCF)
88.0
87.0
86.0
85.0
84.0
83.0
82.0
UCS (PSI)
75
70
65
60
55
50
45
40
35
13.0 15.0 17.0 19.0 21.0 23.0 25.0 27.0 29.0
Moisture (%)
5% MDD
5% UCS

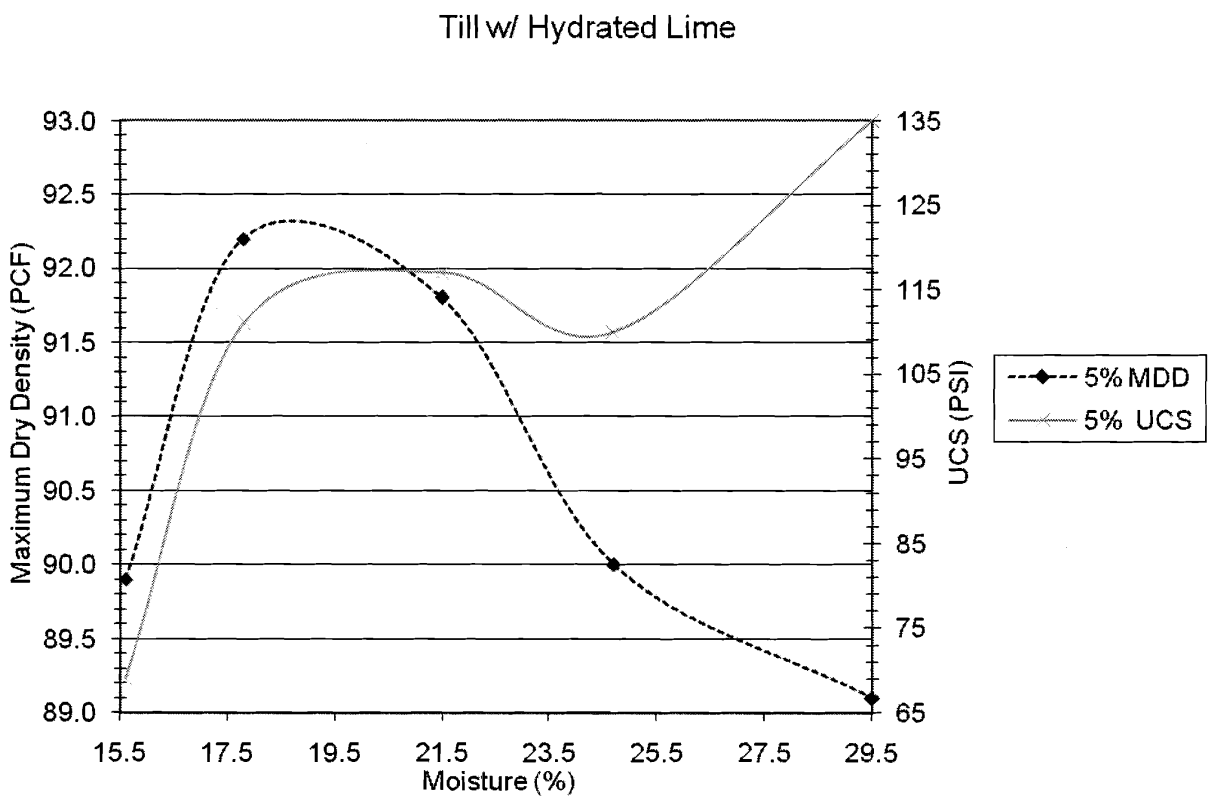

Loess/Till w Flyash
190
180
170
160
150
140
130
120
110
100
90
80
UCS
14.5
15.5
16.5
17.5
18.5
19.5
20.5
21.5
22.5
23.5
Percent Moisture
10% FA
13% FA
15% FA

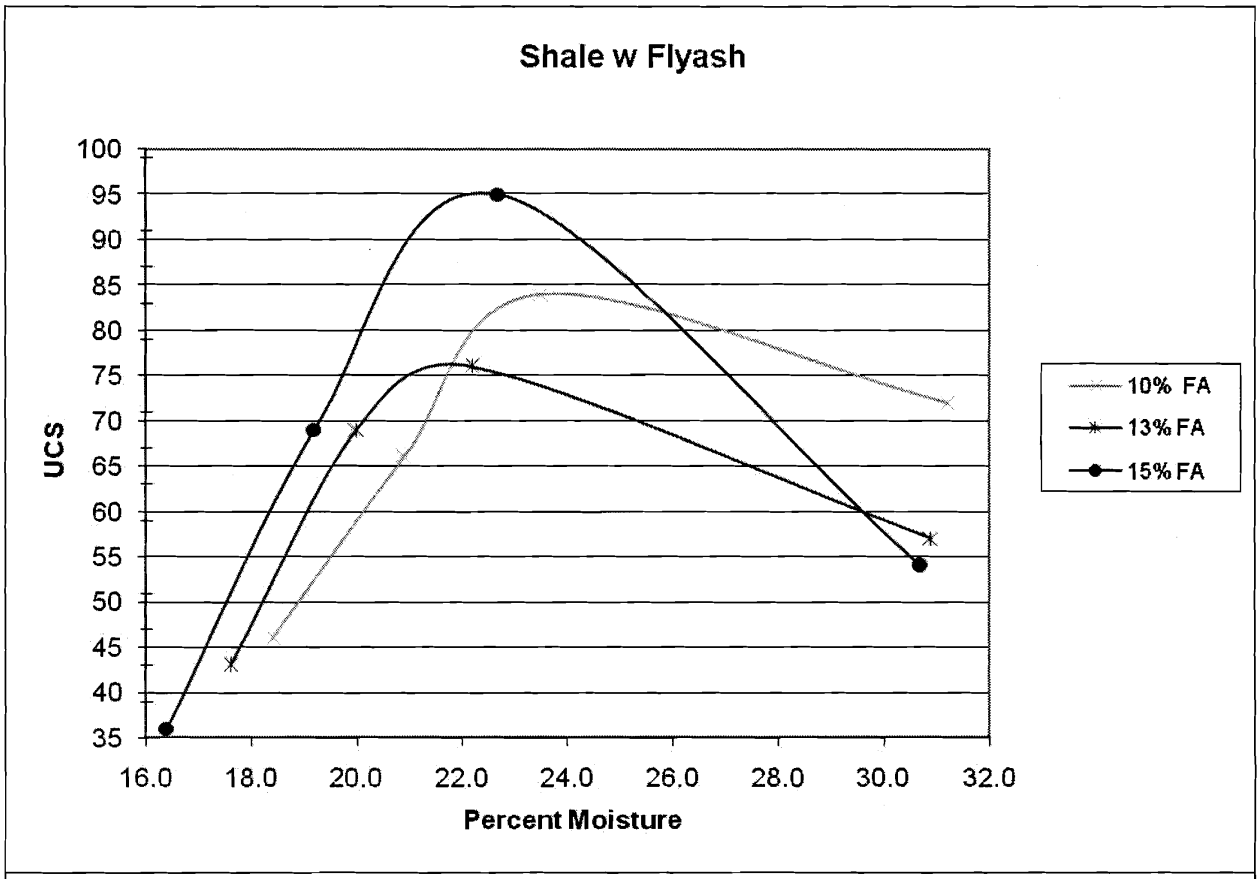

Loess-Till w CKD
190
180
170
160
150
140
130
120
110
100
90
UCS
13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0 21.0 22.0 23.0 24.0 25.0 26.0 27.0
Percent Moisture
5% CKD
7% CKD
9% CKD

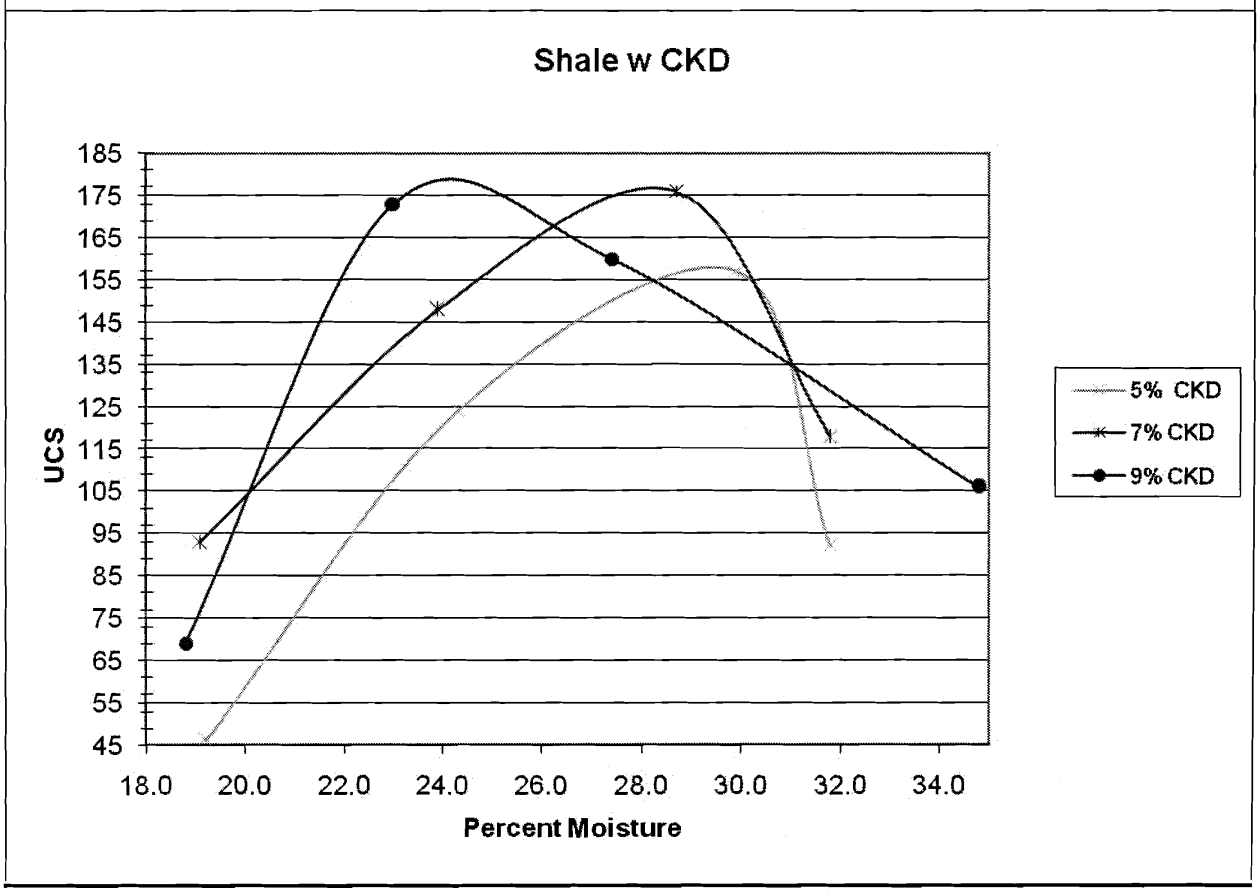

Loess-Till w/ Hyrated Lime
Maximum Dry Density (PCF)
89.0
88.0
87.0
86.0
85.0
84.0
83.0
UCS (PSI)
80
75
70
65
60
55
50
45
40
16.5
18.5
20.5
22.5
24.5
26.5
28.5
30.5
32.5
Moisture (%)
5% MDD
5% UCS

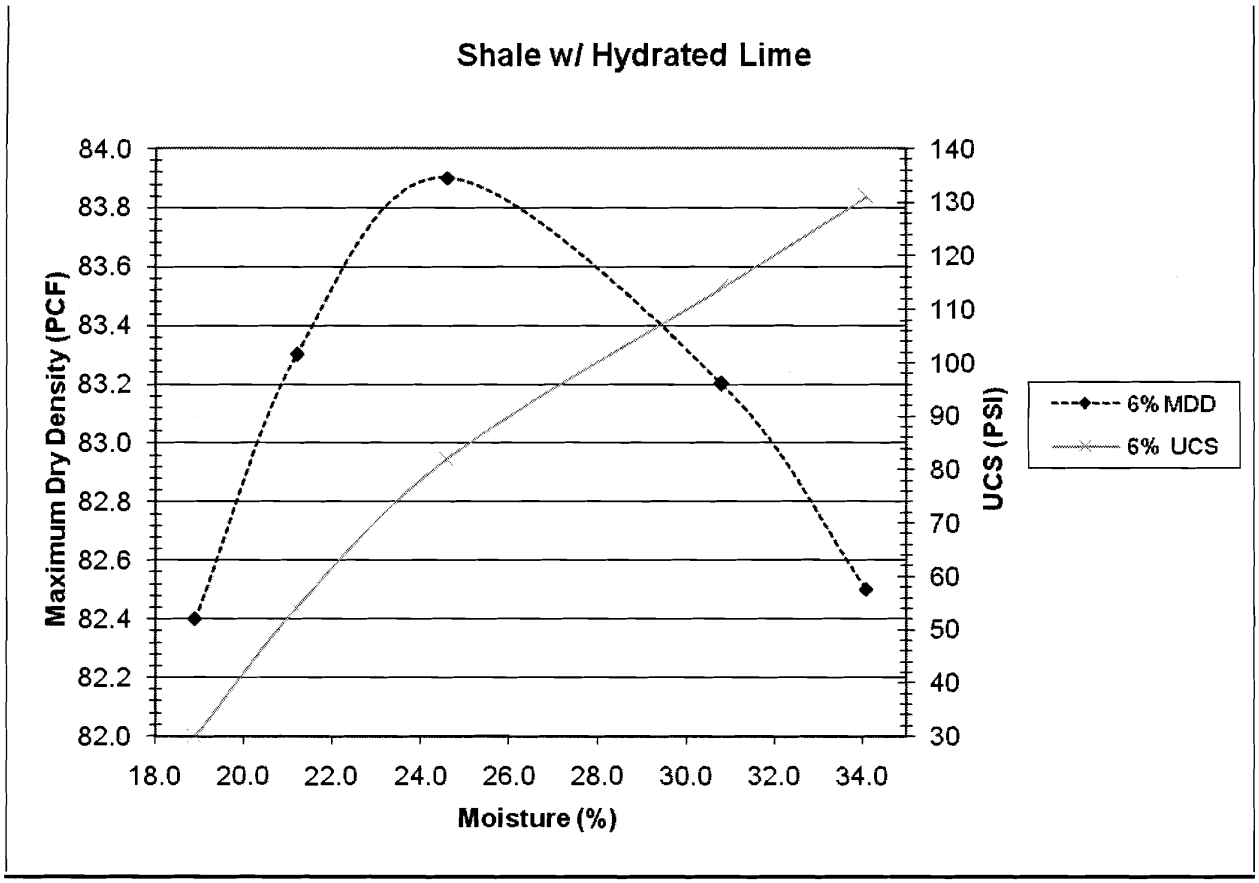

Till w Flyash
UCS
190
180
170
160
150
140
130
120
110
100
90
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0
20.0
21.0
Percent Moisture
10% FA
13% FA
15% FA


Till w CKD
UCS
320
310
300
290
280
270
260
250
240
230
220
14.5
15.5
16.5
17.5
18.5
19.5
20.5
21.5
Percent Moisture
5% CKD
7% CKD
9% CKD


Till w/ Hydrated Lime
Maximum Dry Density (PCF)
93.0
92.5
92.0
91.5
91.0
90.5
90.0
89.5
89.0
UCS (PSI)
135
125
115
105
95
85
75
65
15.5
17.5
19.5
21.5
23.5
25.5
27.5
29.5
Moisture (%)
5% MDD
5% UCS


Shale w Flyash
UCS
100
95
90
85
80
75
70
65
60
55
50
45
40
35
16.0
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
Percent Moisture
10% FA
13% FA
15% FA

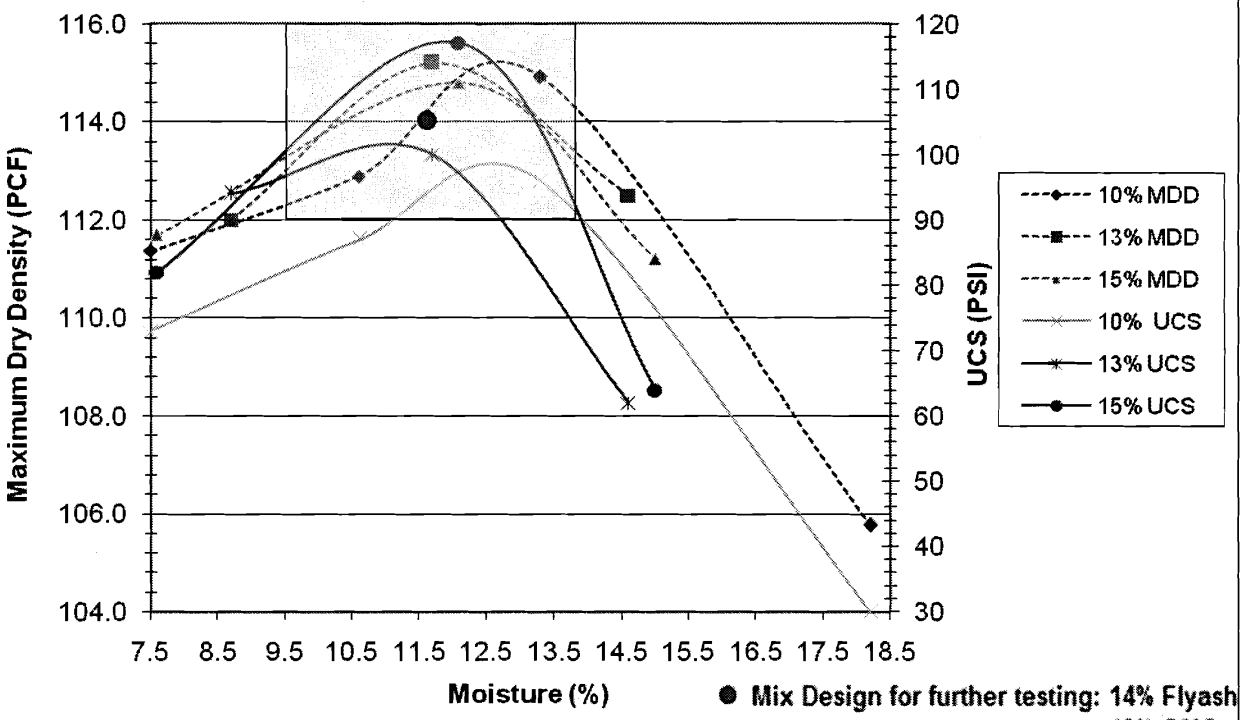

Shale w CKD
UCS
185
175
165
155
145
135
125
115
105
95
85
75
65
55
45
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
Percent Moisture
5% CKD
7% CKD
9% CKD


Shale w/ Hydrated Lime
Maximum Dry Density (PCF)
84.0
83.8
83.6
83.4
83.2
83.0
82.8
82.6
82.4
82.2
82.0
UCS (PSI)
140
130
120
110
100
90
80
70
60
50
40
30
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
Moisture (%)
6% MDD
6% UCS

APPENDIX D

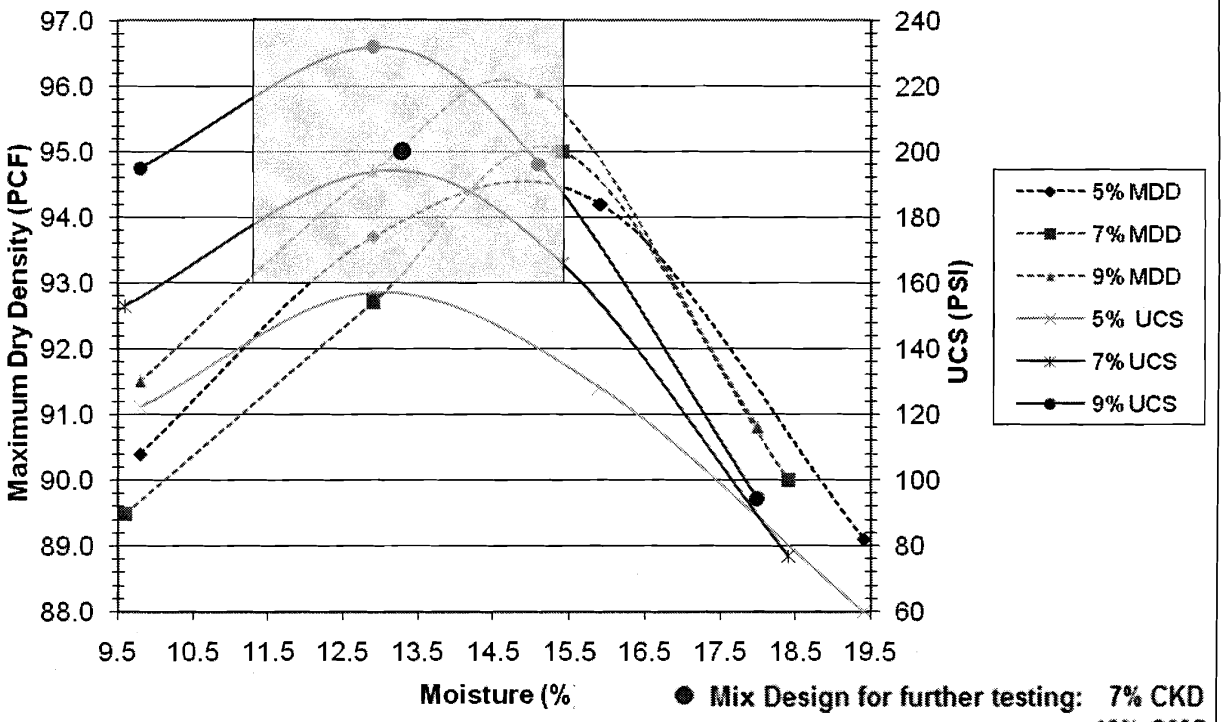
Optimum Pozzolan Percentages with Optimum Moisture Contents

Sandy Silt w/ Flyash

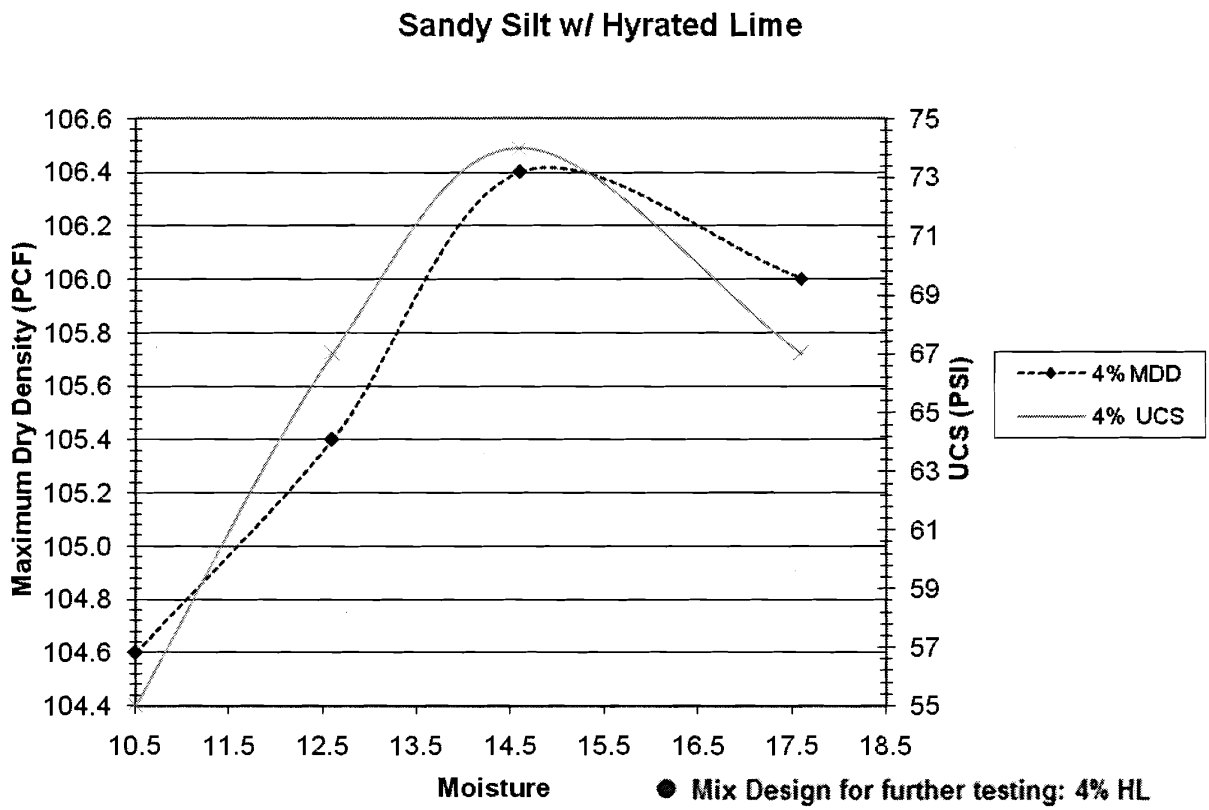


● Mix Design for further testing: 14% Flyash
12% OMC

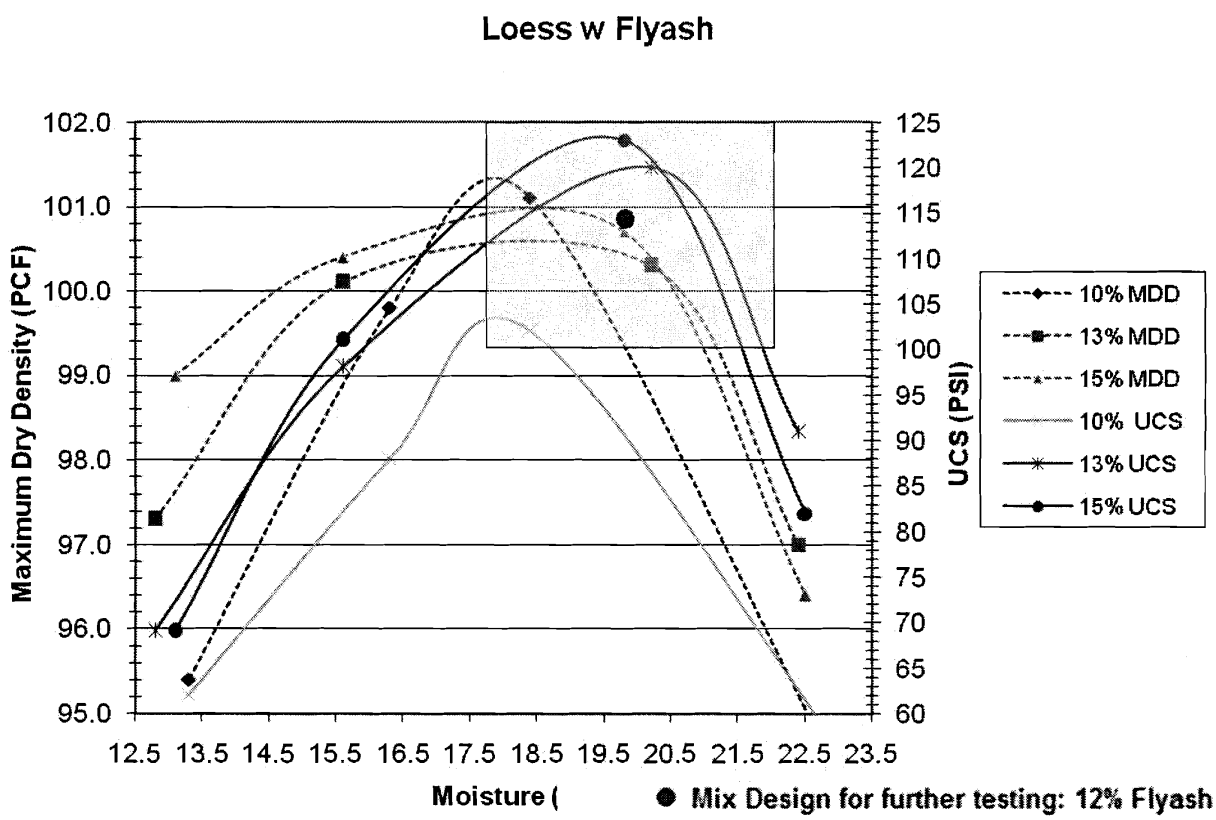
Sandy Silt w/ CKD



● Mix Design for further testing: 7% CKD
13% OMC

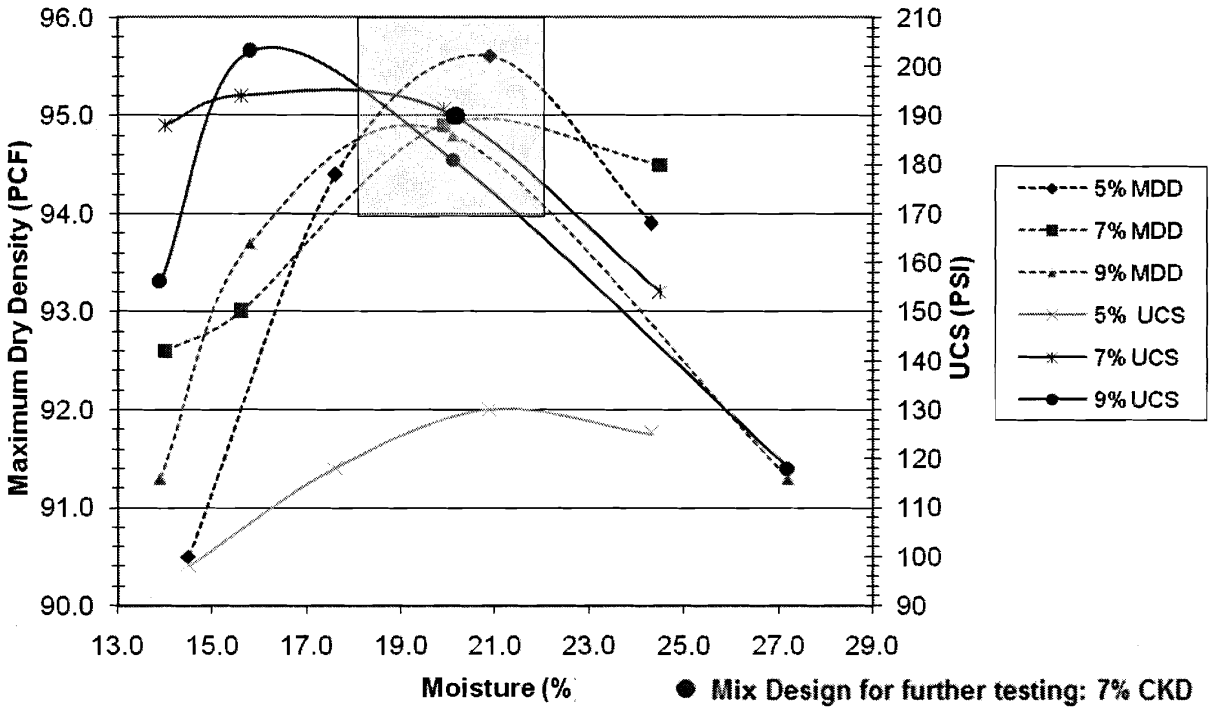


● Mix Design for further testing: 4% HL
14.5% OMC



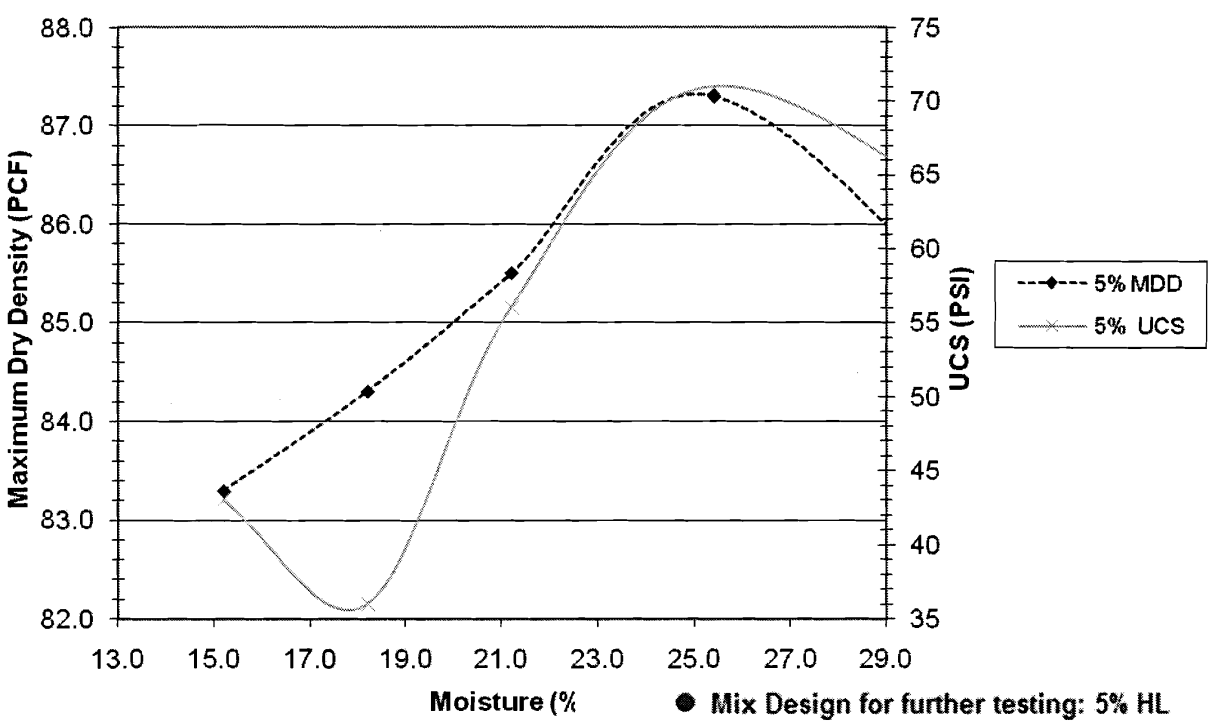
● Mix Design for further testing: 12% Flyash
19.5% OMC

Loess w CKD

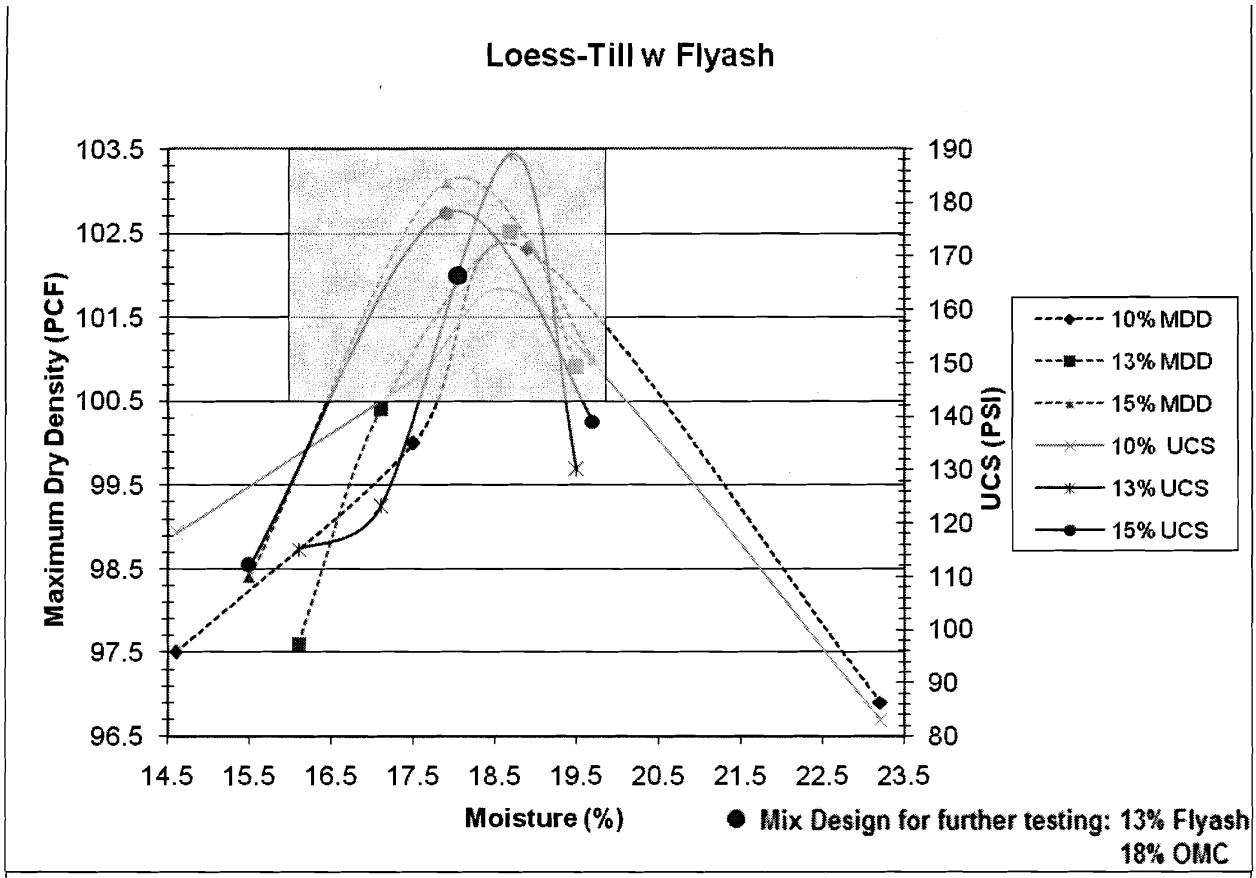


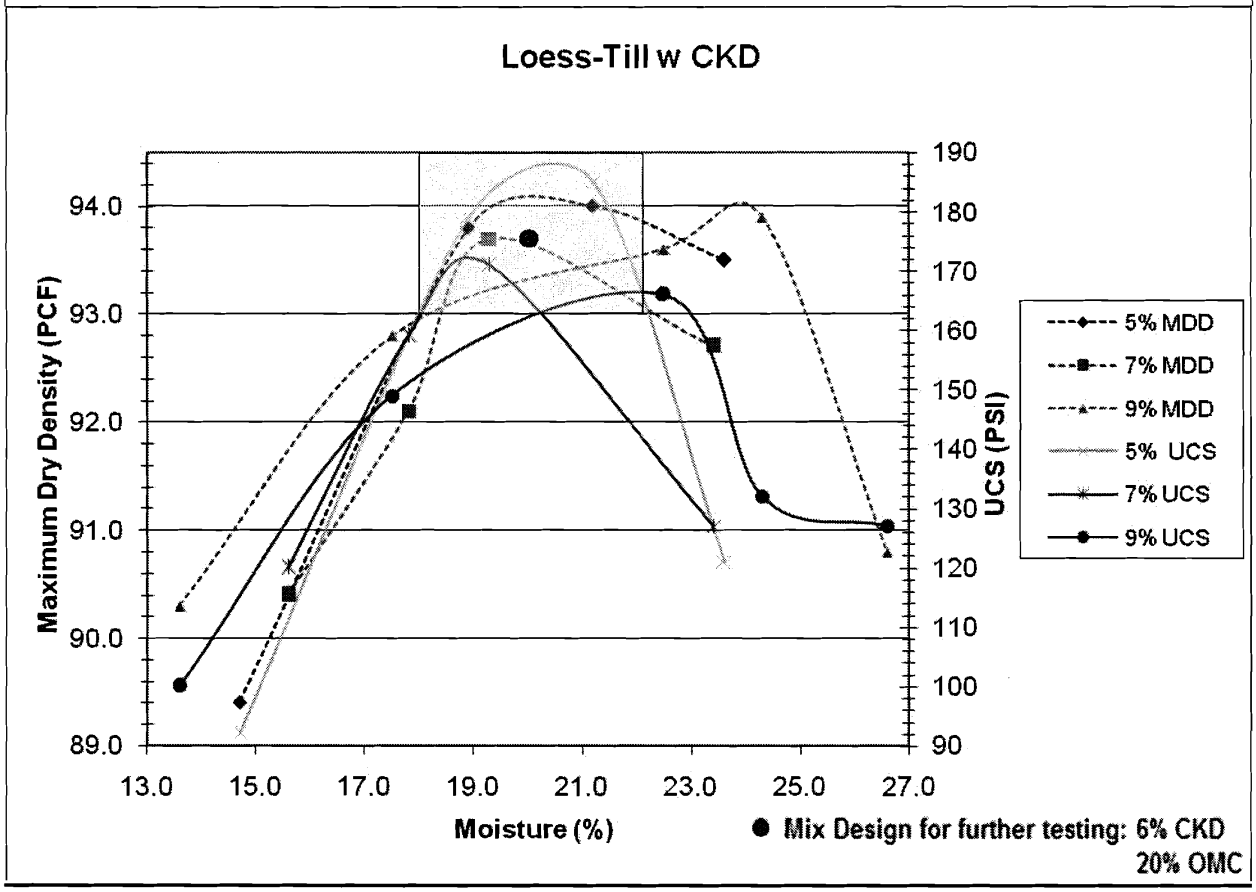
● Mix Design for further testing: 7% CKD
20% OMC

Loess w/ Hyrated Lime

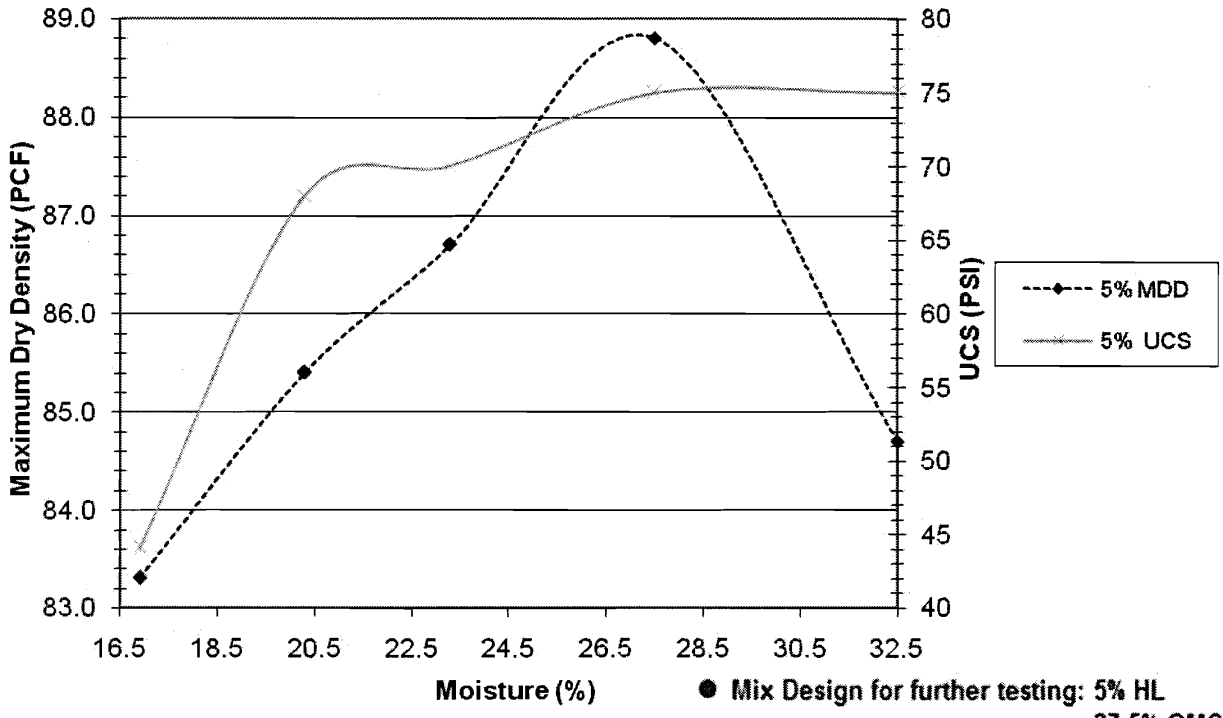


● Mix Design for further testing: 5% HL
25% OMC

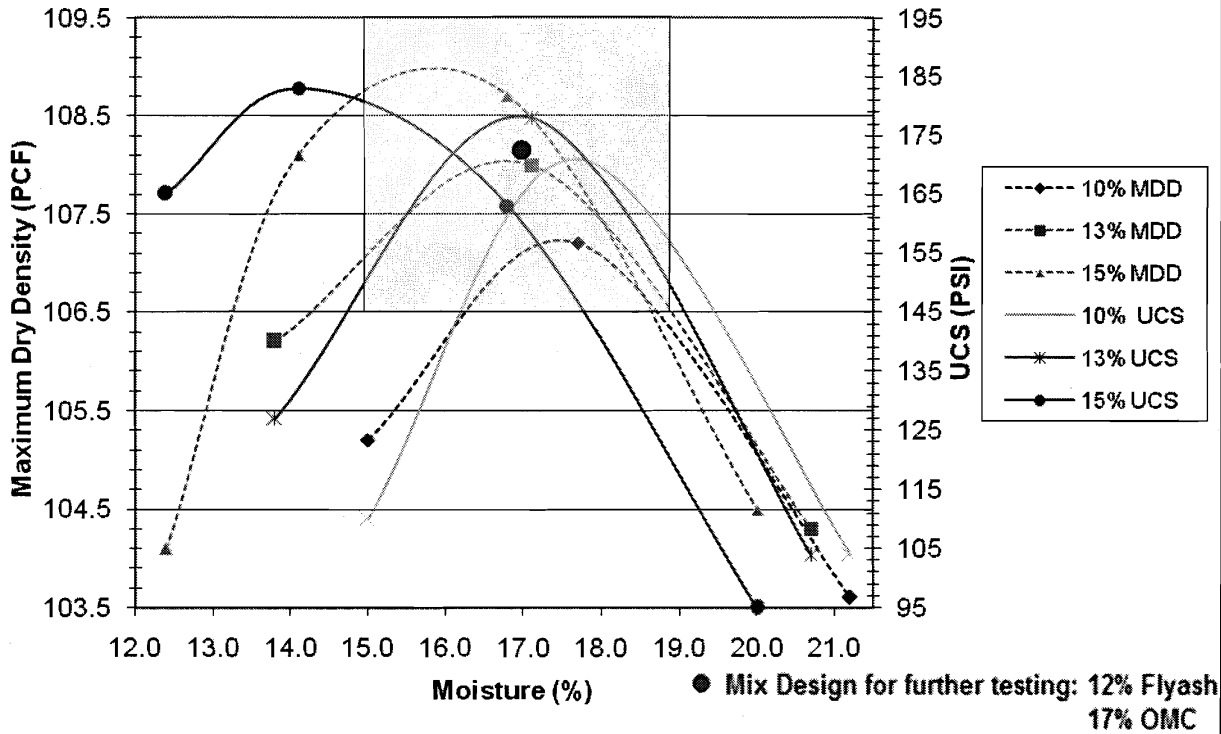

Loess-Till w Flyash
Maximum Dry Density (PCF)
UCS (PSI)
Moisture (%)
103.5
102.5
101.5
100.5
99.5
98.5
97.5
96.5
190
180
170
160
150
140
130
120
110
100
90
80
14.5
15.5
16.5
17.5
18.5
19.5
20.5
21.5
22.5
23.5
10% MDD
13% MDD
15% MDD
10% UCS
13% UCS
15% UCS
Mix Design for further testing: 13% Flyash
18% OMC


Loess-Till w CKD
Maximum Dry Density (PCF)
UCS (PSI)
Moisture (%)
94.0
93.0
92.0
91.0
90.0
89.0
190
180
170
160
150
140
130
120
110
100
90
13.0
15.0
17.0
19.0
21.0
23.0
25.0
27.0
5% MDD
7% MDD
9% MDD
5% UCS
7% UCS
9% UCS
Mix Design for further testing: 6% CKD
20% OMC

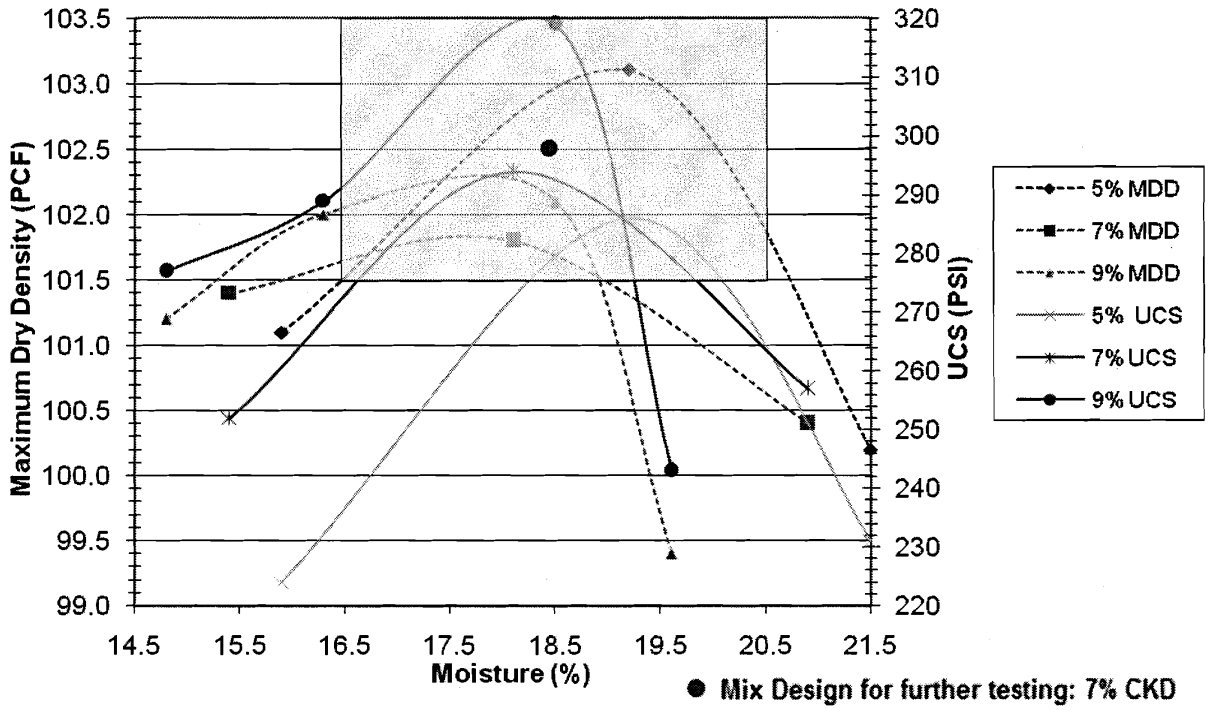
Loess-Till w/ Hyrated Lime



Till w/ Flyash

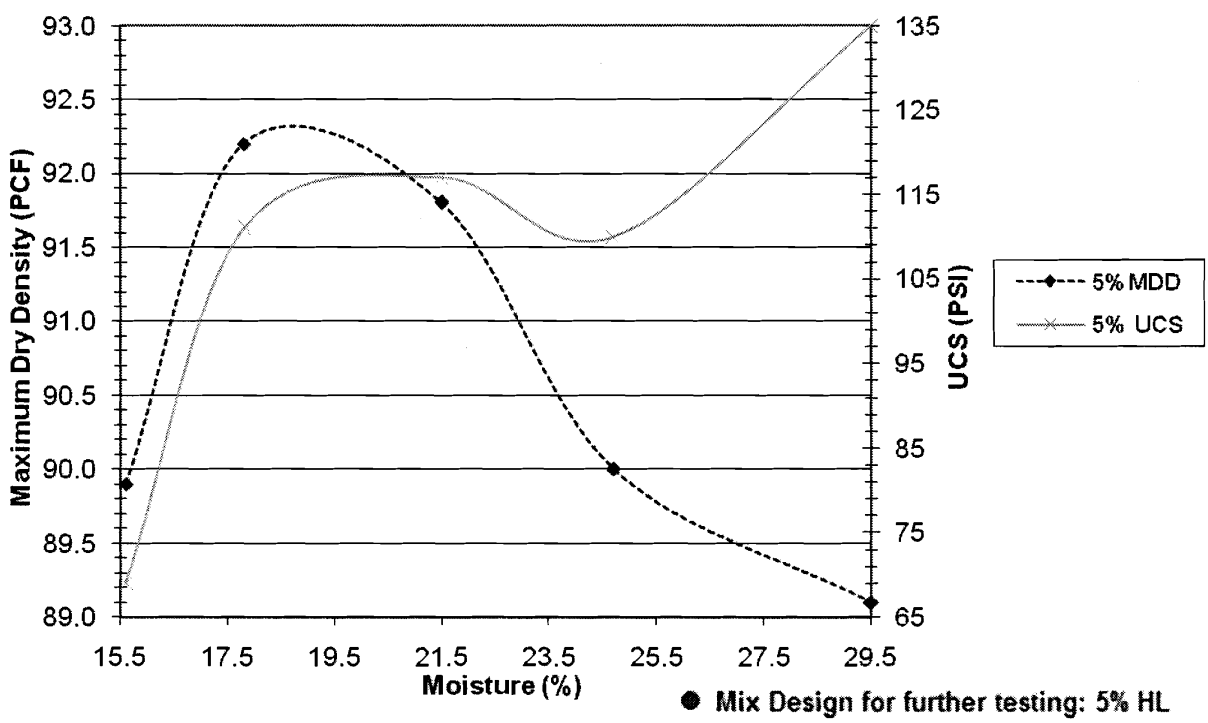


Till w/ CKD



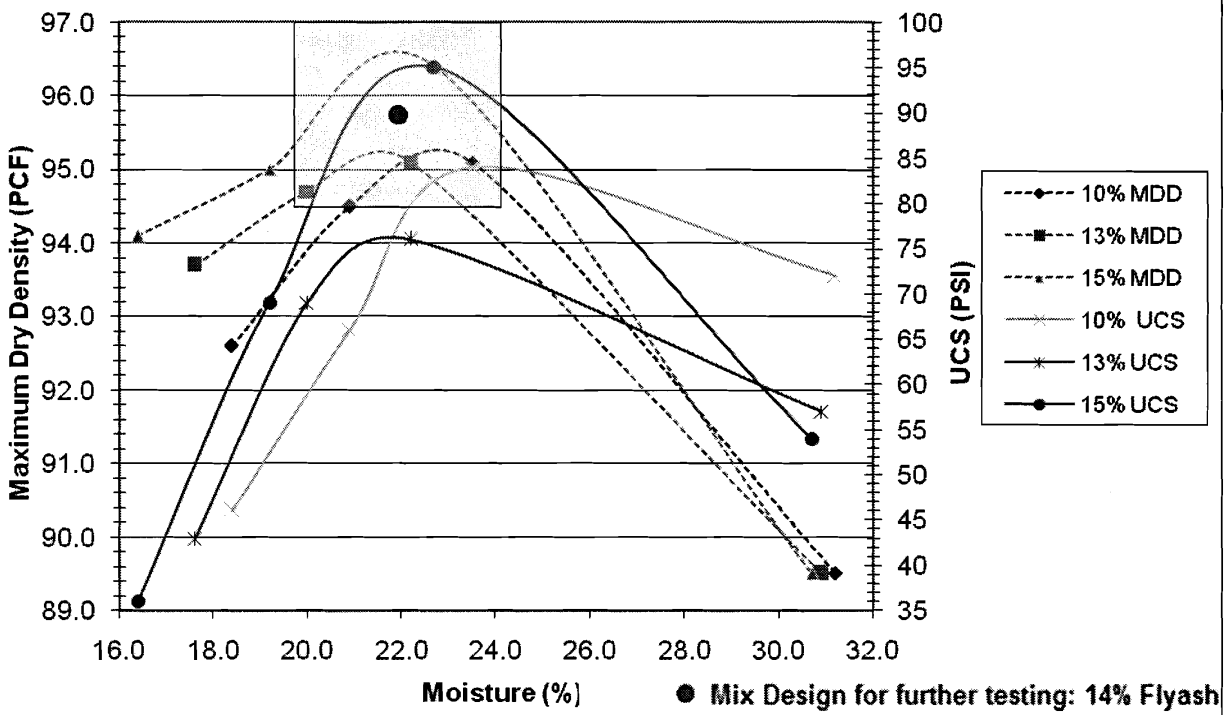
● Mix Design for further testing: 7% CKD
18.5% OMC

Till w/ Hydrated Lime



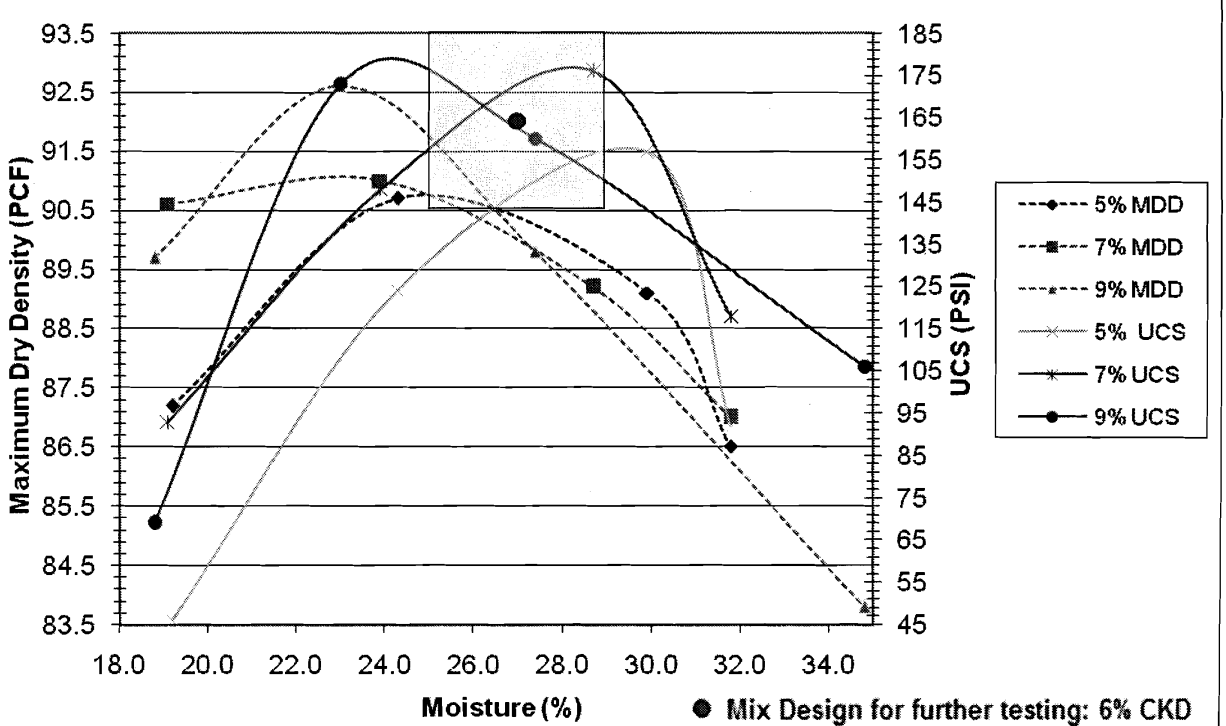
● Mix Design for further testing: 5% HL
18% OMC

Shale w/ Flyash

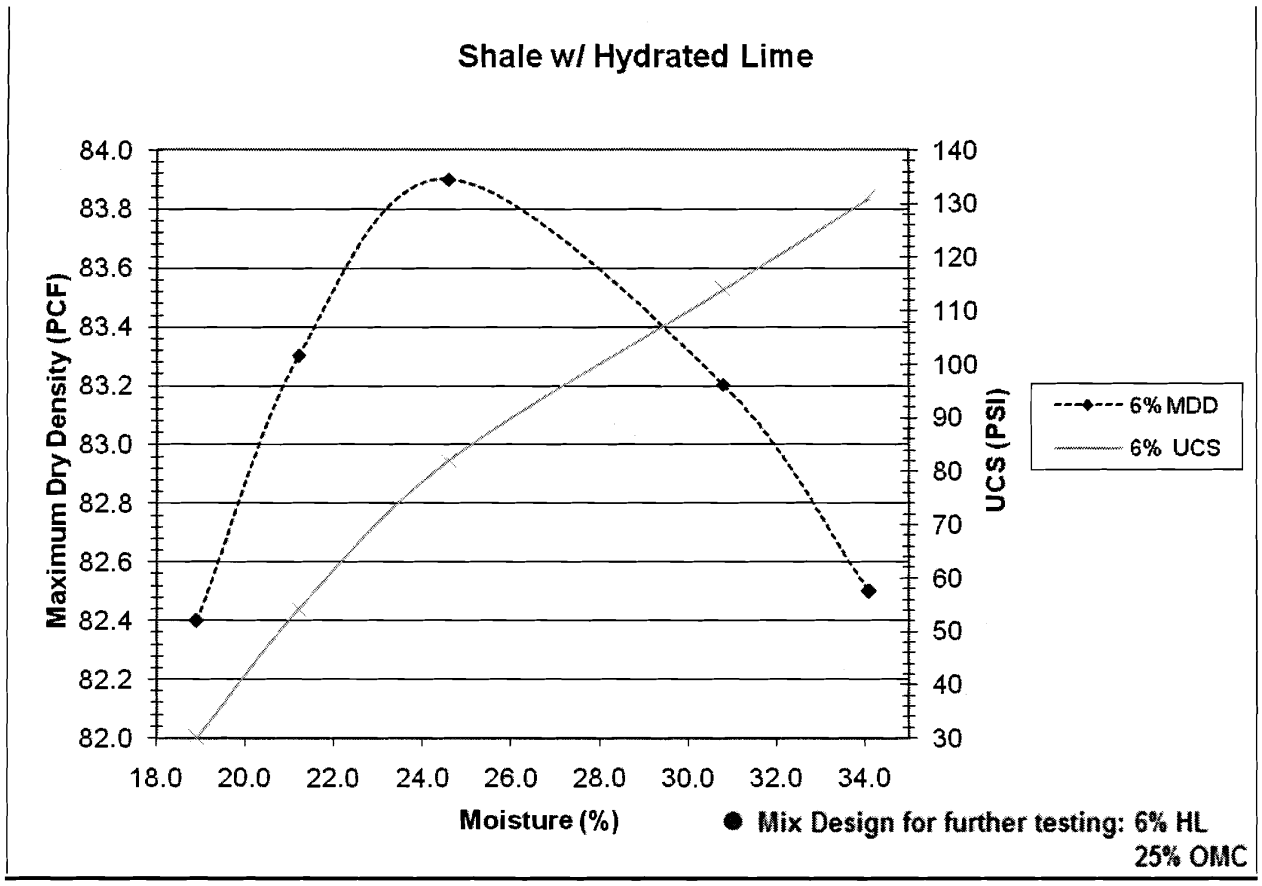


● Mix Design for further testing: 14% Flyash
22% OMC

Shale w/ CKD



● Mix Design for further testing: 6% CKD
27% MC


Shale w/ Hydrated Lime
Maximum Dry Density (PCF)
84.0
83.8
83.6
83.4
83.2
83.0
82.8
82.6
82.4
82.2
82.0
UCS (PSI)
140
130
120
110
100
90
80
70
60
50
40
30
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
Moisture (%)
6% MDD
6% UCS
Mix Design for further testing: 6% HL
25% OMC

APPENDIX E

Resilient Modulus Test Data

Terracon

Resilient Modulus Testing - AASHTO T 307-99 English Units

Report Date:	18-Apr-07
Lab No.:	Loess CKD
Project No.:	03071078
Test Date:	9-Apr-07

Soil Map Unit:	Loess 7% CKD
Soil Symbol:	0
Depth (in.)	0
Compaction Method	Static
Max. Dry Density (pcf)	95.5
Opt. Moisture Content (%)	20.0
Inside Mold Diameter (in)	3.94

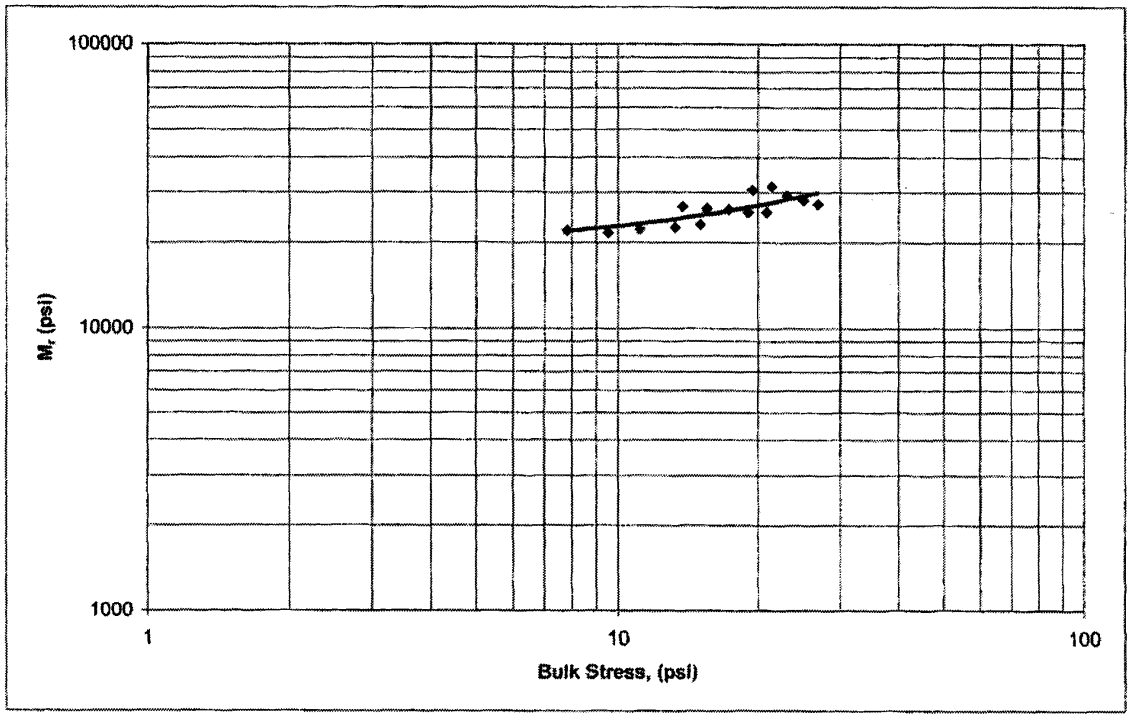
Weight of Wet Soil (lb)	6.04
Initial Sample Diameter (in)	3.94
Initial Sample Height (in)	7.91
Initial Sample Area (in^2)	12.17
Sample Volume (in^3)	96.34
Compacted Moisture Content(%)	21.5
Wet Density (pcf)	108.2
Dry Density (pcf)	89.1

Final Sample Height (in)	7.2
Final Sample Wet Weight (lb)	6.03
Final Moisture Content (%)	21.3
Accumulated Strain (%)	0.63
Percent Passing No. 10	0
Percent Passing No. 200	0.0
Liquid Limit	0
Plasticity Index	0

Chamber Confining Pressure (S_3) psi	Nominal Maximum Axial Stress (S_{cyclic}) psi	Actual Applied Max. Axial Load (P_{max}) lb	Actual Applied Cyclic Load (P_{cyclic}) lb	Actual Applied Contact Load ($P_{contact}$) lb	Actual Applied Max. Axial Stress (S_{max}) psi	Actual Applied Cyclic Stress (S_{cyclic}) psi	Actual Applied Contact Stress ($S_{contact}$) psi	Recov. Def. LVDT #1 Reading (H_1) in	Recov. Def. LVDT #2 Reading (H_2) in	Average Recov. Def. LVDT 1 and 2 (H_{avg}) in	Resilient Strain (ϵ_r) in/in	Resilient Modulus (M_r) psi
5.95	1.80	16.0	19.7	-3.6	1.32	1.62	-0.2992	0.0005	0.0004	0.0004	0.0000530	30469.8
6.00	3.60	40.4	42.2	-1.8	3.31	3.46	-0.1482	0.0010	0.0008	0.0009	0.0001106	31298.4
5.97	5.41	65.3	63.5	1.8	5.36	5.22	0.1440	0.0017	0.0012	0.0014	0.0001787	29183.4
6.01	7.21	90.0	85.2	4.8	7.39	6.99	0.3947	0.0023	0.0016	0.0020	0.0002498	27996.5
6.02	8.99	114.5	106.9	7.6	9.40	8.78	0.6203	0.0030	0.0021	0.0026	0.0003229	27191.3
4.06	1.80	16.6	19.6	-3.0	1.36	1.61	-0.2462	0.0005	0.0004	0.0005	0.0000605	26611.8
4.02	3.60	41.2	41.7	-0.5	3.39	3.43	-0.0420	0.0011	0.0009	0.0010	0.0001302	26326.0
4.02	5.41	66.1	64.0	2.1	5.43	5.25	0.1710	0.0018	0.0014	0.0016	0.0002018	26037.3
3.99	7.21	90.9	86.3	4.6	7.46	7.09	0.3769	0.0026	0.0018	0.0022	0.0002776	25523.6
4.00	8.99	115.1	108.1	7.0	9.45	8.88	0.5744	0.0032	0.0023	0.0027	0.0003459	25673.7
2.05	1.80	17.8	20.1	-2.3	1.46	1.65	-0.1927	0.0006	0.0006	0.0006	0.0000750	22036.7
2.02	4.00	42.2	42.3	-0.1	3.47	3.47	-0.0059	0.0013	0.0012	0.0013	0.0001600	21699.4
1.95	6.00	66.8	64.2	2.6	5.49	5.27	0.2161	0.0021	0.0017	0.0019	0.0002362	22324.3
2.07	8.00	91.5	86.1	5.5	7.52	7.07	0.4488	0.0028	0.0022	0.0025	0.0003122	22645.1
2.03	9.99	116.1	108.3	7.8	9.54	8.89	0.6443	0.0034	0.0027	0.0030	0.0003843	23133.7

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Loess CKD
Project No. 03071078



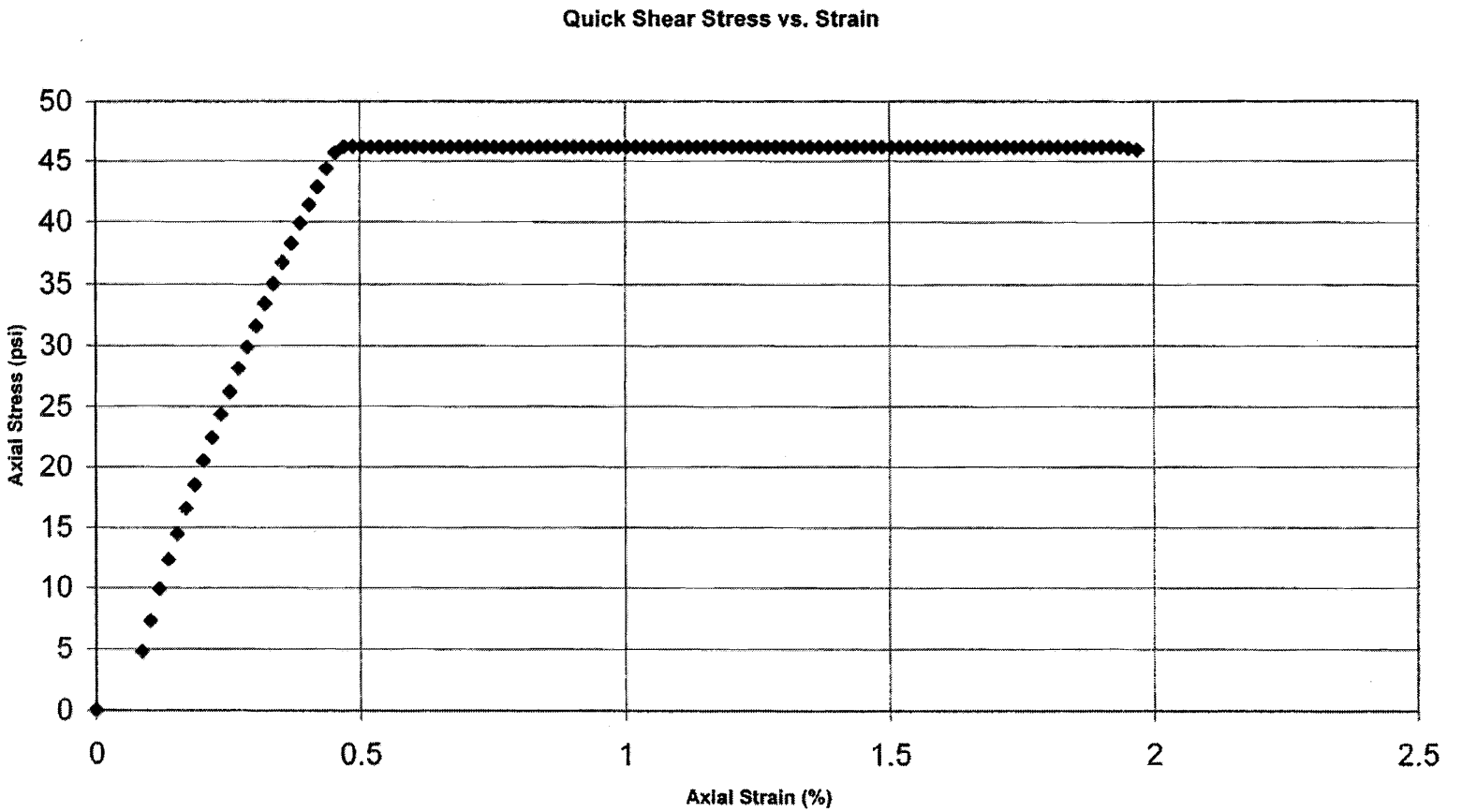
$Mr = K1 \times \Theta^{k2}$

$[\Theta = S_{cyclic} + 3\ (S3)]$

S3 (psi)	K1	K2	R^2
6	107829.5	-0.417	0.82
4	34550.8	-0.100	0.90
2	18347.2	0.082	0.75
All	12265.2	0.265	0.65

Terracon

Date Reported:	4/18/2007
Terracon Lab No.	Loess CKD
Project No.	03071078



Terracon

Resilient Modulus Testing - AASHTO T 307-99 English Units

Report Date:	18-Apr-07
Lab No.:	Loess Fly Ash
Project No.:	03071078

Soil Map Unit:	Loess 12% Fly Ash
Soil Symbol:	0
Depth (in.)	0
Compaction Method	Static
Max. Dry Density (pcf)	101.0
Opt. Moisture Content (%)	19.5
Inside Mold Diameter (in)	3.94

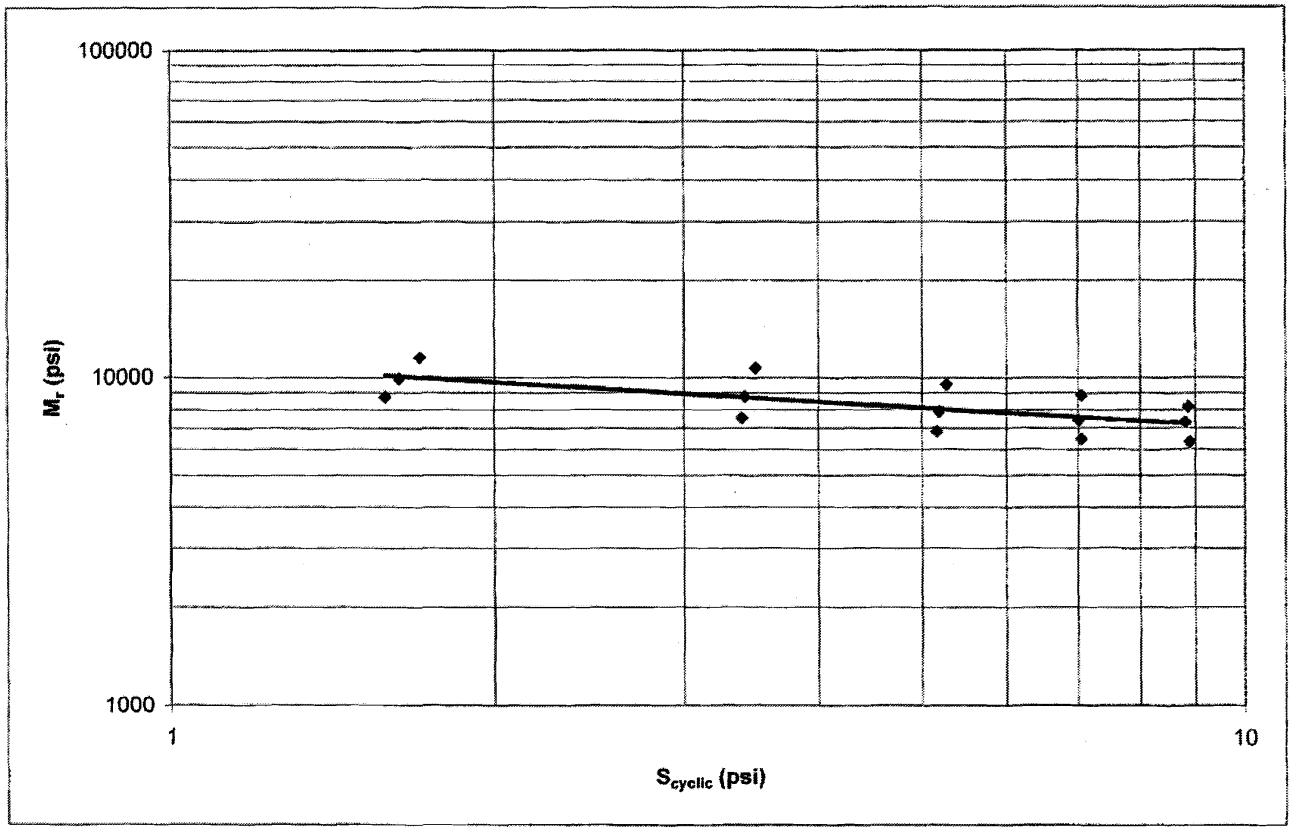
Weight of Wet Soil (lb)	6.36
Initial Sample Diameter (in)	3.94
Initial Sample Height (in)	7.91
Initial Sample Area (in^2)	12.17
Sample Volume (in^3)	96.34
Compacted Moisture Content(%)	22.3
Wet Density (pcf)	114.0
Dry Density (pcf)	93.2

Test Date:	9-Apr-07
Final Sample Height (in)	7.2
Final Sample Wet Weight (lb)	6.36
Final Moisture Content (%)	22.3
Accumulated Strain (%)	1.66
Percent Passing No. 10	0
Percent Passing No. 200	0.0
Liquid Limit	0
Plasticity Index	0

Chamber Confining Pressure (S_3) psi	Nominal Maximum Axial Stress (S_{cyclic}) psi	Actual Applied Max. Axial Load (P_{max}) lb	Actual Applied Cyclic Load (P_{cyclic}) lb	Actual Applied Contact Load ($P_{contact}$) lb	Actual Applied Max. Axial Stress (S_{max}) psi	Actual Applied Cyclic Stress (S_{cyclic}) psi	Actual Applied Contact Stress ($S_{contact}$) psi	Recov. Def. LVDT #1 Reading (H_1) in	Recov. Def. LVDT #2 Reading (H_2) in	Average Recov. Def. LVDT 1 and 2 (H_{avg}) in	Resilient Strain (ϵ_r) in/in	Resilient Modulus (M_r) psi
5.97	1.80	16.1	20.7	-4.6	1.32	1.70	-0.3800	0.0013	0.0011	0.0012	0.0001477	11523.1
6.01	3.60	40.4	42.5	-2.1	3.32	3.49	-0.1741	0.0028	0.0024	0.0026	0.0003277	10660.5
6.02	5.41	65.2	64.2	1.1	5.36	5.27	0.0865	0.0047	0.0040	0.0044	0.0005541	9510.4
5.97	7.21	89.7	85.9	3.9	7.37	7.05	0.3166	0.0067	0.0060	0.0063	0.0008014	8799.7
6.02	8.99	114.4	108.0	6.4	9.39	8.87	0.5265	0.0091	0.0081	0.0086	0.0010864	8161.5
4.02	1.80	16.6	19.8	-3.3	1.36	1.63	-0.2673	0.0014	0.0012	0.0013	0.0001650	9871.0
4.01	3.60	41.0	41.6	-0.6	3.37	3.42	-0.0482	0.0033	0.0029	0.0031	0.0003908	8740.9
4.04	5.41	65.5	63.1	2.4	5.38	5.19	0.1955	0.0055	0.0049	0.0052	0.0006586	7873.7
4.01	7.21	90.0	85.3	4.7	7.39	7.01	0.3851	0.0078	0.0072	0.0075	0.0009481	7388.5
4.01	8.99	114.7	107.3	7.4	9.42	8.81	0.6102	0.0100	0.0091	0.0095	0.0012067	7301.5
1.95	1.80	17.2	19.2	-2.0	1.41	1.58	-0.1673	0.0016	0.0013	0.0014	0.0001810	8730.5
2.02	4.00	41.8	41.4	0.4	3.43	3.40	0.0318	0.0038	0.0033	0.0036	0.0004515	7526.0
2.03	6.00	66.2	62.8	3.4	5.44	5.16	0.2826	0.0065	0.0055	0.0060	0.0007577	6806.2
2.01	8.00	91.3	85.8	5.5	7.50	7.05	0.4496	0.0091	0.0082	0.0087	0.0010939	6442.9
2.04	9.99	116.0	108.2	7.8	9.53	8.89	0.6420	0.0116	0.0107	0.0111	0.0014084	6310.3

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Loess Fly Ash
Project No. 03071078

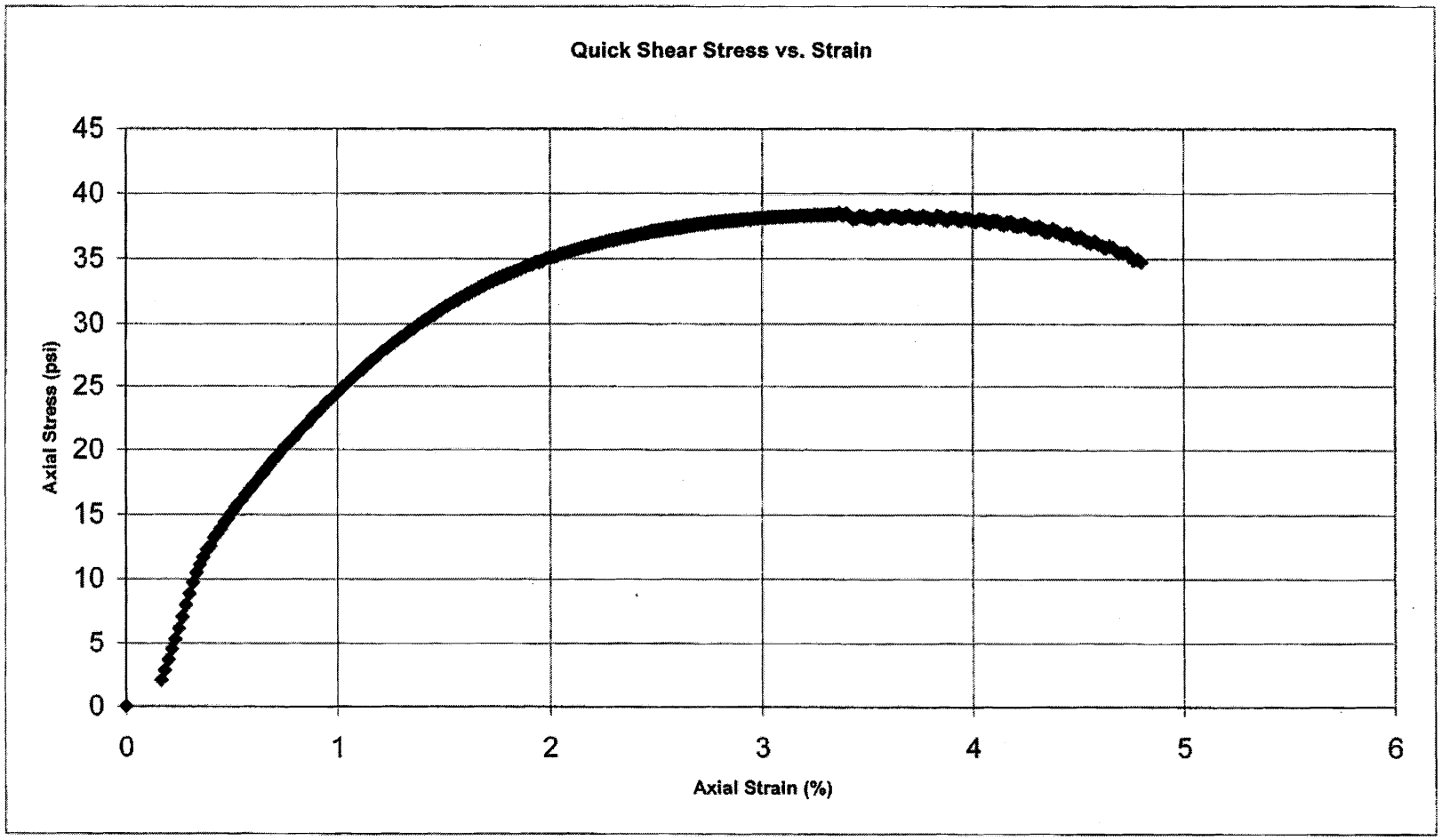


$Mr = K1 \times S_{cylic}^{k2}$

S3 (psi)	K1	K2	R^2
6	13264.1	-0.209	0.95
4	10859.6	-0.189	0.99
2	9513.2	-0.195	0.99
All	11042.569	-0.194091	0.447873

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Loess Fly Ash
Project No. 03071078



Terracon

Resilient Modulus Testing - AASHTO T 307-99 English Units

Report Date:	18-Apr-07
Lab No.:	Loess Lime
Project No.:	03071078
Test Date:	10-Apr-07

Soil Map Unit:	Loess 5% Lime
Soil Symbol:	0
Depth (in.)	0
Compaction Method	Static
Max. Dry Density (pcf)	87.5
Opt. Moisture Content (%)	25.0
Inside Mold Diameter (in)	3.94

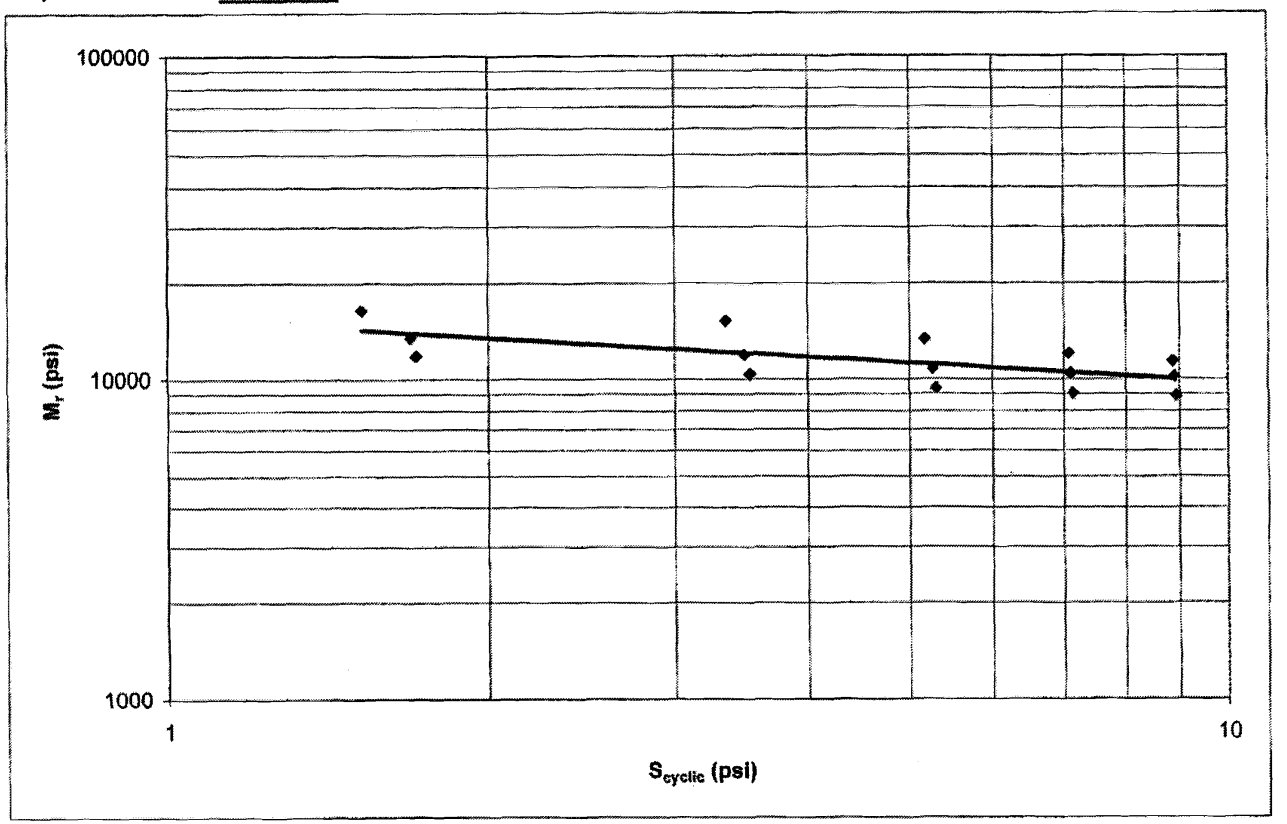
Weight of Wet Soil (lb)	5.76
Initial Sample Diameter (in)	3.94
Initial Sample Height (in)	7.87
Initial Sample Area (in^2)	12.17
Sample Volume (in^3)	95.86
Compacted Moisture Content(%)	28.3
Wet Density (pcf)	103.9
Dry Density (pcf)	81.0

Final Sample Height (in)	7.1
Final Sample Wet Weight (lb)	5.76
Final Moisture Content (%)	28.5
Accumulated Strain (%)	1.53
Percent Passing No. 10	0
Percent Passing No. 200	0.0
Liquid Limit	0
Plasticity Index	0

Chamber Confining Pressure (S_3) psi	Nominal Maximum Axial Stress (S_{cyclic}) psi	Actual Applied Max. Axial Load (P_{max}) lb	Actual Applied Cyclic Load (P_{cyclic}) lb	Actual Applied Contact Load ($P_{contact}$) lb	Actual Applied Max. Axial Stress (S_{max}) psi	Actual Applied Cyclic Stress (S_{cyclic}) psi	Actual Applied Contact Stress ($S_{contact}$) psi	Recov. Def. LVDT #1 Reading (H_1) in	Recov. Def. LVDT #2 Reading (H_2) in	Average Recov. Def. LVDT 1 and 2 (H_{avg}) in	Resilient Strain (ϵ_r) in/in	Resilient Modulus (M_r) psi
6.02	1.80	15.2	18.5	-3.3	1.25	1.52	-0.2727	0.0008	0.0007	0.0007	0.0000927	16415.6
6.02	3.60	39.7	40.7	-1.0	3.26	3.34	-0.0806	0.0018	0.0017	0.0017	0.0002211	15124.7
6.06	5.41	65.2	62.9	2.3	5.36	5.17	0.1896	0.0031	0.0030	0.0031	0.0003894	13265.1
6.07	7.21	89.8	86.1	3.6	7.37	7.07	0.2997	0.0047	0.0046	0.0046	0.0005899	11988.3
5.97	8.99	114.6	108.0	6.6	9.41	8.87	0.5389	0.0062	0.0061	0.0062	0.0007821	11340.6
3.96	1.80	17.3	20.6	-3.3	1.42	1.69	-0.2693	0.0010	0.0010	0.0010	0.0001252	13516.7
4.07	3.60	41.8	42.4	-0.6	3.43	3.48	-0.0499	0.0024	0.0022	0.0023	0.0002935	11868.4
3.95	5.41	66.4	64.1	2.2	5.45	5.27	0.1845	0.0039	0.0039	0.0039	0.0004905	10736.3
3.96	7.21	91.1	86.5	4.5	7.48	7.11	0.3730	0.0055	0.0052	0.0054	0.0006852	10371.4
4.02	8.99	115.6	108.4	7.2	9.49	8.90	0.5899	0.0070	0.0068	0.0069	0.0008753	10169.3
2.01	1.80	18.8	20.9	-2.0	1.55	1.71	-0.1671	0.0012	0.0011	0.0011	0.0001450	11814.9
2.03	4.00	43.3	42.9	0.4	3.56	3.53	0.0318	0.0027	0.0026	0.0027	0.0003421	10309.9
2.04	6.00	67.5	64.6	3.0	5.55	5.30	0.2445	0.0046	0.0044	0.0045	0.0005676	9342.4
2.03	8.00	92.4	86.9	5.6	7.59	7.13	0.4572	0.0064	0.0060	0.0062	0.0007897	9033.3
1.97	9.99	116.9	108.7	8.2	9.60	8.93	0.6753	0.0081	0.0077	0.0079	0.0010070	8866.5

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Loess Lime
Project No. 03071078

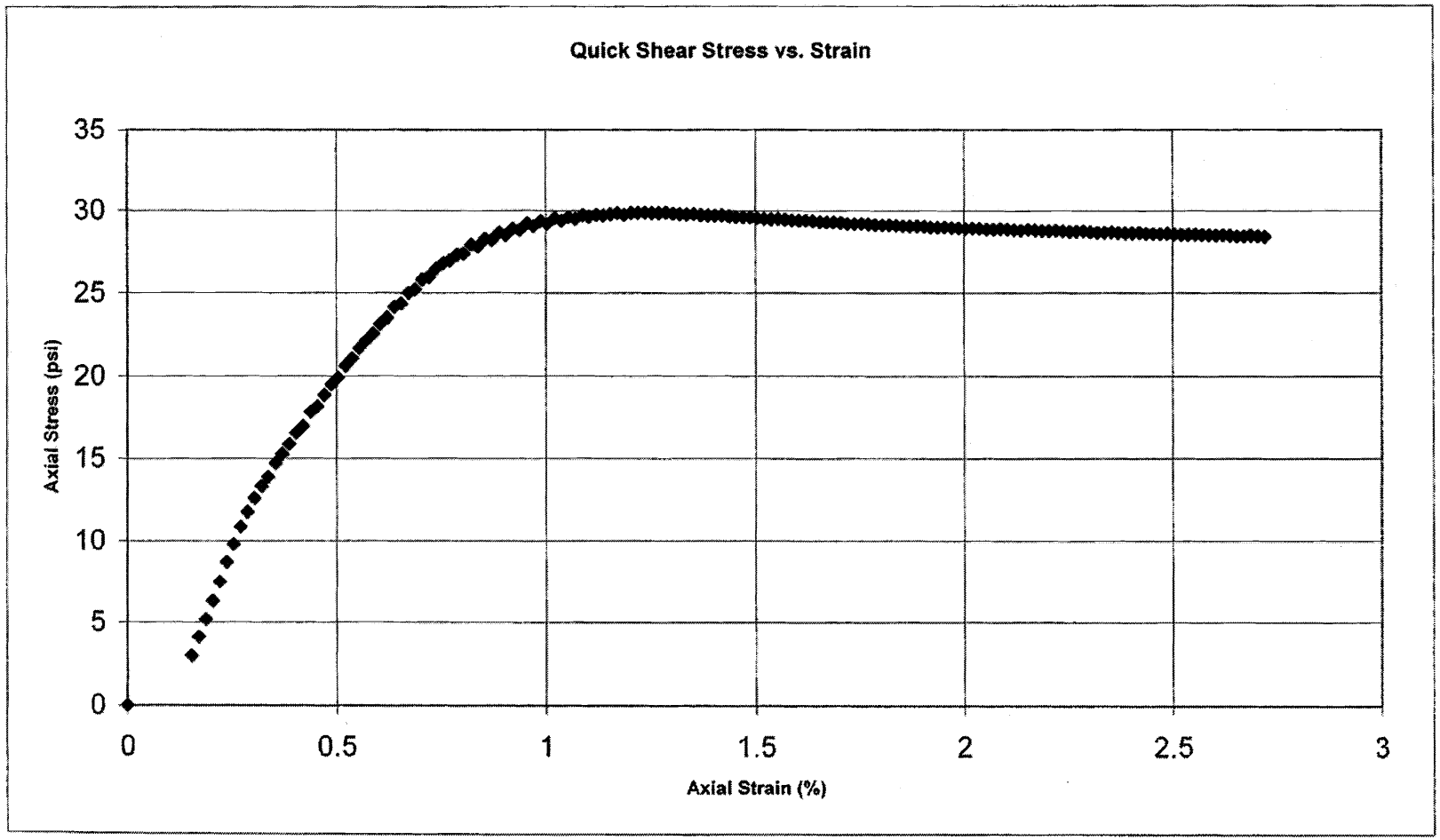


$Mr = K1 \times S_{cylic}^{k2}$

S3 (psi)	K1	K2	R^2
6	18587.0	-0.216	0.95
4	14766.1	-0.178	0.98
2	12930.0	-0.181	0.98
All	15428.475	-0.199068	0.459764

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Loess Lime
Project No. 03071078



Terracon

Resilient Modulus Testing - AASHTO T 307-99 English Units

Report Date:	18-Apr-07
Lab No.:	Shale CKD
Project No.:	03071078
Test Date:	12-Apr-07

Soil Map Unit:	Shale 7% CKD
Soil Symbol:	0
Depth (in.)	0
Compaction Method	Static
Max. Dry Density (pcf)	91.0
Opt. Moisture Content (%)	27.0
Inside Mold Diameter (in)	3.94

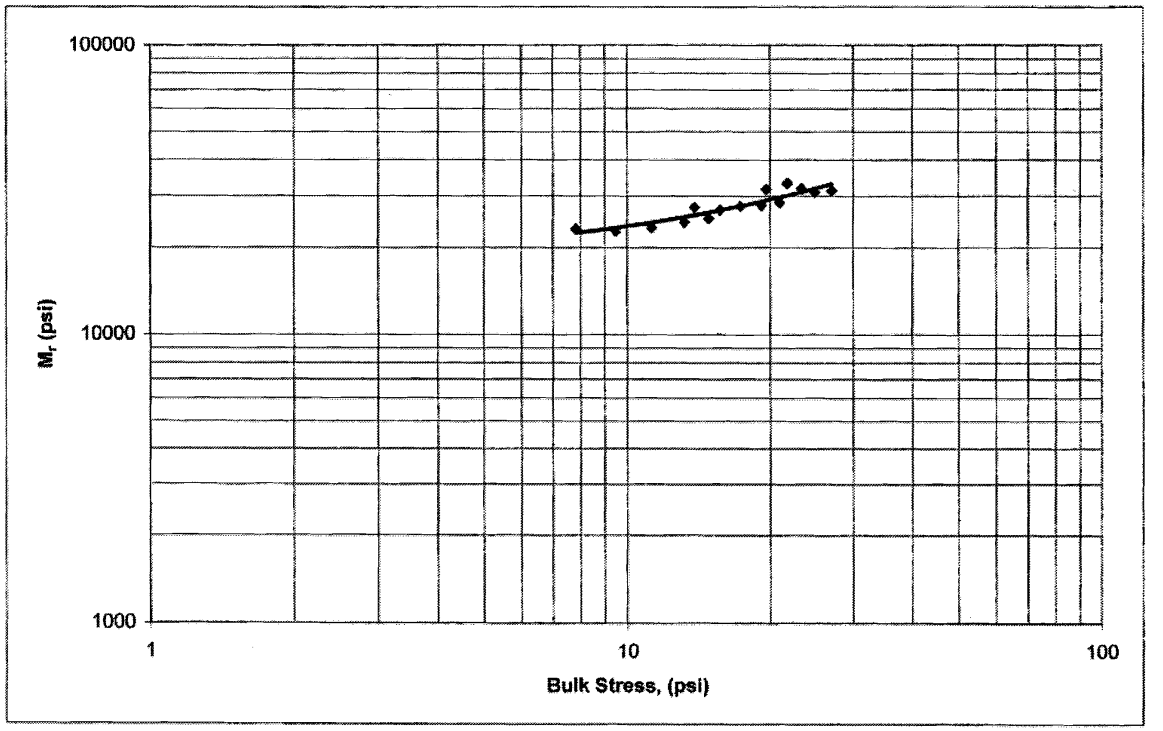
Weight of Wet Soil (lb)	6.08
Initial Sample Diameter (in)	3.94
Initial Sample Height (in)	7.87
Initial Sample Area (in^2)	12.17
Sample Volume (in^3)	95.86
Compacted Moisture Content(%)	29.4
Wet Density (pcf)	109.6
Dry Density (pcf)	84.7

Final Sample Height (in)	7.9
Final Sample Wet Weight (lb)	6.08
Final Moisture Content (%)	28.8
Accumulated Strain (%)	0.79
Percent Passing No. 10	0
Percent Passing No. 200	0.0
Liquid Limit	0
Plasticity Index	0

Chamber Confining Pressure (S_3) psi	Nominal Maximum Axial Stress (S_{cyclic}) psi	Actual Applied Max. Axial Load (P_{max}) lb	Actual Applied Cyclic Load (P_{cyclic}) lb	Actual Applied Contact Load ($P_{contact}$) lb	Actual Applied Max. Axial Stress (S_{max}) psi	Actual Applied Cyclic Stress (S_{cyclic}) psi	Actual Applied Contact Stress ($S_{contact}$) psi	Recov. Def. LVDT #1 Reading (H_1) in	Recov. Def. LVDT #2 Reading (H_2) in	Average Recov. Def. LVDT 1 and 2 (H_{avg}) in	Resilient Strain (ϵ_r) in/in	Resilient Modulus (M_r) psi
5.96	1.80	16.1	21.4	-5.3	1.32	1.76	-0.4355	0.0005	0.0004	0.0004	0.0000556	31614.9
6.06	3.60	40.5	43.1	-2.6	3.33	3.54	-0.2155	0.0010	0.0007	0.0008	0.0001071	33062.1
5.99	5.41	65.0	65.1	-0.1	5.34	5.35	-0.0113	0.0015	0.0011	0.0013	0.0001680	31820.1
5.93	7.21	89.6	87.0	2.5	7.36	7.15	0.2090	0.0022	0.0015	0.0018	0.0002323	30773.6
6.04	8.99	114.2	108.7	5.5	9.38	8.93	0.4538	0.0027	0.0018	0.0023	0.0002865	31164.7
4.03	1.80	17.3	21.6	-4.4	1.42	1.78	-0.3575	0.0006	0.0004	0.0005	0.0000649	27341.5
4.04	3.60	41.6	43.5	-1.9	3.42	3.57	-0.1572	0.0013	0.0008	0.0011	0.0001337	26727.2
3.98	5.41	66.1	65.4	0.7	5.43	5.37	0.0572	0.0018	0.0013	0.0015	0.0001949	27571.6
4.01	7.21	90.5	87.0	3.5	7.43	7.15	0.2854	0.0024	0.0017	0.0020	0.0002579	27714.0
4.01	8.99	114.9	108.9	6.0	9.44	8.94	0.4961	0.0029	0.0020	0.0025	0.0003154	28351.6
2.03	1.80	17.7	21.3	-3.6	1.45	1.75	-0.2966	0.0007	0.0005	0.0006	0.0000759	23023.0
1.97	4.00	42.2	43.3	-1.1	3.47	3.56	-0.0910	0.0015	0.0010	0.0012	0.0001571	22654.2
1.97	6.00	66.7	65.1	1.6	5.48	5.34	0.1335	0.0021	0.0015	0.0018	0.0002288	23358.1
2.02	8.00	91.2	87.1	4.1	7.49	7.15	0.3372	0.0027	0.0020	0.0023	0.0002940	24317.0
1.97	9.99	115.4	108.7	6.7	9.47	8.93	0.5474	0.0032	0.0024	0.0028	0.0003554	25117.7

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Shale CKD
Project No. 03071078



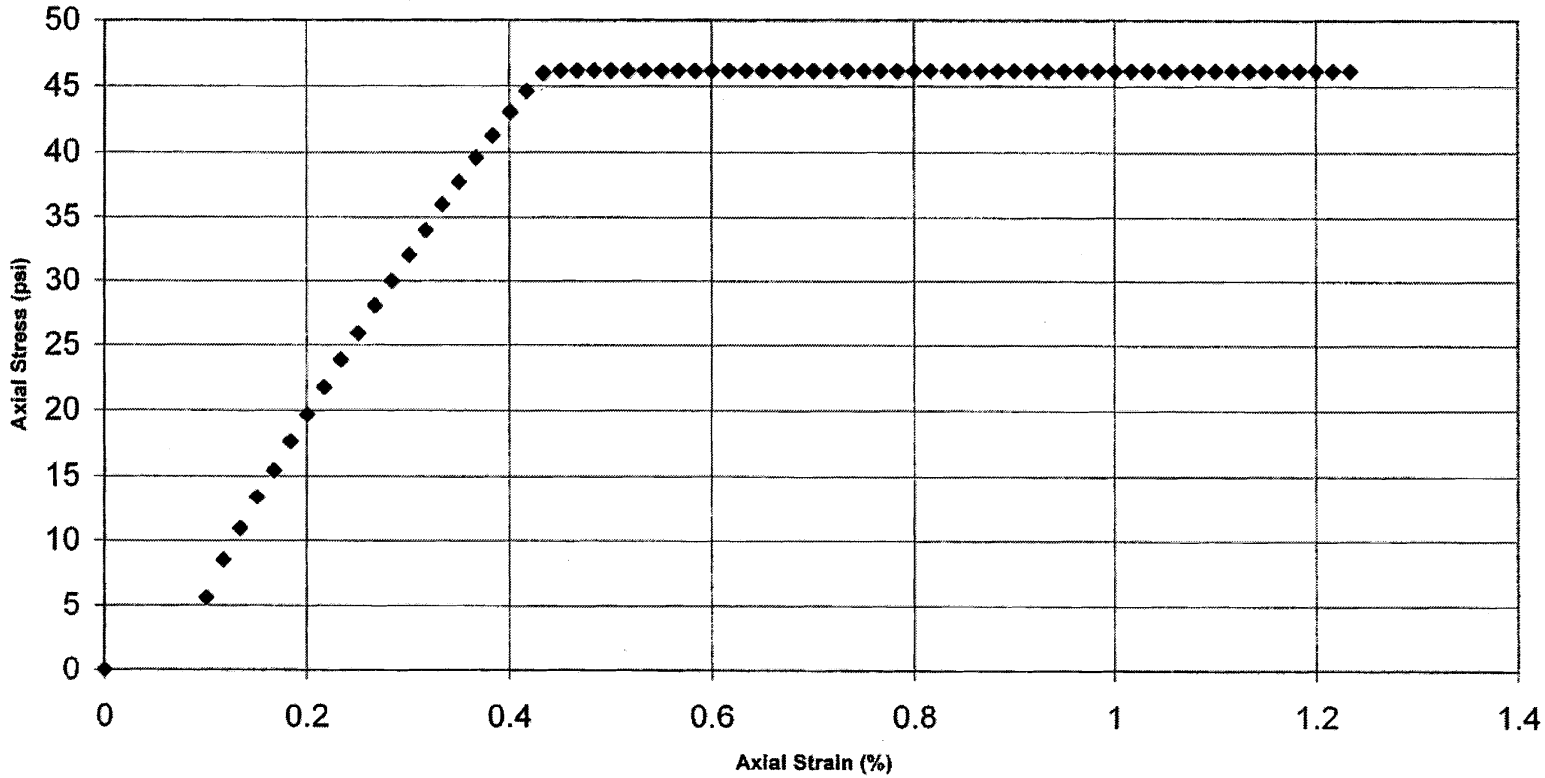
$Mr = K1 \times \Theta^{k2}$

$[\Theta = S_{cyclic} + 3\ (S3)]$

S3 (psi)	K1	K2	R^2
6	45519.9	-0.115	0.27
4	20624.7	0.102	0.60
2	16651.3	0.147	0.79
All	11213.1	0.320	0.83

Terracon

Date Reported:	4/18/2007
Terracon Lab No.	Shale CKD
Project No.	03071078



Terracon

Resilient Modulus Testing - AASHTO T 307-99 English Units

Report Date:	18-Apr-07
Lab No.:	Shale Fly Ash
Project No.:	03071078

Soil Map Unit:	Shale 14% Fly Ash
Soil Symbol:	0
Depth (in.)	0
Compaction Method	Static
Max. Dry Density (pcf)	96.0
Opt. Moisture Content (%)	22.0
Inside Mold Diameter (in)	3.94

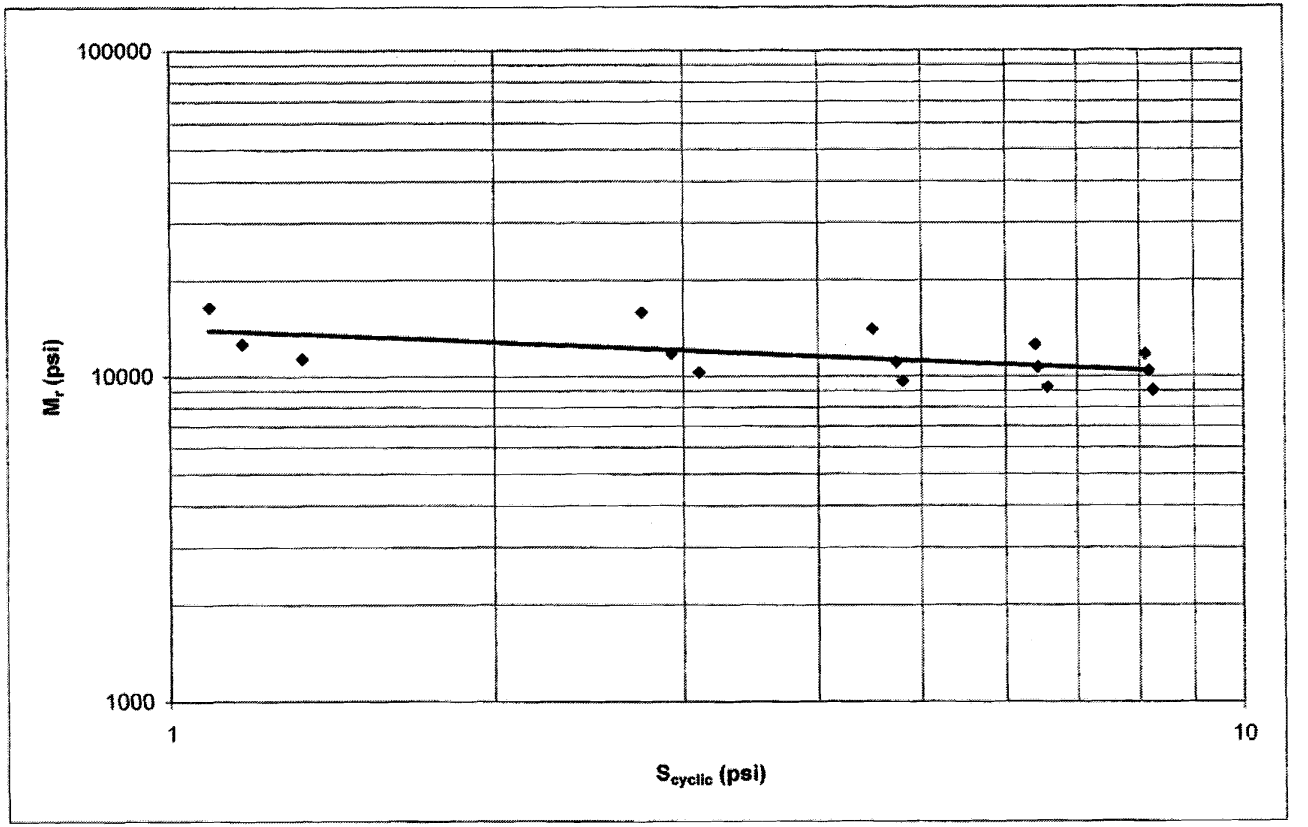
Weight of Wet Soil (lb)	6.17
Initial Sample Diameter (in)	3.94
Initial Sample Height (in)	7.95
Initial Sample Area (in^2)	12.17
Sample Volume (in^3)	96.81
Compacted Moisture Content(%)	24.4
Wet Density (pcf)	110.2
Dry Density (pcf)	88.6

Test Date:	12-Apr-07
Final Sample Height (in)	7.9
Final Sample Wet Weight (lb)	6.18
Final Moisture Content (%)	24.0
Accumulated Strain (%)	3.02
Percent Passing No. 10	0
Percent Passing No. 200	0.0
Liquid Limit	0
Plasticity Index	0

Chamber Confining Pressure (S_3) psi	Nominal Maximum Axial Stress (S_{cyclic}) psi	Actual Applied Max. Axial Load (P_{max}) lb	Actual Applied Cyclic Load (P_{cyclic}) lb	Actual Applied Contact Load ($P_{contact}$) lb	Actual Applied Max. Axial Stress (S_{max}) psi	Actual Applied Cyclic Stress (S_{cyclic}) psi	Actual Applied Contact Stress ($S_{contact}$) psi	Recov. Def. LVDT #1 Reading (H_1) in	Recov. Def. LVDT #2 Reading (H_2) in	Average Recov. Def. LVDT 1 and 2 (H_{avg}) in	Resilient Strain (ϵ_r) in/in	Resilient Modulus (M_r) psi
6.01	1.80	11.8	13.2	-1.4	0.97	1.09	-0.1183	0.0005	0.0005	0.0005	0.0000662	16440.1
5.96	3.60	35.0	33.4	1.6	2.88	2.74	0.1321	0.0014	0.0013	0.0014	0.0001734	15821.8
6.09	5.41	59.1	54.8	4.3	4.85	4.50	0.3493	0.0026	0.0025	0.0026	0.0003211	14024.8
5.95	7.21	83.9	77.8	6.1	6.89	6.39	0.5034	0.0041	0.0040	0.0041	0.0005114	12494.1
6.02	8.99	108.4	98.6	9.8	8.90	8.10	0.8049	0.0056	0.0054	0.0055	0.0006917	11707.7
4.04	1.80	13.4	14.2	-0.8	1.10	1.17	-0.0628	0.0008	0.0007	0.0007	0.0000928	12571.5
4.04	3.60	37.4	35.6	1.8	3.07	2.92	0.1493	0.0020	0.0019	0.0020	0.0002487	11756.4
4.01	5.41	61.3	57.7	3.6	5.03	4.74	0.2972	0.0035	0.0033	0.0034	0.0004294	11028.6
4.04	7.21	85.5	78.3	7.2	7.02	6.43	0.5947	0.0049	0.0047	0.0048	0.0006042	10640.8
4.01	8.99	109.2	99.3	9.9	8.97	8.16	0.8094	0.0064	0.0062	0.0063	0.0007874	10359.9
1.96	1.80	15.3	16.1	-0.9	1.26	1.33	-0.0707	0.0010	0.0009	0.0009	0.0001175	11290.3
1.95	4.00	39.2	37.7	1.5	3.22	3.10	0.1220	0.0025	0.0023	0.0024	0.0003020	10253.3
2.04	6.00	63.1	58.5	4.6	5.18	4.80	0.3758	0.0041	0.0039	0.0040	0.0004997	9613.3
1.95	8.00	86.9	79.9	7.1	7.14	6.56	0.5798	0.0058	0.0055	0.0057	0.0007127	9205.7
2.00	9.99	110.5	100.3	10.2	9.08	8.24	0.8418	0.0074	0.0071	0.0073	0.0009146	9005.5

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Shale Fly Ash
Project No. 03071078

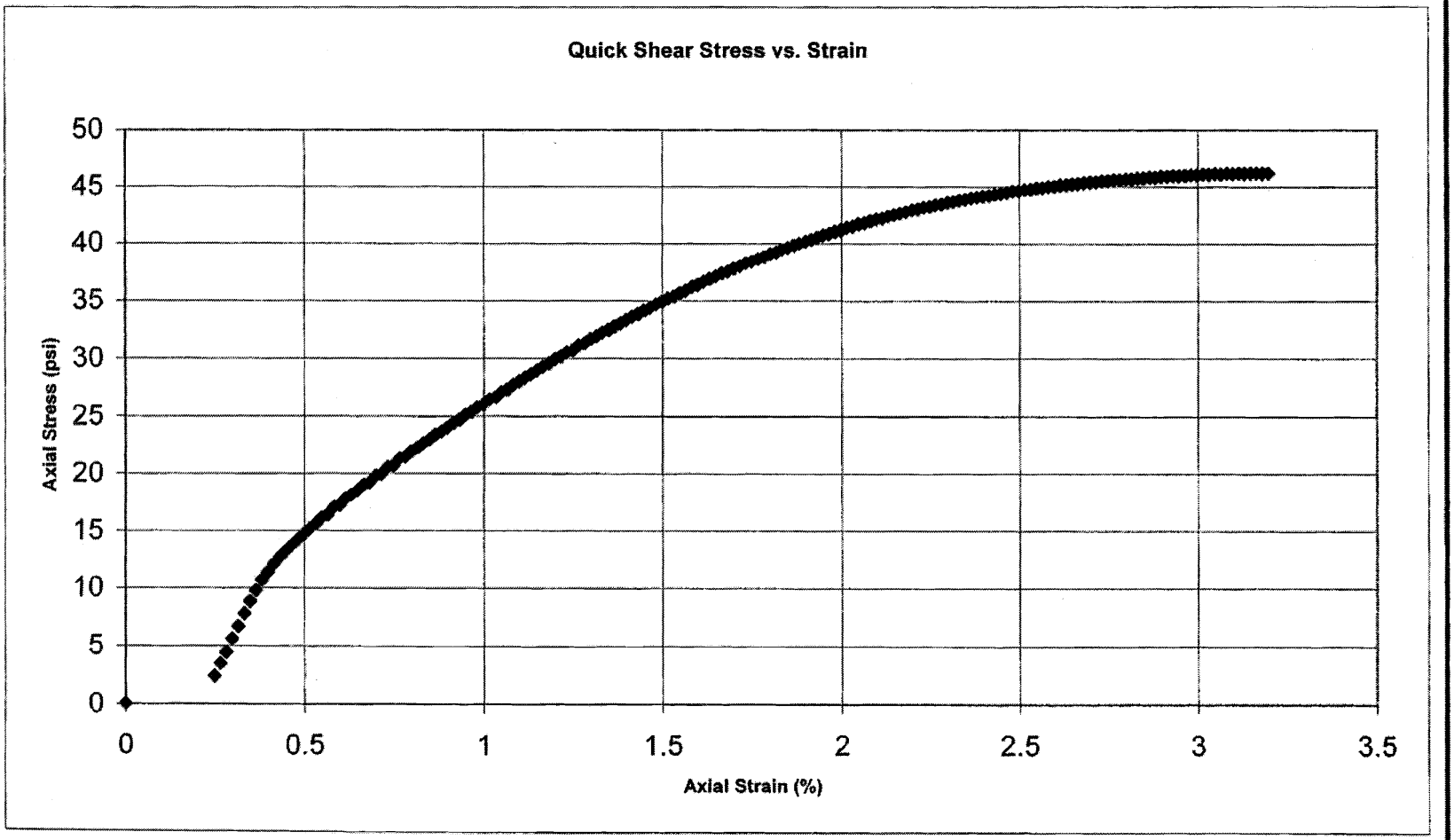


$Mr = K1 \times S_{cylic}^{k2}$

S3 (psi)	K1	K2	R^2
6	17493.5	-0.171	0.87
4	12882.8	-0.101	0.98
2	11737.8	-0.126	1.00
All	14054.56	-0.144407	0.319487

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Shale Fly Ash
Project No. 03071078



Terracon

Resilient Modulus Testing - AASHTO T 307-99 English Units

Report Date:	18-Apr-07
Lab No.:	Shale Lime
Project No.:	03071078
Test Date:	10-Apr-07

Soil Map Unit:	Shale 6% Lime
Soil Symbol:	0
Depth (in.)	0
Compaction Method	Static
Max. Dry Density (pcf)	81.0
Opt. Moisture Content (%)	25.0
Inside Mold Diameter (in)	3.94

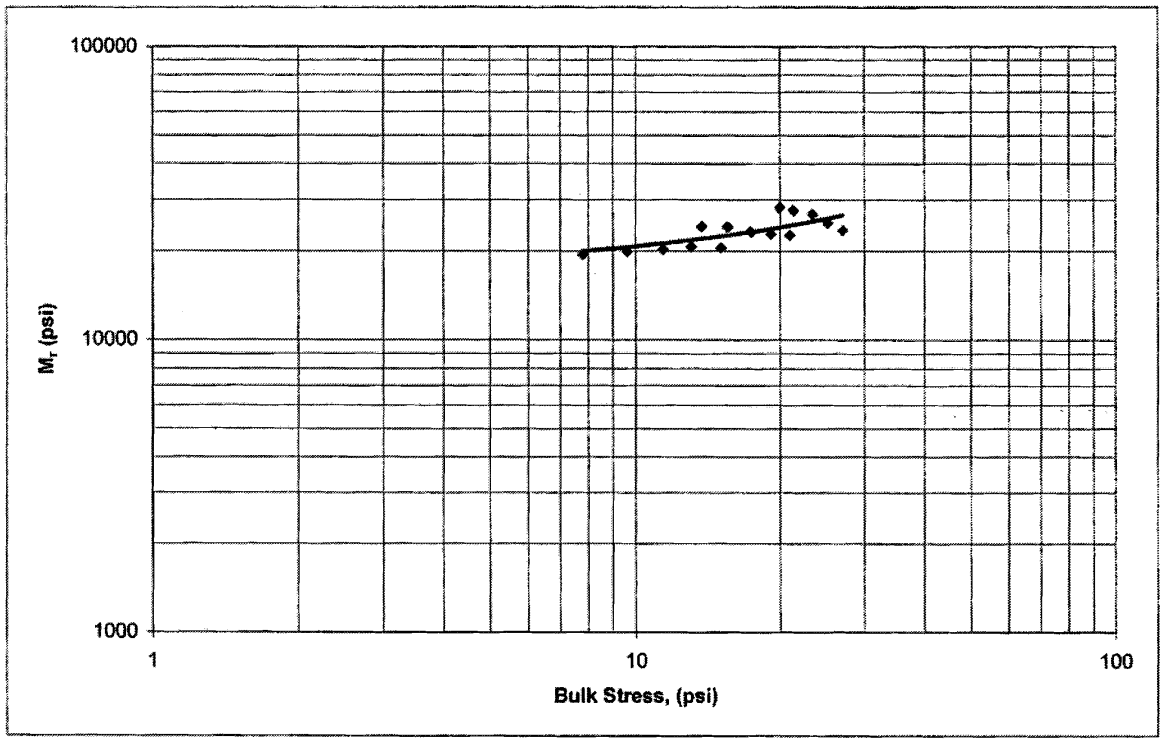
Weight of Wet Soil (lb)	5.34
Initial Sample Diameter (in)	3.94
Initial Sample Height (in)	7.87
Initial Sample Area (in^2)	12.17
Sample Volume (in^3)	95.86
Compacted Moisture Content(%)	27.8
Wet Density (pcf)	96.2
Dry Density (pcf)	75.2

Final Sample Height (in)	7.1
Final Sample Wet Weight (lb)	5.33
Final Moisture Content (%)	27.7
Accumulated Strain (%)	0.42
Percent Passing No. 10	0
Percent Passing No. 200	0.0
Liquid Limit	0
Plasticity Index	0

Chamber Confining Pressure (S_3) psi	Nominal Maximum Axial Stress (S_{cyclic}) psi	Actual Applied Max. Axial Load (P_{max}) lb	Actual Applied Cyclic Load (P_{cyclic}) lb	Actual Applied Contact Load ($P_{contact}$) lb	Actual Applied Max. Axial Stress (S_{max}) psi	Actual Applied Cyclic Stress (S_{cyclic}) psi	Actual Applied Contact Stress ($S_{contact}$) psi	Recov. Def. LVDT #1 Reading (H_1) in	Recov. Def. LVDT #2 Reading (H_2) in	Average Recov. Def. LVDT 1 and 2 (H_{avg}) in	Resilient Strain (ϵ_r) in/in	Resilient Modulus (M_r) psi
6.08	1.80	16.5	21.2	-4.8	1.35	1.74	-0.3905	0.0005	0.0005	0.0005	0.0000619	28127.9
5.93	3.60	40.6	43.0	-2.4	3.34	3.53	-0.1941	0.0010	0.0010	0.0010	0.0001284	27495.0
6.01	5.41	65.2	64.9	0.3	5.36	5.33	0.0242	0.0016	0.0015	0.0016	0.0001999	26684.8
5.98	7.21	90.0	87.5	2.6	7.39	7.18	0.2096	0.0024	0.0022	0.0023	0.0002879	24952.3
6.03	8.99	114.7	109.3	5.4	9.42	8.98	0.4403	0.0031	0.0029	0.0030	0.0003813	23544.0
4.00	1.80	17.3	21.3	-3.9	1.42	1.75	-0.3206	0.0006	0.0005	0.0006	0.0000719	24260.8
4.01	3.60	41.9	43.2	-1.3	3.44	3.55	-0.1104	0.0012	0.0011	0.0012	0.0001471	24119.5
4.02	5.41	66.2	65.3	0.9	5.44	5.36	0.0755	0.0019	0.0017	0.0018	0.0002309	23213.7
4.01	7.21	91.0	87.1	3.9	7.47	7.15	0.3186	0.0026	0.0023	0.0025	0.0003136	22812.9
4.00	8.99	115.4	109.0	6.4	9.48	8.95	0.5240	0.0032	0.0030	0.0031	0.0003962	22596.1
2.03	1.80	17.7	20.8	-3.1	1.46	1.71	-0.2549	0.0008	0.0006	0.0007	0.0000882	19391.8
2.03	4.00	42.6	43.0	-0.4	3.50	3.53	-0.0338	0.0016	0.0012	0.0014	0.0001777	19898.2
2.02	6.00	67.2	65.1	2.1	5.52	5.34	0.1744	0.0023	0.0019	0.0021	0.0002648	20182.5
1.98	8.00	91.7	87.1	4.6	7.53	7.15	0.3764	0.0029	0.0025	0.0027	0.0003461	20665.2
2.04	9.99	116.4	109.4	7.1	9.56	8.98	0.5795	0.0036	0.0033	0.0034	0.0004378	20520.8

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Shale Lime
Project No. 03071078



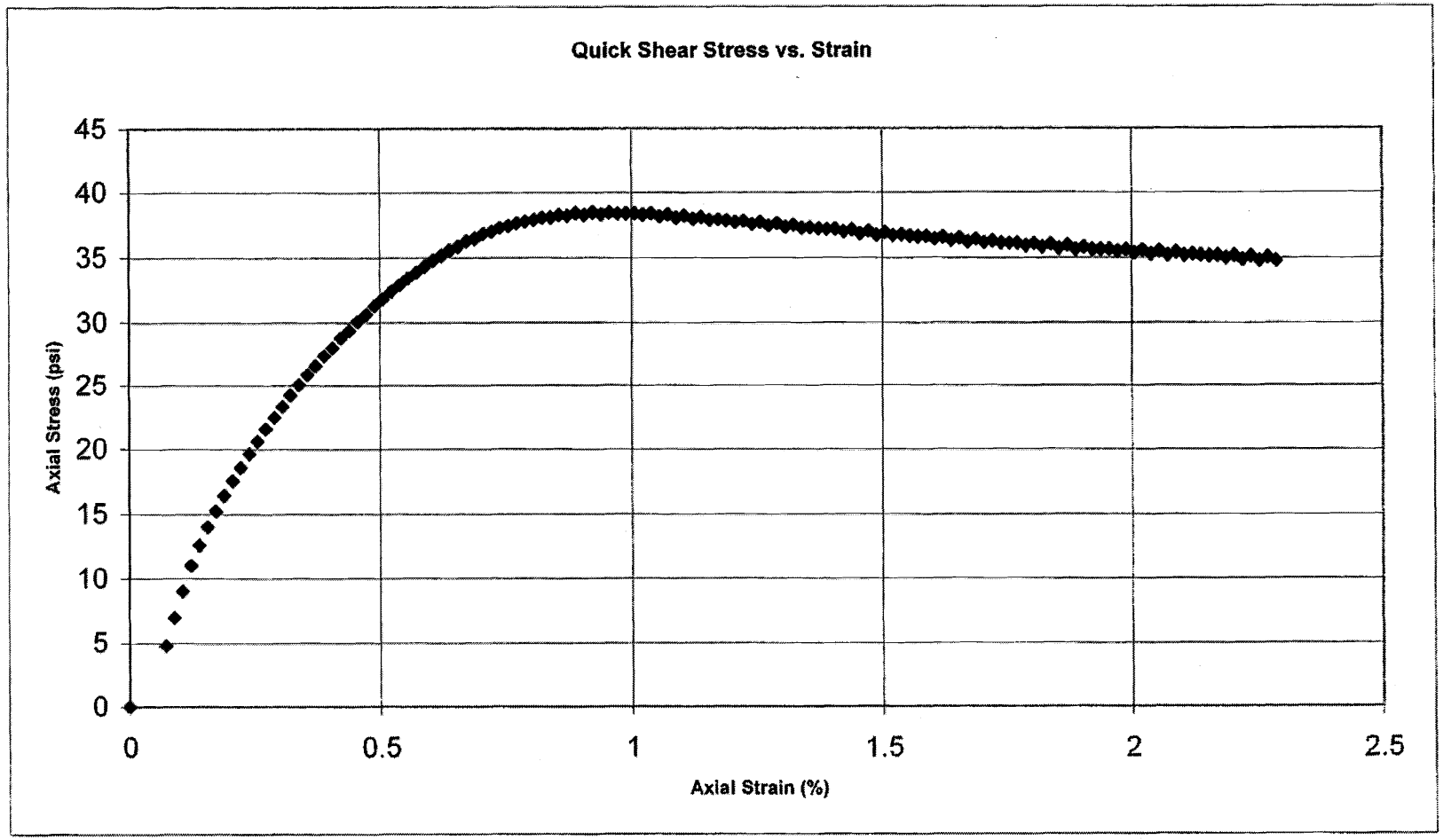
$Mr = K1 \times \Theta^{k2}$

$[\Theta = S_{cyclic} + 3\ (S3)]$

S3 (psi)	K1	K2	R^2
6	164995.7	-0.586	0.95
4	39891.3	-0.188	0.94
2	16055.3	0.094	0.91
All	11466.8	0.250	0.57

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Shale Lime
Project No. 03071078



Terracon

Resilient Modulus Testing - AASHTO T 307-99 English Units

Report Date:	18-Apr-07
Lab No.:	Till CKD
Project No.:	03071078
Test Date:	11-Apr-07

Soil Map Unit:	Till 7% CKD
Soil Symbol:	0
Depth (in.)	0
Compaction Method	Static
Max. Dry Density (pcf)	102.0
Opt. Moisture Content (%)	18.5
Inside Mold Diameter (in)	3.94

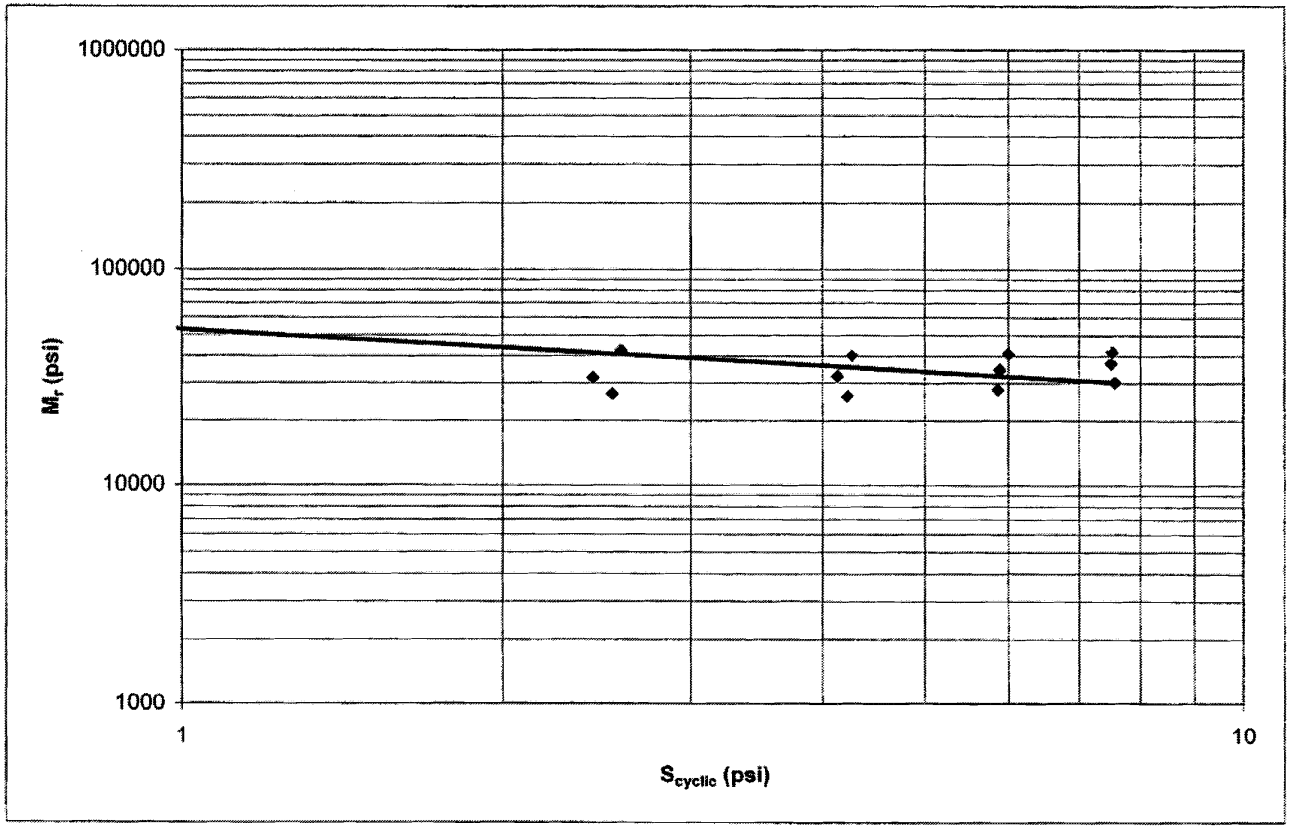
Weight of Wet Soil (lb)	6.37
Initial Sample Diameter (in)	3.94
Initial Sample Height (in)	7.87
Initial Sample Area (in^2)	12.17
Sample Volume (in^3)	95.86
Compacted Moisture Content(%)	19.7
Wet Density (pcf)	114.8
Dry Density (pcf)	95.9

Final Sample Height (in)	7.9
Final Sample Wet Weight (lb)	6.37
Final Moisture Content (%)	19.6
Accumulated Strain (%)	2.00
Percent Passing No. 10	0
Percent Passing No. 200	0.0
Liquid Limit	0
Plasticity Index	0

Chamber Confining Pressure (S_3) psi	Nominal Maximum Axial Stress (S_{cyclic}) psi	Actual Applied Max. Axial Load (P_{max}) lb	Actual Applied Cyclic Load (P_{cyclic}) lb	Actual Applied Contact Load ($P_{contact}$) lb	Actual Applied Max. Axial Stress (S_{max}) psi	Actual Applied Cyclic Stress (S_{cyclic}) psi	Actual Applied Contact Stress ($S_{contact}$) psi	Recov. Def. LVDT #1 Reading (H_1) in	Recov. Def. LVDT #2 Reading (H_2) in	Average Recov. Def. LVDT 1 and 2 (H_{avg}) in	Resilient Strain (ϵ_r) in/in	Resilient Modulus (M_r) psi
6.06	1.80	9.2	7.1	2.1	0.75	0.58	0.1721	0.0000	0.0000	0.0000	0.0000035	167117.8
5.97	3.60	33.6	31.5	2.2	2.76	2.58	0.1780	0.0005	0.0004	0.0005	0.0000612	42213.0
6.04	5.41	58.3	51.9	6.3	4.79	4.27	0.5206	0.0009	0.0008	0.0008	0.0001064	40100.0
6.00	7.21	82.0	73.1	8.9	6.74	6.00	0.7339	0.0012	0.0011	0.0012	0.0001470	40833.9
6.03	8.99	105.0	91.6	13.3	8.62	7.52	1.0953	0.0014	0.0014	0.0014	0.0001806	41666.3
4.02	1.80	9.9	7.3	2.6	0.81	0.60	0.2102	0.0001	0.0001	0.0001	0.0000114	52701.7
4.03	3.60	34.4	29.6	4.8	2.83	2.43	0.3966	0.0007	0.0005	0.0006	0.0000767	31687.7
4.02	5.41	58.1	50.3	7.8	4.77	4.13	0.6395	0.0011	0.0010	0.0010	0.0001281	32233.6
4.02	7.21	81.8	71.7	10.1	6.71	5.89	0.8268	0.0014	0.0013	0.0013	0.0001702	34586.8
4.02	8.99	105.0	91.4	13.6	8.63	7.51	1.1181	0.0016	0.0016	0.0016	0.0002041	36782.3
2.00	1.80	11.5	9.9	1.6	0.95	0.81	0.1332	0.0002	0.0002	0.0002	0.0000264	30723.5
1.97	4.00	35.4	30.9	4.5	2.91	2.53	0.3721	0.0008	0.0007	0.0008	0.0000953	26576.3
2.01	6.00	58.9	51.4	7.5	4.84	4.22	0.6172	0.0013	0.0012	0.0013	0.0001627	25937.0
2.04	8.00	82.8	71.4	11.4	6.80	5.86	0.9381	0.0017	0.0016	0.0017	0.0002101	27919.1
1.96	9.99	105.9	92.1	13.7	8.69	7.57	1.1274	0.0020	0.0019	0.0020	0.0002511	30135.1

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Till CKD
Project No. 03071078

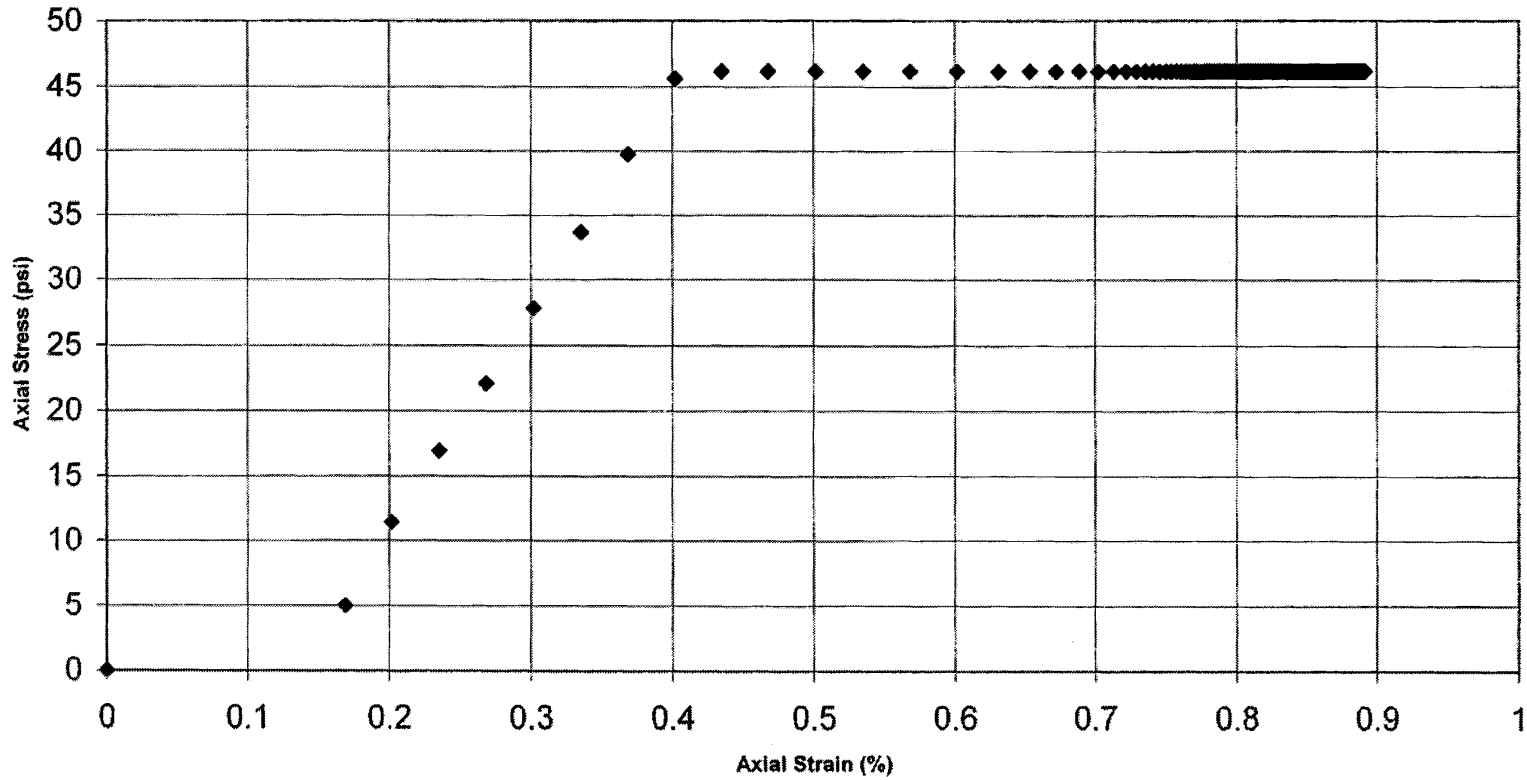


$Mr = K1 \times S_{cyclic}^{k2}$

S3 (psi)	K1	K2	R^2
6	103477.5	-0.566	0.85
4	43959.7	-0.157	0.57
2	29023.4	-0.024	0.08
All	52862.21	-0.27819	0.30627

Terracon

Date Reported:	4/18/2007
Terracon Lab No.	Till CKD
Project No.	03071078



Terracon

Resilient Modulus Testing - AASHTO T 307-99 English Units

Report Date:	18-Apr-07
Lab No.:	Till Fly Ash
Project No.:	03071078
Test Date:	11-Apr-07

Soil Map Unit:	Till 12% Fly Ash
Soil Symbol:	0
Depth (in.)	0
Compaction Method	Static
Max. Dry Density (pcf)	107.5
Opt. Moisture Content (%)	17.0
Inside Mold Diameter (in)	3.94

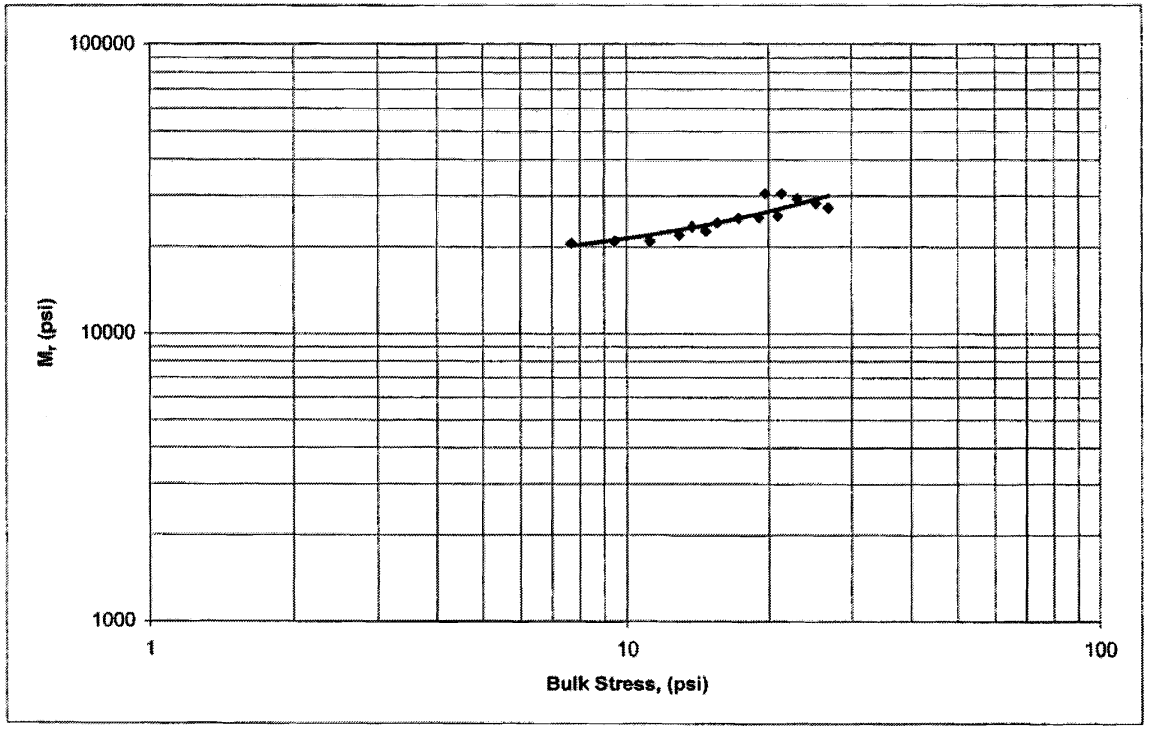
Weight of Wet Soil (lb)	6.62
Initial Sample Diameter (in)	3.94
Initial Sample Height (in)	7.91
Initial Sample Area (in^2)	12.17
Sample Volume (in^3)	96.34
Compacted Moisture Content(%)	18.7
Wet Density (pcf)	118.8
Dry Density (pcf)	100.1

Final Sample Height (in)	7.2
Final Sample Wet Weight (lb)	6.62
Final Moisture Content (%)	18.6
Accumulated Strain (%)	0.60
Percent Passing No. 10	0
Percent Passing No. 200	0.0
Liquid Limit	0
Plasticity Index	0

Chamber Confining Pressure (S_3) psi	Nominal Maximum Axial Stress (S_{cyclic}) psi	Actual Applied Max. Axial Load (P_{max}) lb	Actual Applied Cyclic Load (P_{cyclic}) lb	Actual Applied Contact Load ($P_{contact}$) lb	Actual Applied Max. Axial Stress (S_{max}) psi	Actual Applied Cyclic Stress (S_{cyclic}) psi	Actual Applied Contact Stress ($S_{contact}$) psi	Recov. Def. LVDT #1 Reading (H_1) in	Recov. Def. LVDT #2 Reading (H_2) in	Average Recov. Def. LVDT 1 and 2 (H_{avg}) in	Resilient Strain (ϵ_r) in/in	Resilient Modulus (M_r) psi
5.99	1.80	16.4	20.8	-4.5	1.34	1.71	-0.3671	0.0005	0.0004	0.0004	0.0000563	30413.4
5.95	3.60	40.3	42.4	-2.1	3.31	3.48	-0.1752	0.0010	0.0008	0.0009	0.0001146	30386.2
5.93	5.41	64.3	63.8	0.5	5.28	5.24	0.0414	0.0016	0.0013	0.0014	0.0001793	29211.4
6.07	7.21	88.8	85.8	3.0	7.29	7.04	0.2493	0.0022	0.0018	0.0020	0.0002503	28141.5
6.00	8.99	112.8	107.5	5.4	9.27	8.83	0.4417	0.0028	0.0023	0.0026	0.0003240	27239.1
4.00	1.80	17.3	21.2	-3.9	1.42	1.74	-0.3206	0.0007	0.0005	0.0006	0.0000743	23427.9
4.01	3.60	41.4	42.9	-1.5	3.40	3.53	-0.1240	0.0013	0.0010	0.0012	0.0001457	24200.5
4.00	5.41	65.5	64.0	1.5	5.38	5.26	0.1200	0.0018	0.0015	0.0017	0.0002098	25063.7
4.01	7.21	89.7	86.1	3.6	7.36	7.07	0.2927	0.0025	0.0020	0.0022	0.0002807	25193.4
4.03	8.99	113.8	107.5	6.3	9.35	8.83	0.5206	0.0030	0.0025	0.0027	0.0003448	25602.4
1.98	1.80	18.3	21.1	-2.8	1.50	1.73	-0.2296	0.0007	0.0006	0.0007	0.0000843	20545.6
1.97	4.00	42.6	42.9	-0.4	3.50	3.53	-0.0301	0.0015	0.0012	0.0013	0.0001691	20853.1
1.97	6.00	66.6	64.4	2.1	5.47	5.29	0.1764	0.0022	0.0018	0.0020	0.0002526	20949.3
1.97	8.00	90.4	85.3	5.0	7.42	7.01	0.4136	0.0028	0.0023	0.0025	0.0003207	21851.4
1.97	9.99	114.4	106.7	7.7	9.39	8.76	0.6302	0.0033	0.0028	0.0031	0.0003865	22678.9

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Till Fly Ash
Project No. 03071078



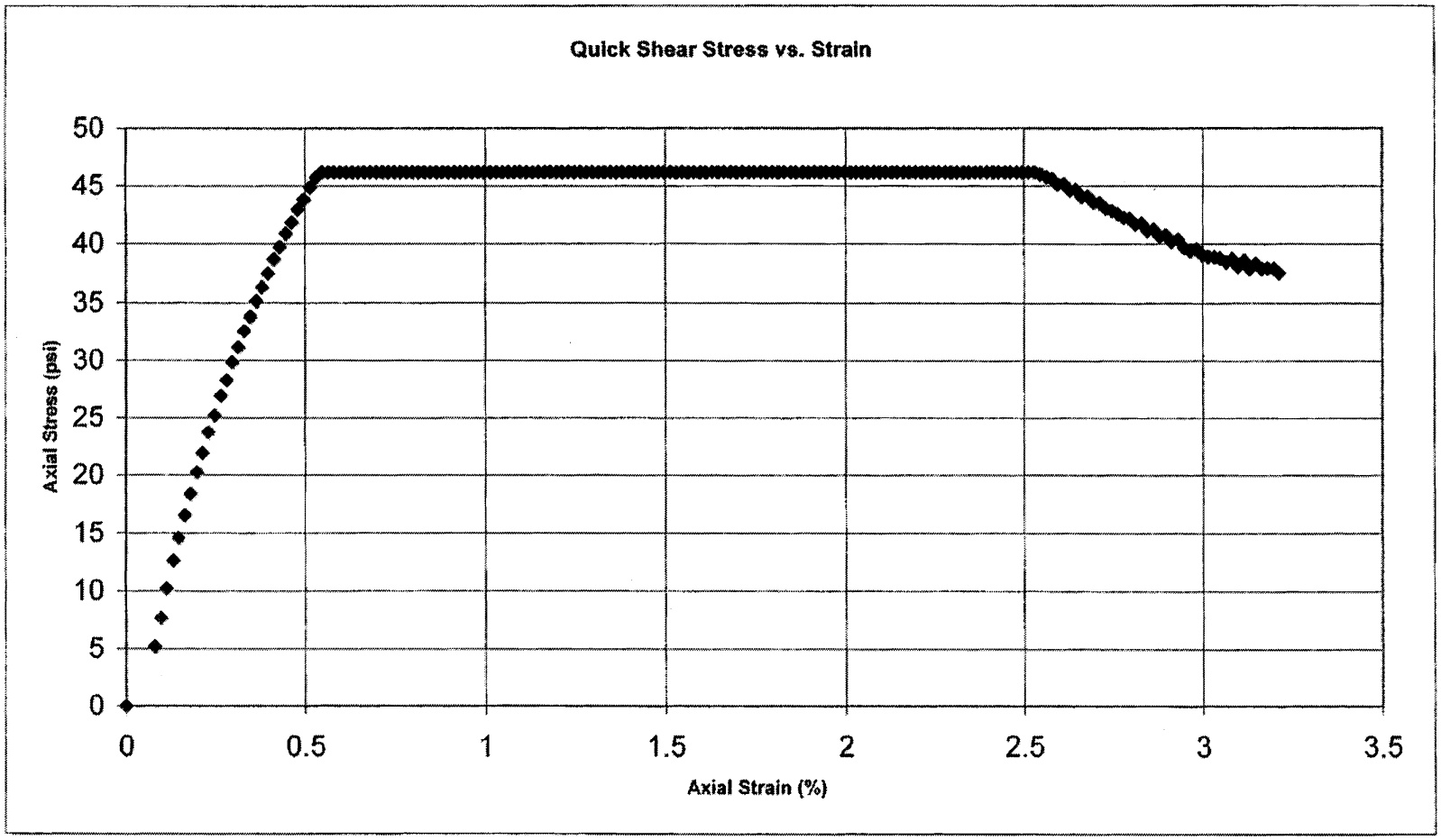
$Mr = K1 \times \Theta^{k2}$

$[\Theta = S_{cyclic} + 3\ (S3)]$

S3 (psi)	K1	K2	R^2
6	94597.9	-0.376	0.94
4	13574.8	0.210	0.95
2	15076.0	0.146	0.85
All	9915.7	0.329	0.78

Terracon

Date Reported:	4/18/2007
Terracon Lab No.	Till Fly Ash
Project No.	03071078



Terracon

Resilient Modulus Testing - AASHTO T 307-99 English Units

Report Date:	18-Apr-07
Lab No.:	Till Lime
Project No.:	03071078
Test Date:	10-Apr-07

Soil Map Unit:	Till 5% Lime
Soil Symbol:	0
Depth (in.)	0
Compaction Method	Static
Max. Dry Density (pcf)	92.5
Opt. Moisture Content (%)	18.0
Inside Mold Diameter (in)	3.94

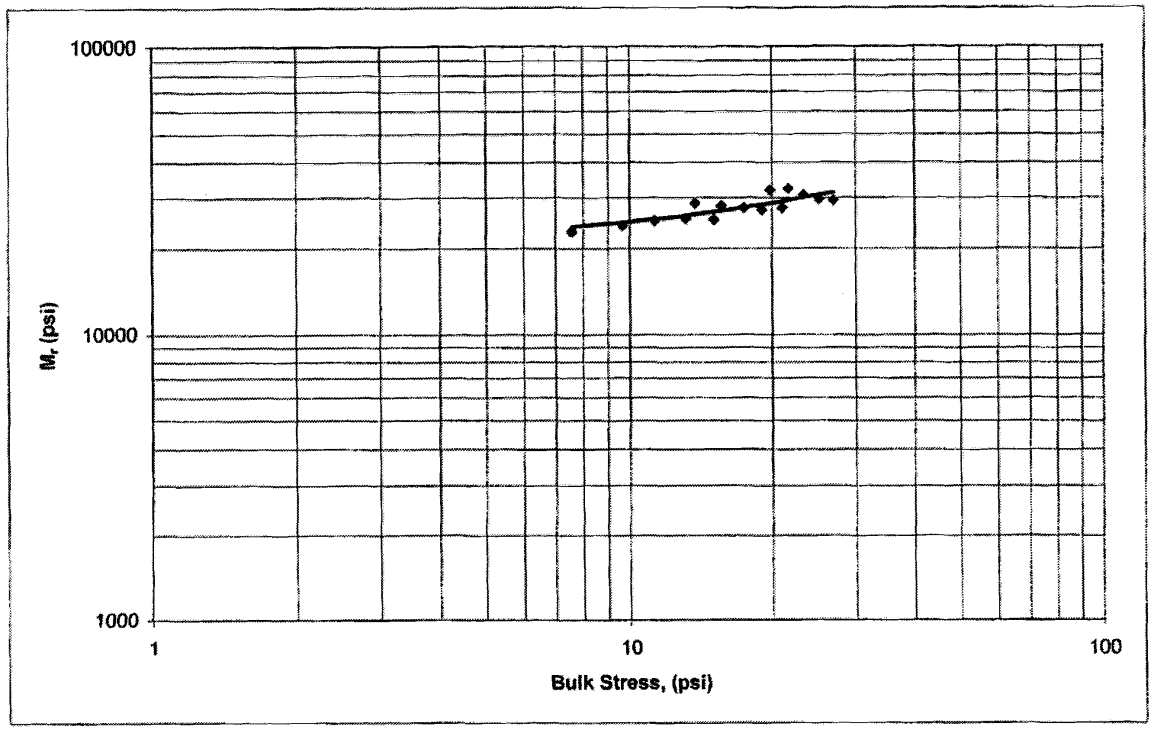
Weight of Wet Soil (lb)	5.75
Initial Sample Diameter (in)	3.94
Initial Sample Height (in)	7.87
Initial Sample Area (in^2)	12.17
Sample Volume (in^3)	95.86
Compacted Moisture Content(%)	20.0
Wet Density (pcf)	103.7
Dry Density (pcf)	86.4

Final Sample Height (in)	7.2
Final Sample Wet Weight (lb)	5.74
Final Moisture Content (%)	20.0
Accumulated Strain (%)	0.49
Percent Passing No. 10	0
Percent Passing No. 200	0.0
Liquid Limit	0
Plasticity Index	0

Chamber Confining Pressure (S_3) psi	Nominal Maximum Axial Stress (S_{cyclic}) psi	Actual Applied Max. Axial Load (P_{max}) lb	Actual Applied Cyclic Load (P_{cyclic}) lb	Actual Applied Contact Load ($P_{contact}$) lb	Actual Applied Max. Axial Stress (S_{max}) psi	Actual Applied Cyclic Stress (S_{cyclic}) psi	Actual Applied Contact Stress ($S_{contact}$) psi	Recov. Def. LVDT #1 Reading (H_1) in	Recov. Def. LVDT #2 Reading (H_2) in	Average Recov. Def. LVDT 1 and 2 (H_{avg}) in	Resilient Strain (ϵ_r) in/in	Resilient Modulus (M_r) psi
6.02	1.80	16.7	21.1	-4.3	1.38	1.73	-0.3569	0.0005	0.0004	0.0004	0.0000546	31740.0
6.04	3.60	41.3	43.3	-2.1	3.39	3.56	-0.1713	0.0010	0.0007	0.0009	0.0001103	32278.8
5.99	5.41	65.7	65.0	0.7	5.40	5.34	0.0580	0.0016	0.0012	0.0014	0.0001749	30517.4
6.00	7.21	90.3	87.2	3.1	7.42	7.16	0.2564	0.0022	0.0016	0.0019	0.0002423	29549.1
5.99	8.99	114.8	109.3	5.5	9.43	8.98	0.4519	0.0027	0.0021	0.0024	0.0003068	29266.3
4.01	1.80	17.5	21.1	-3.6	1.44	1.73	-0.2972	0.0005	0.0004	0.0005	0.0000607	28551.9
4.02	3.60	42.0	43.5	-1.4	3.45	3.57	-0.1172	0.0011	0.0009	0.0010	0.0001275	27985.6
4.02	5.41	66.6	65.4	1.2	5.47	5.37	0.0983	0.0018	0.0013	0.0015	0.0001954	27501.3
3.96	7.21	91.1	87.3	3.8	7.48	7.17	0.3104	0.0024	0.0018	0.0021	0.0002642	27140.3
4.03	8.99	115.4	108.8	6.6	9.48	8.93	0.5454	0.0029	0.0022	0.0026	0.0003243	27542.1
1.94	1.80	18.2	21.3	-3.1	1.50	1.75	-0.2516	0.0007	0.0005	0.0006	0.0000762	22945.0
2.04	4.00	42.7	43.2	-0.5	3.50	3.55	-0.0448	0.0013	0.0010	0.0012	0.0001479	23995.7
1.97	6.00	67.3	65.4	1.9	5.53	5.37	0.1586	0.0019	0.0015	0.0017	0.0002154	24933.0
2.01	8.00	91.8	86.9	4.9	7.54	7.13	0.4040	0.0025	0.0019	0.0022	0.0002824	25264.8
2.05	9.99	116.3	109.1	7.2	9.55	8.96	0.5916	0.0032	0.0024	0.0028	0.0003558	25170.8

Terracon

Date Reported: 4/18/2007
Terracon Lab No. Till Lime
Project No. 03071078



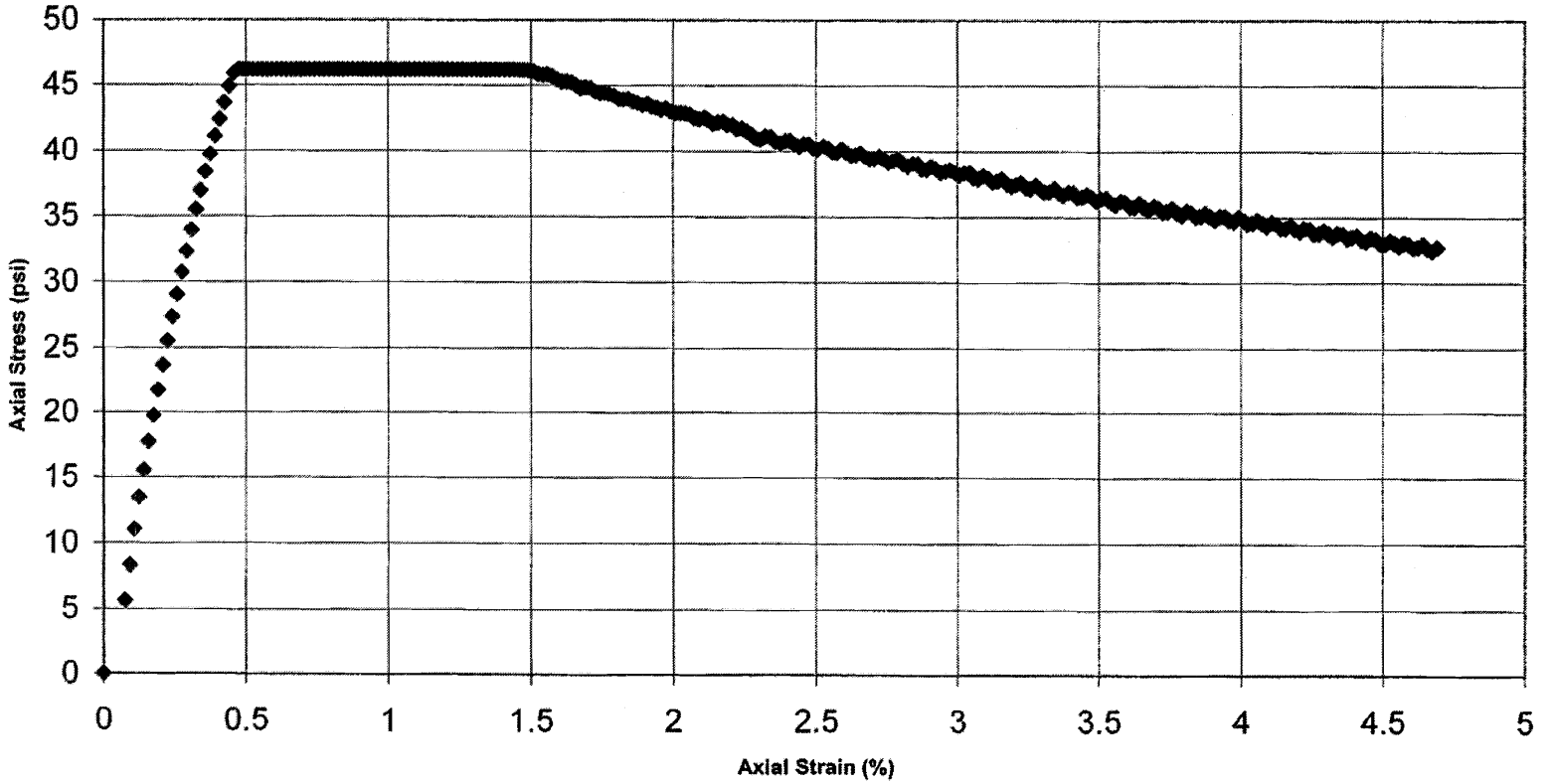
$Mr = K1 \times \Theta^{k2}$

$[\Theta = S_{cyclic} + 3\ (S3)]$

S3 (psi)	K1	K2	R^2
6	84563.1	-0.323	0.83
4	36939.3	-0.101	0.74
2	17287.6	0.144	0.90
All	14276.9	0.234	0.71

Terracon

Date Reported:	4/18/2007
Terracon Lab No.	Till Lime
Project No.	03071078



Appendix F

Field Manual for Soil Stabilization

Nebraska Group Index

Gravel	Fine Sand	Sandy/ Silt	Loess	Loess/ Till	Till	Shale
-2	-1 to 1	5 - 7	8 -12	13 - 14	15 - 21	22 - 24

2007 Cost Comparison of Pozzolans for One Mile (Section of Roadway 12' Wide)

Pozzolan Type	Percentage Pozzolan	Average Unit Wt. lb/ft^3	Application lb/yd^2 @ 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 yd^2
2. CKD cost is based upon product delivery to Lincoln, NE (2007), 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.

Sample 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

Summary Properties of Native Soils

	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/ft³	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

Atterberg Limits – Native Soils and with Pozzolan Additive

	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

Application of Pozzolans

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. Off-site mixing may not be feasible 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. A soil stabilizer is preferable over mixing with a towed disc because it mixes the materials much more thoroughly. Stabilizers are designed with a continuous mixing chamber and shaped rotors assuring a complete blending of materials. Disking of materials is not recommended unless it is the sole practical method of incorporating pozzolanic material. Disking fails to provide the compete blending needed to maximize the effects of most pozzolans.

Water

The most important step during the stabilization process is adding (or subtracting) 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, plus it aids in achieving proper compaction. With the moisture too low or too high, achieving a specified density becomes almost impossible.

Water is sometimes added to the subgrade directly ahead of the stabilizer. This may cause problems, by 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 additional passes with the soil stabilizer. While this process works well, the increased 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.

Curing and Compaction

Lime stabilized subgrades should be allowed to cure a minimum of 48 hours before initial compaction. Subgrades stabilized with CKD or fly ash should be compacted as soon as practical after incorporation of the pozzolan.

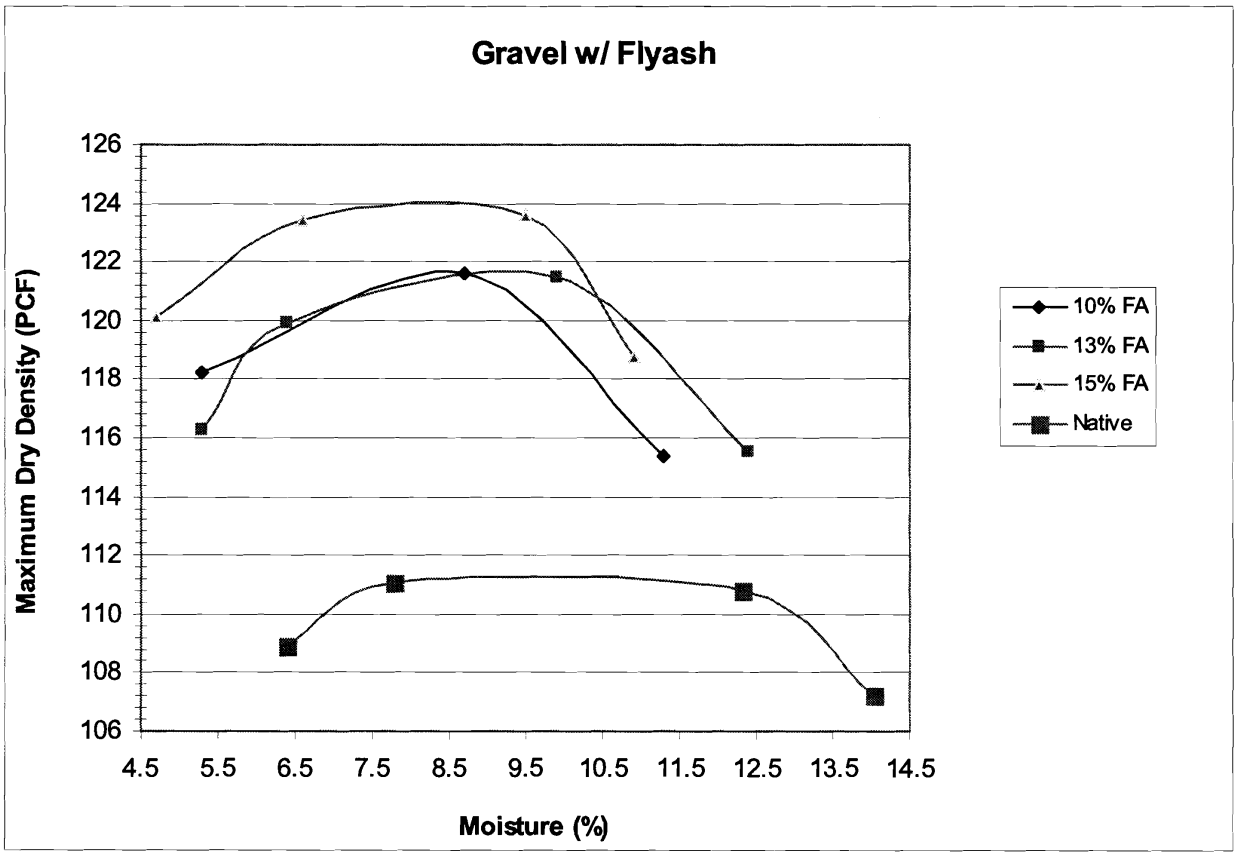
Design Criteria

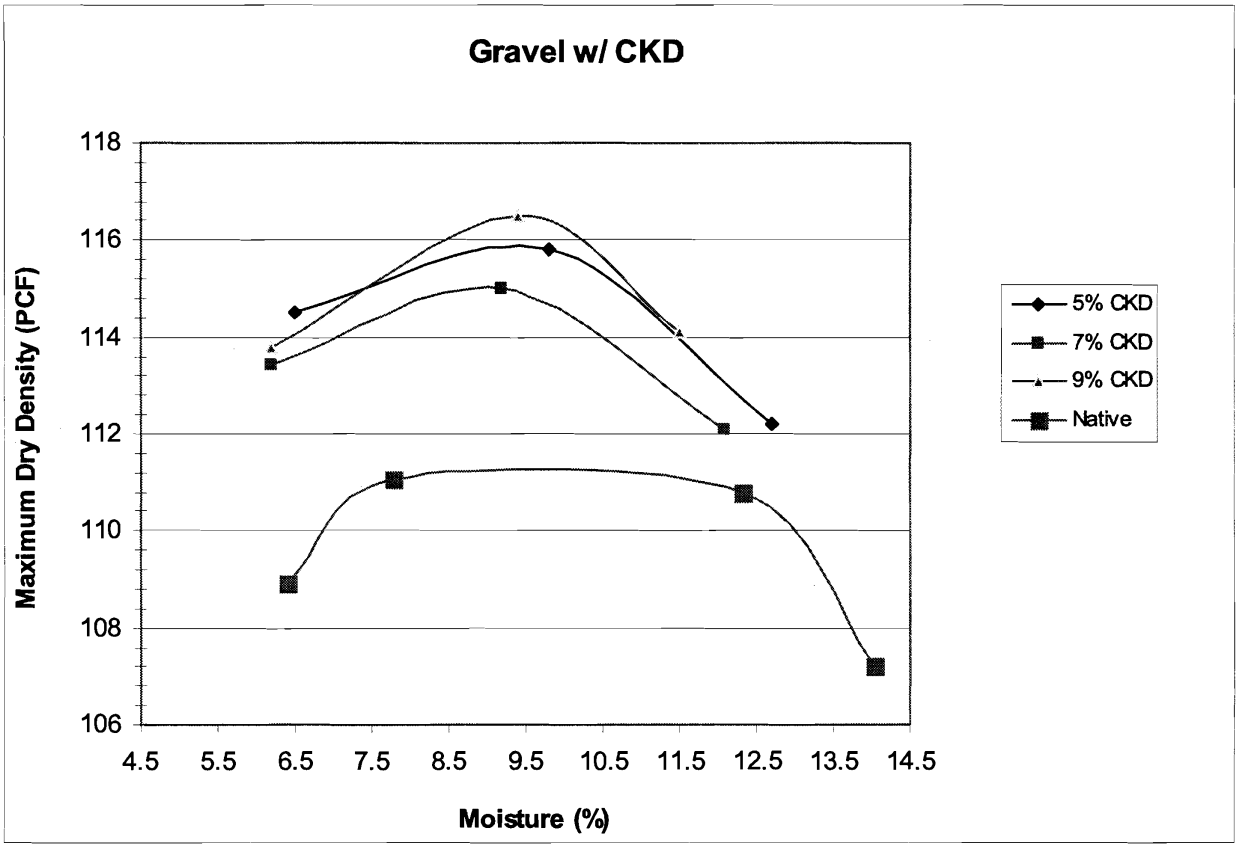
Gravel (NGI -2)

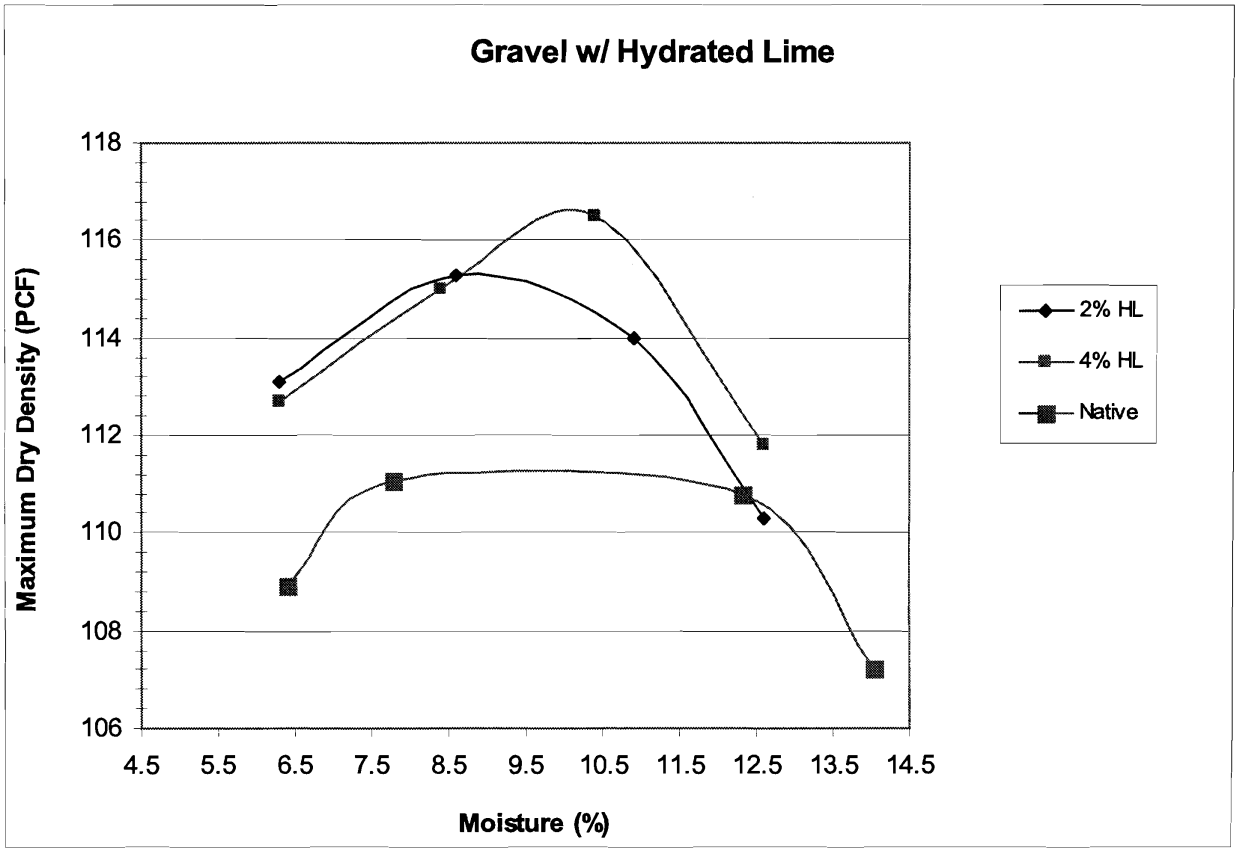
Gravel is not normally stabilized through addition of a pozzolan because of its granular nature; instead it is stabilized through vibratory compaction.

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




Gravel w/ CKD
Maximum Dry Density (PCF)
118
116
114
112
110
108
106
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
Moisture (%)
5% CKD
7% CKD
9% CKD
Native


Gravel w/ Hydrated Lime
Maximum Dry Density (PCF)
118
116
114
112
110
108
106
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
Moisture (%)
2% HL
4% HL
Native

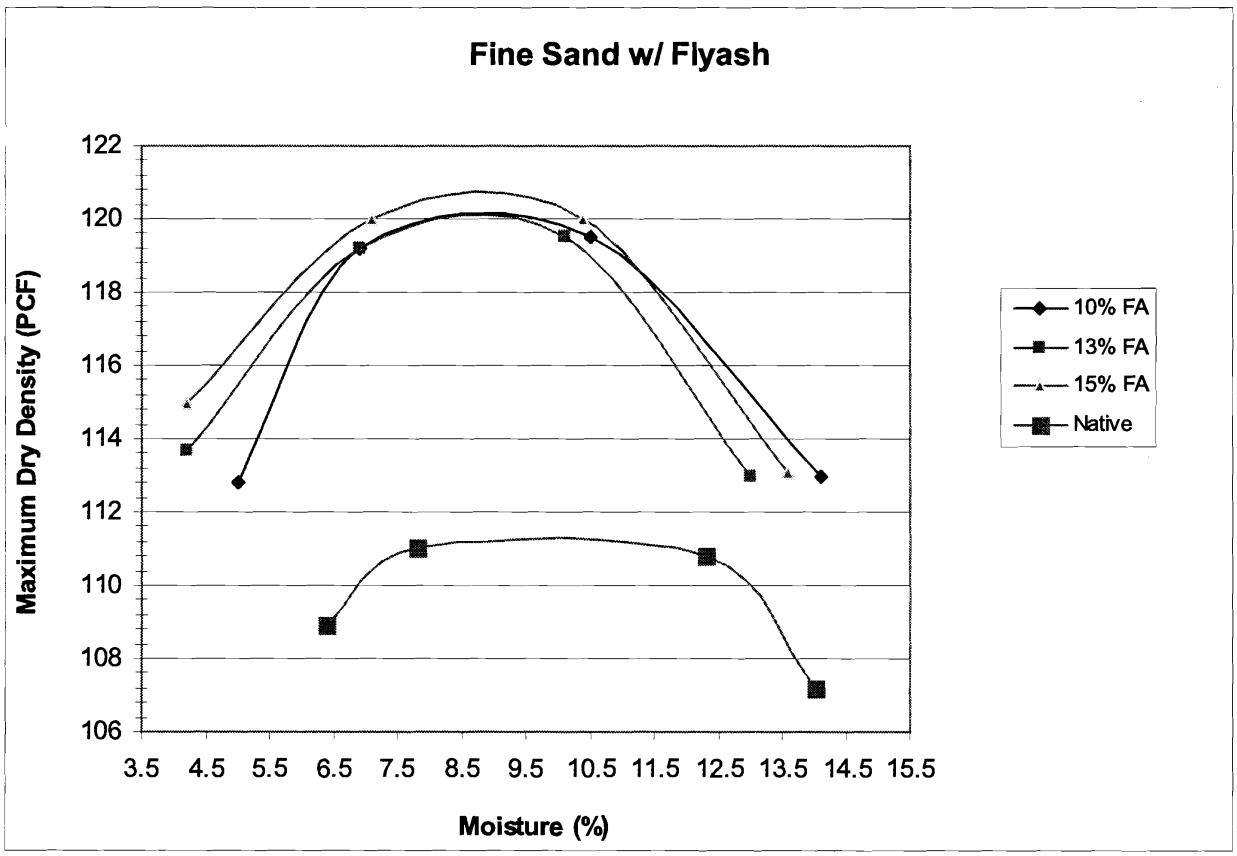
Design Criteria

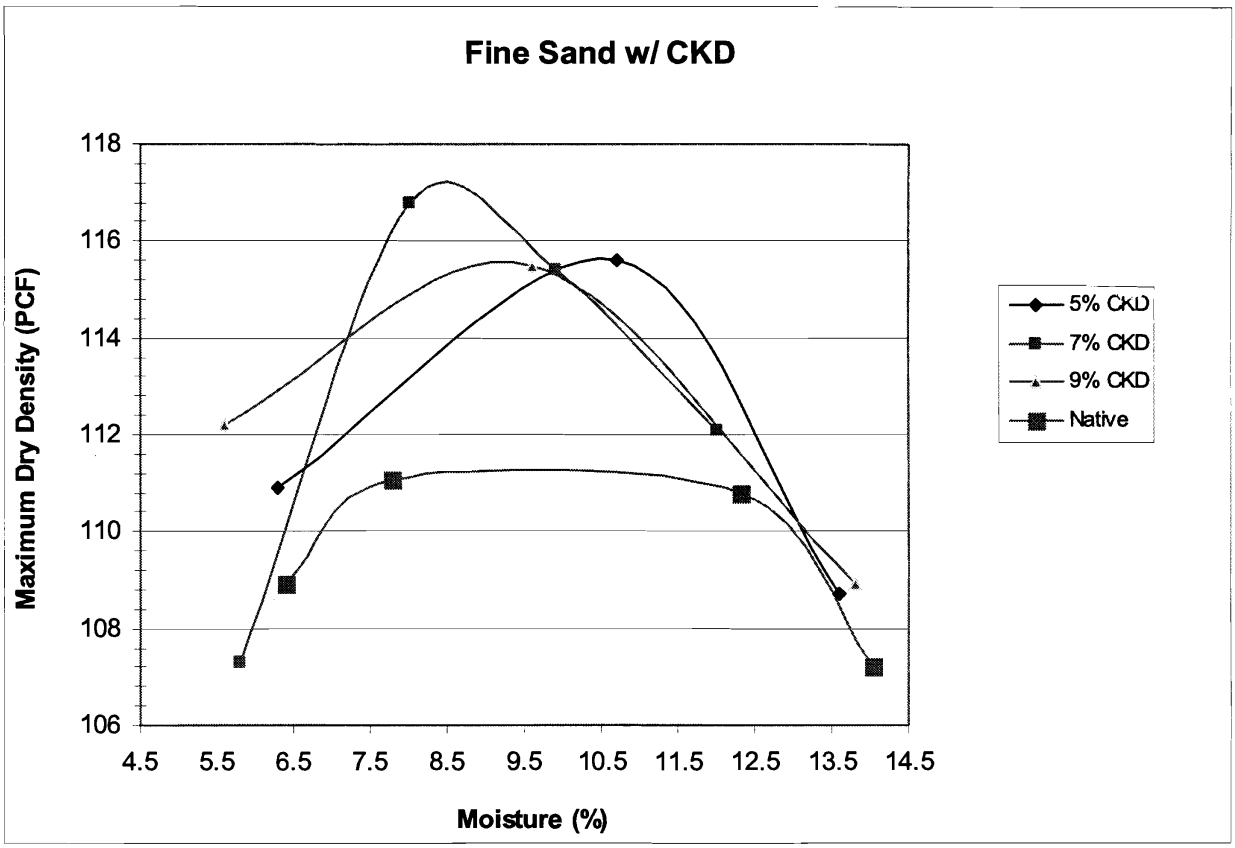
Fine Sand (NGI 0)

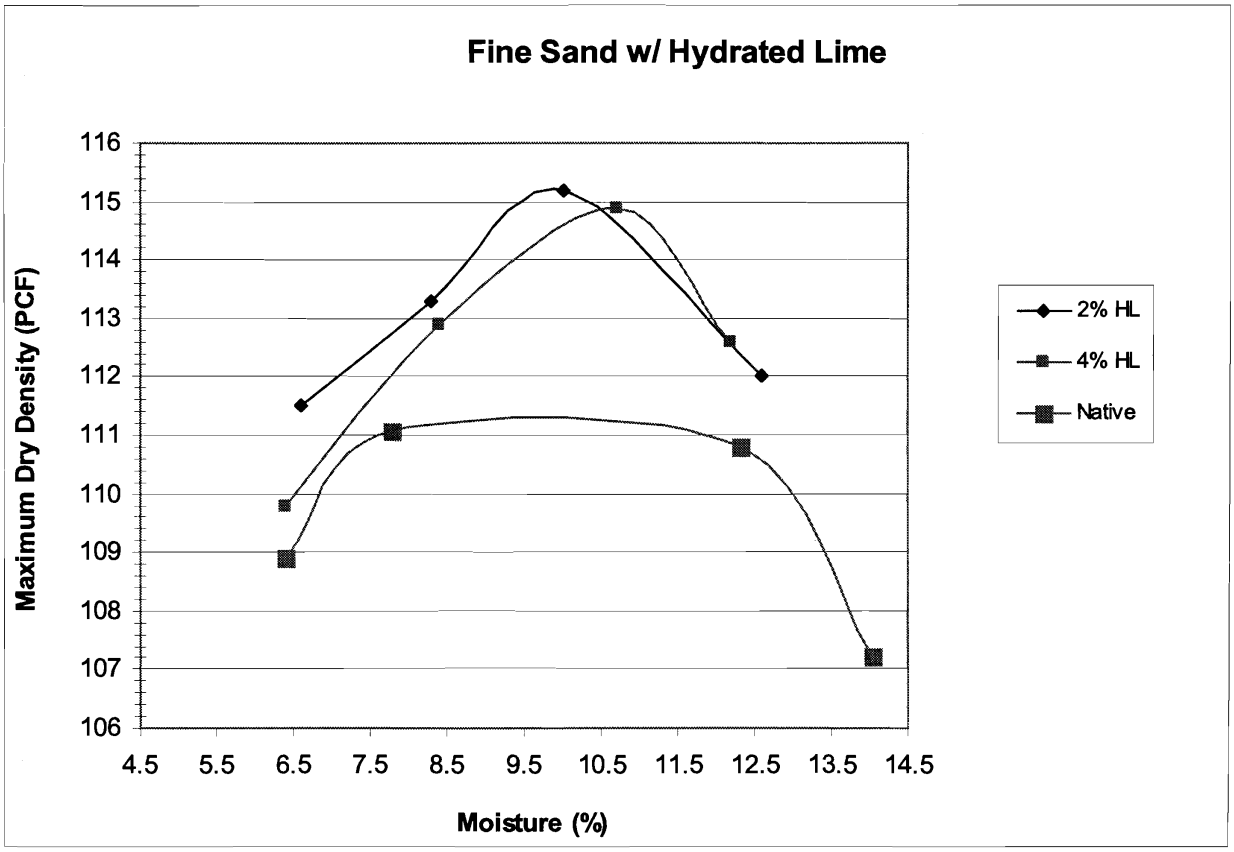
Fine sand is not normally stabilized through addition of a pozzolan because of its granular nature; instead it is stabilized through vibratory compaction.

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




Fine Sand w/ CKD
Maximum Dry Density (PCF)
118
116
114
112
110
108
106
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
Moisture (%)
5% CKD
7% CKD
9% CKD
Native


Fine Sand w/ Hydrated Lime
Maximum Dry Density (PCF)
116
115
114
113
112
111
110
109
108
107
106
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
14.5
Moisture (%)
2% HL
4% HL
Native

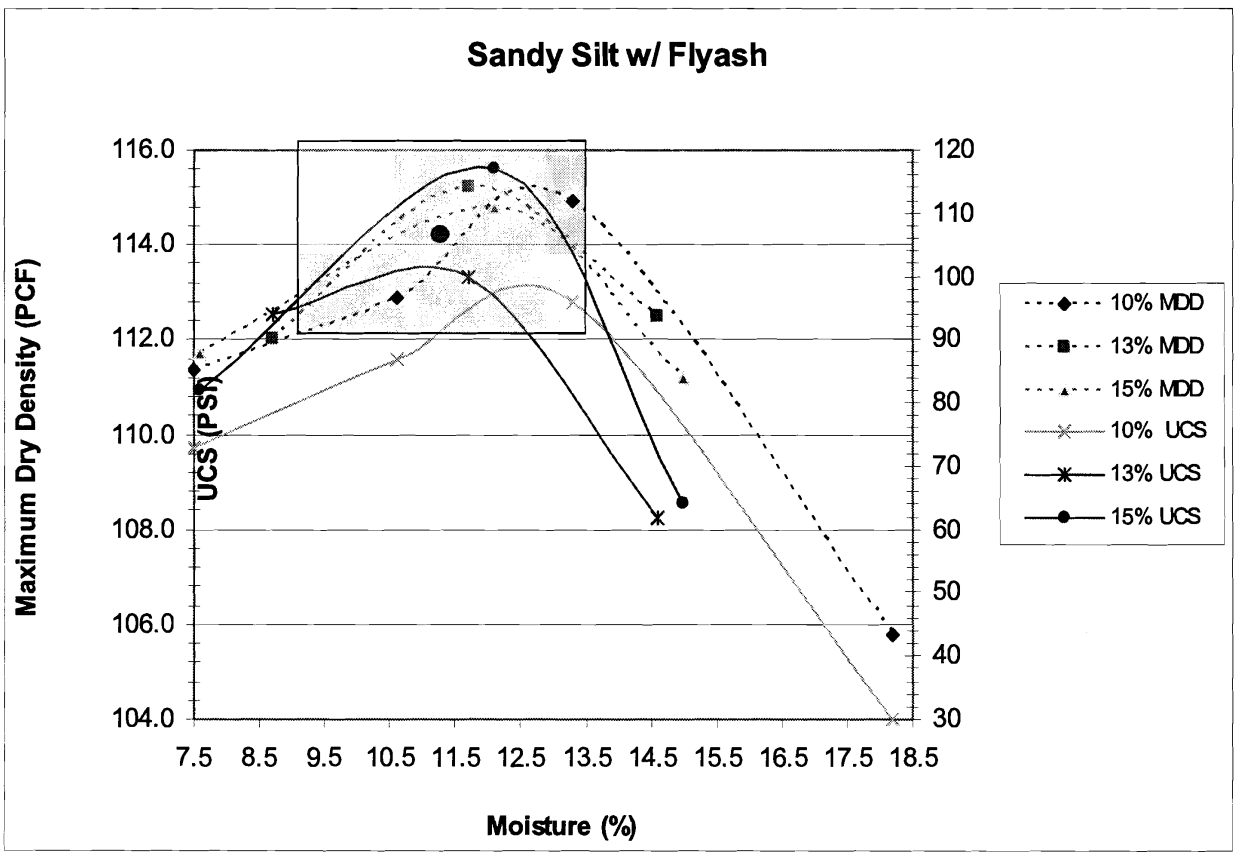
Design Criteria

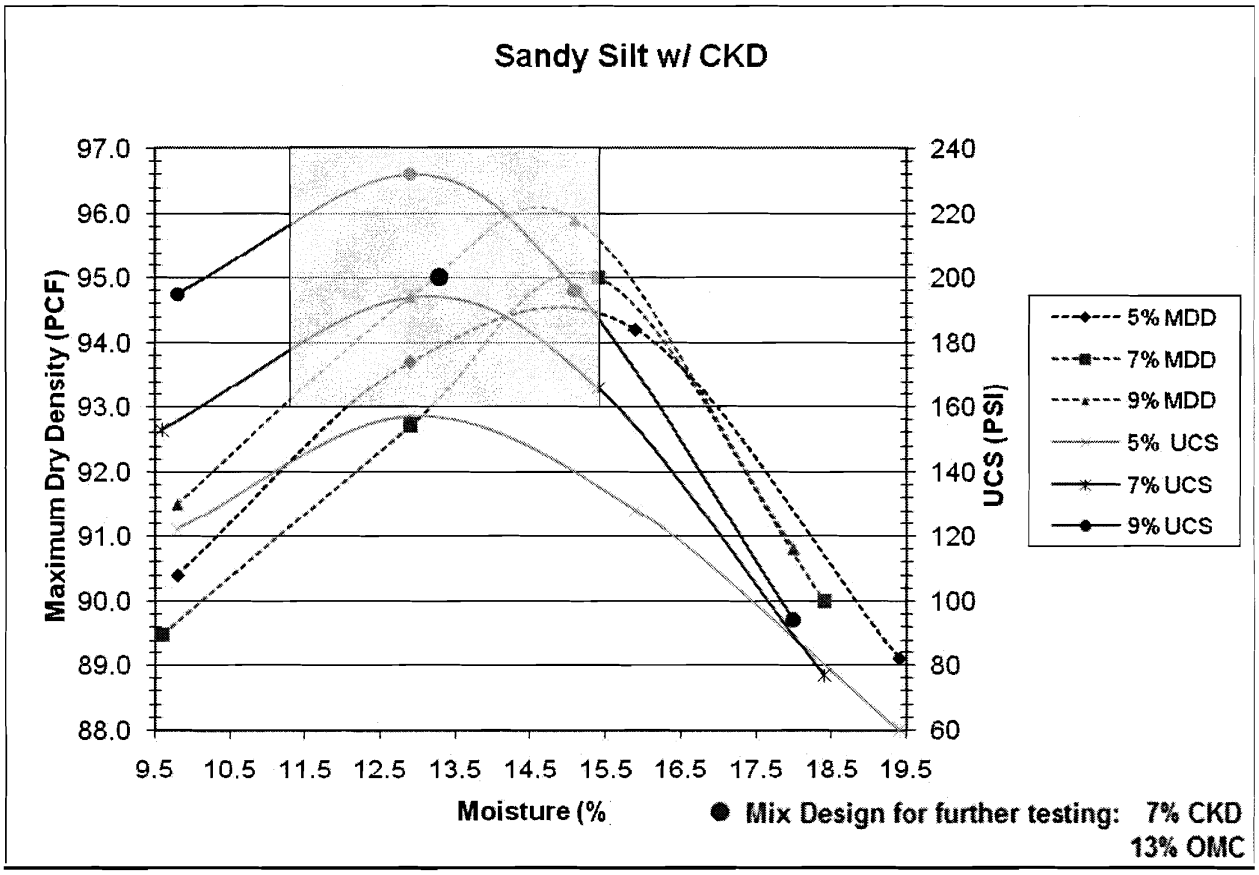
Sandy Silt (NGI 5)

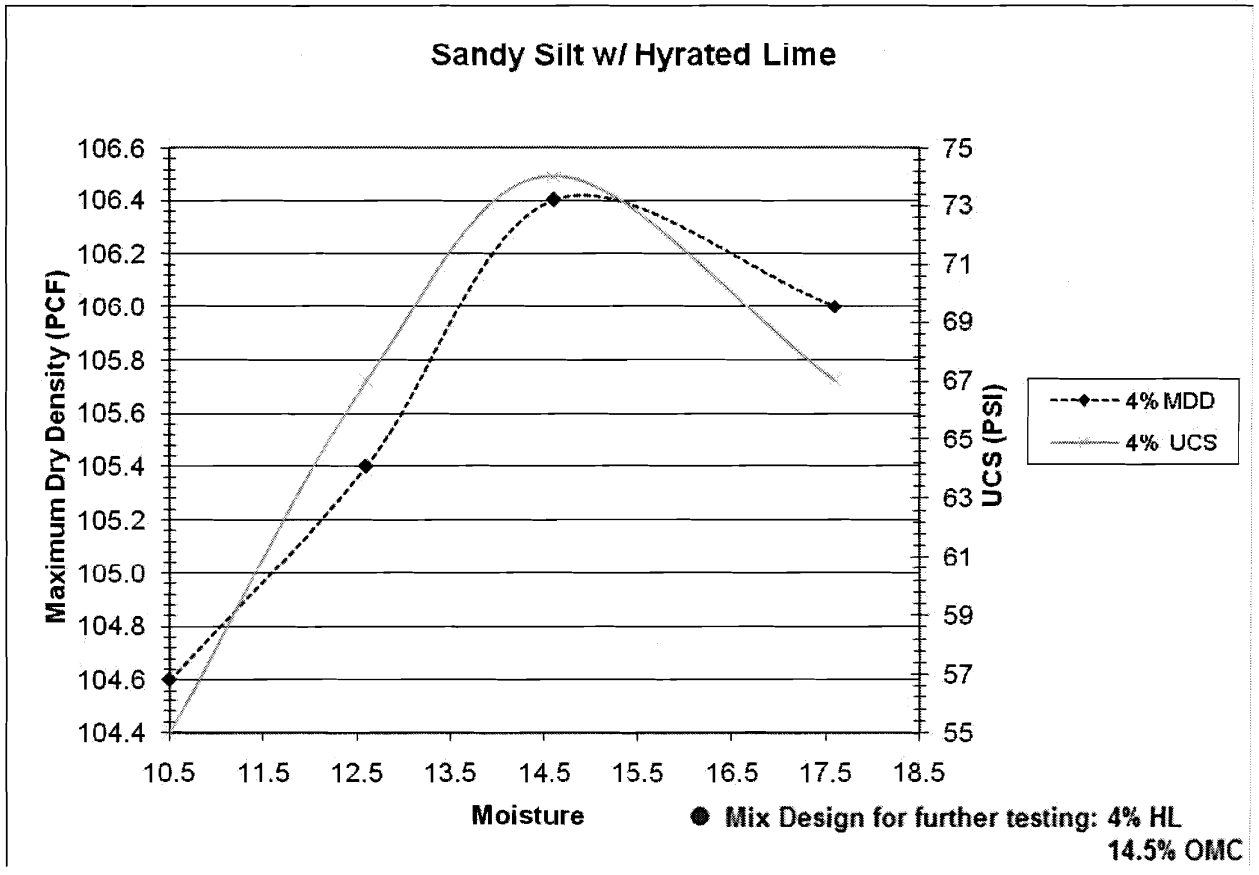
Pozzolans are often used to stabilize cohesive soils. The optimum moisture content and design mix of pozzolan to stabilize sandy silt are outlined below:

Moisture Content and Pozzolan Percentages for Sandy Silt

Sandy Silt						
Pozzolan	Optimum Native Moisture	Design				
		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




Sandy Silt w/ CKD
Maximum Dry Density (PCF)
97.0
96.0
95.0
94.0
93.0
92.0
91.0
90.0
89.0
88.0
UCS (PSI)
240
220
200
180
160
140
120
100
80
60
9.5 10.5 11.5 12.5 13.5 14.5 15.5 16.5 17.5 18.5 19.5
Moisture (%
5% MDD
7% MDD
9% MDD
5% UCS
7% UCS
9% UCS
Mix Design for further testing: 7% CKD
13% OMC


Sandy Silt w/ Hyrated Lime
Maximum Dry Density (PCF)
106.6
106.4
106.2
106.0
105.8
105.6
105.4
105.2
105.0
104.8
104.6
104.4
UCS (PSI)
75
73
71
69
67
65
63
61
59
57
55
10.5 11.5 12.5 13.5 14.5 15.5 16.5 17.5 18.5
Moisture
4% MDD
4% UCS
Mix Design for further testing: 4% HL
14.5% OMC

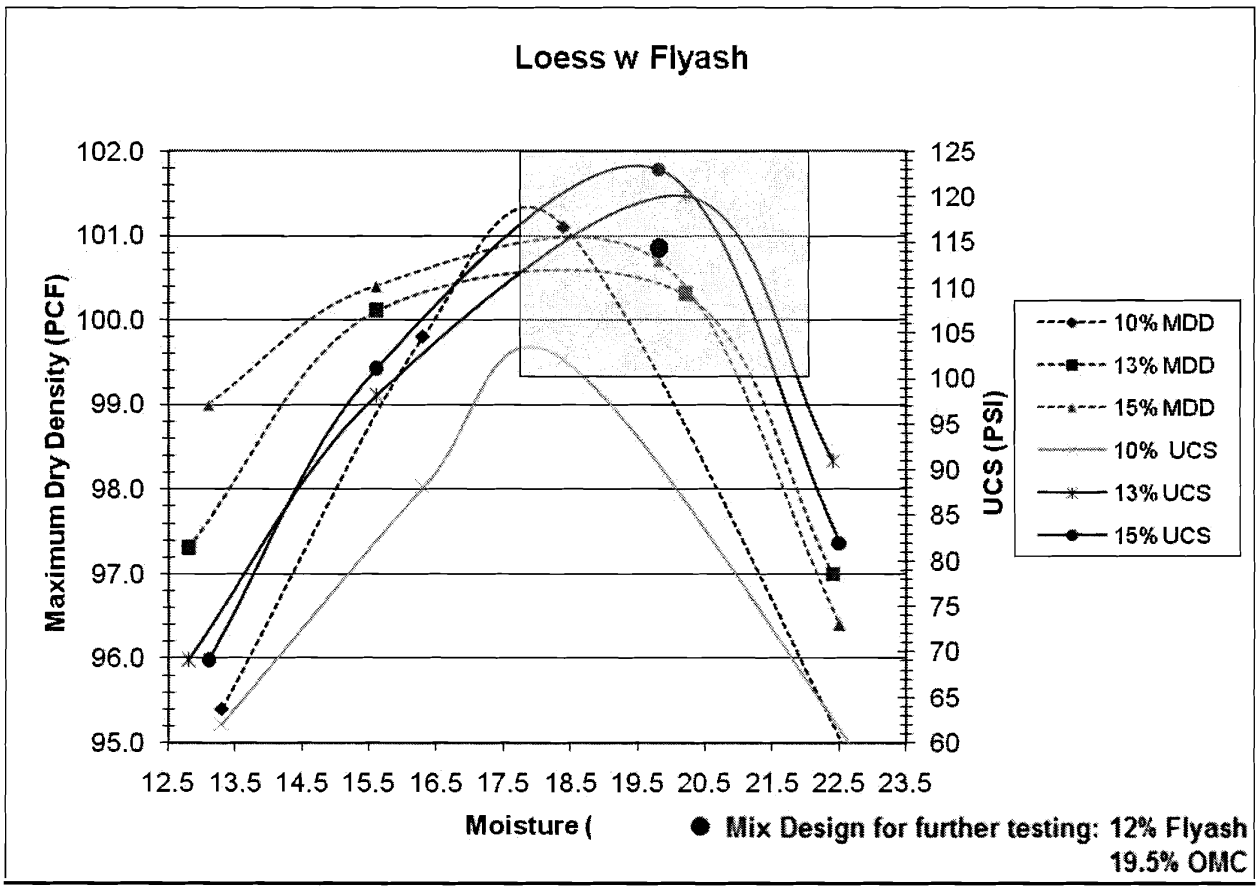
Design Criteria

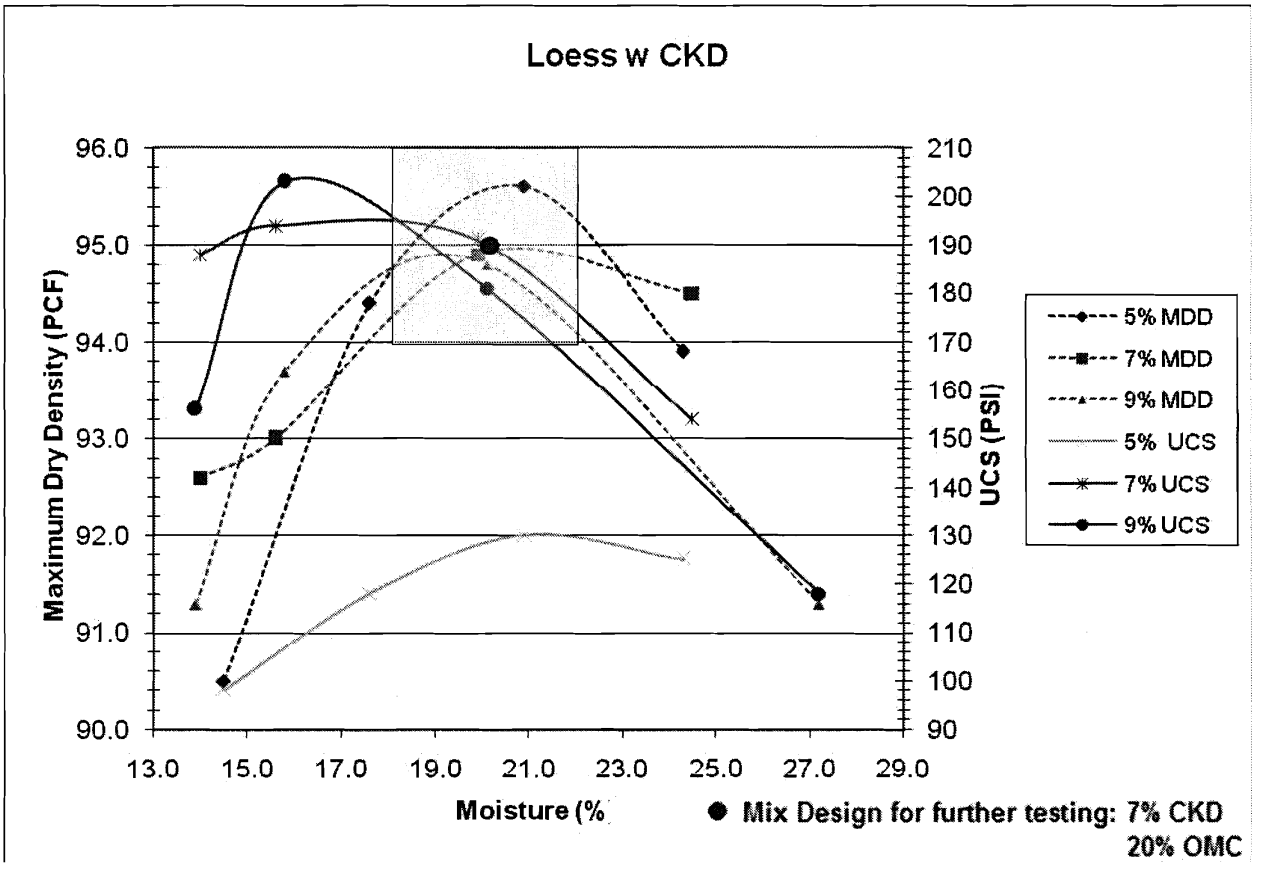
Loess (NGI 8)

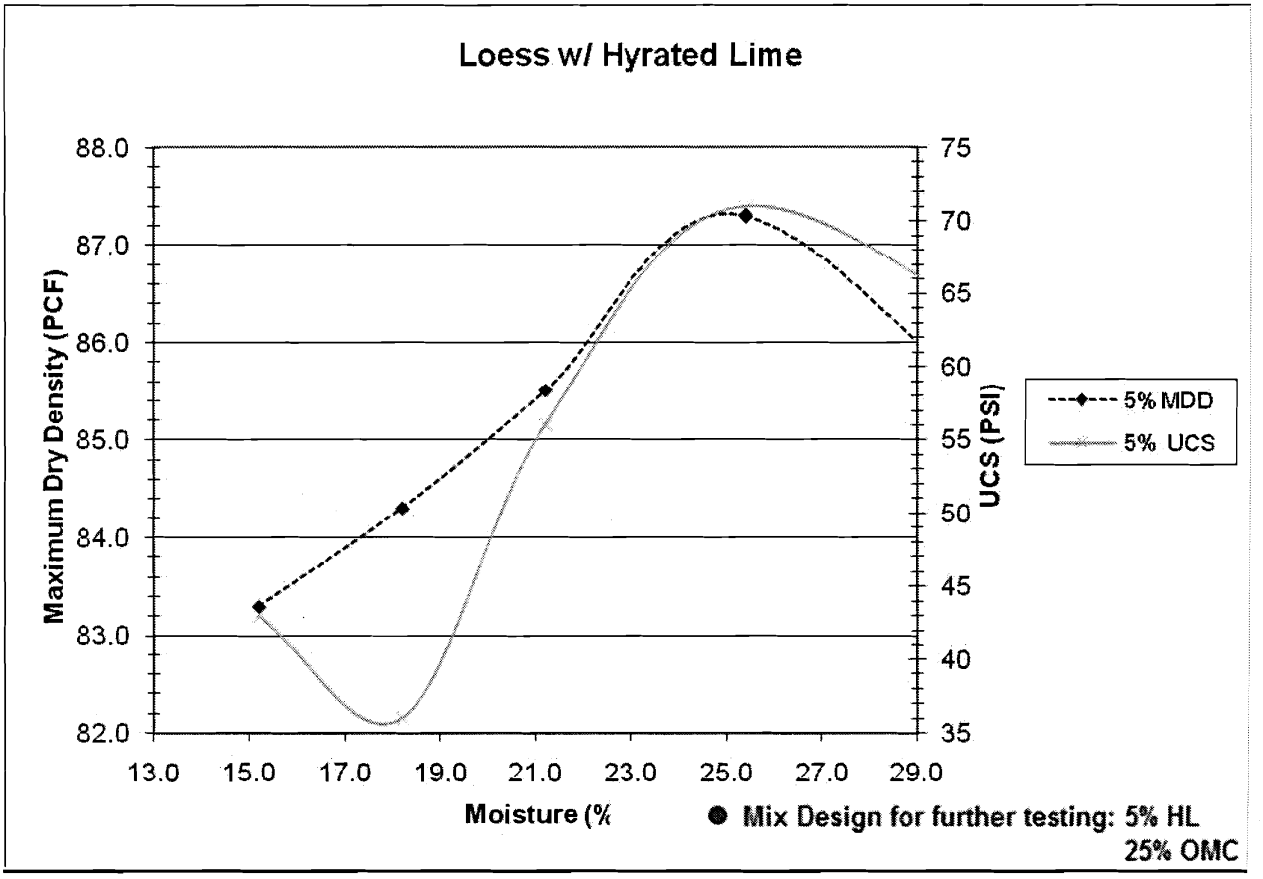
Pozzolans are often used to stabilize cohesive soils. The optimum moisture content and design mix of pozzolan to stabilized loess are outlined below:

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




Loess w CKD
Maximum Dry Density (PCF)
96.0
95.0
94.0
93.0
92.0
91.0
90.0
UCS (PSI)
210
200
190
180
170
160
150
140
130
120
110
100
90
13.0
15.0
17.0
19.0
21.0
23.0
25.0
27.0
29.0
Moisture (%
5% MDD
7% MDD
9% MDD
5% UCS
7% UCS
9% UCS
Mix Design for further testing: 7% CKD
20% OMC

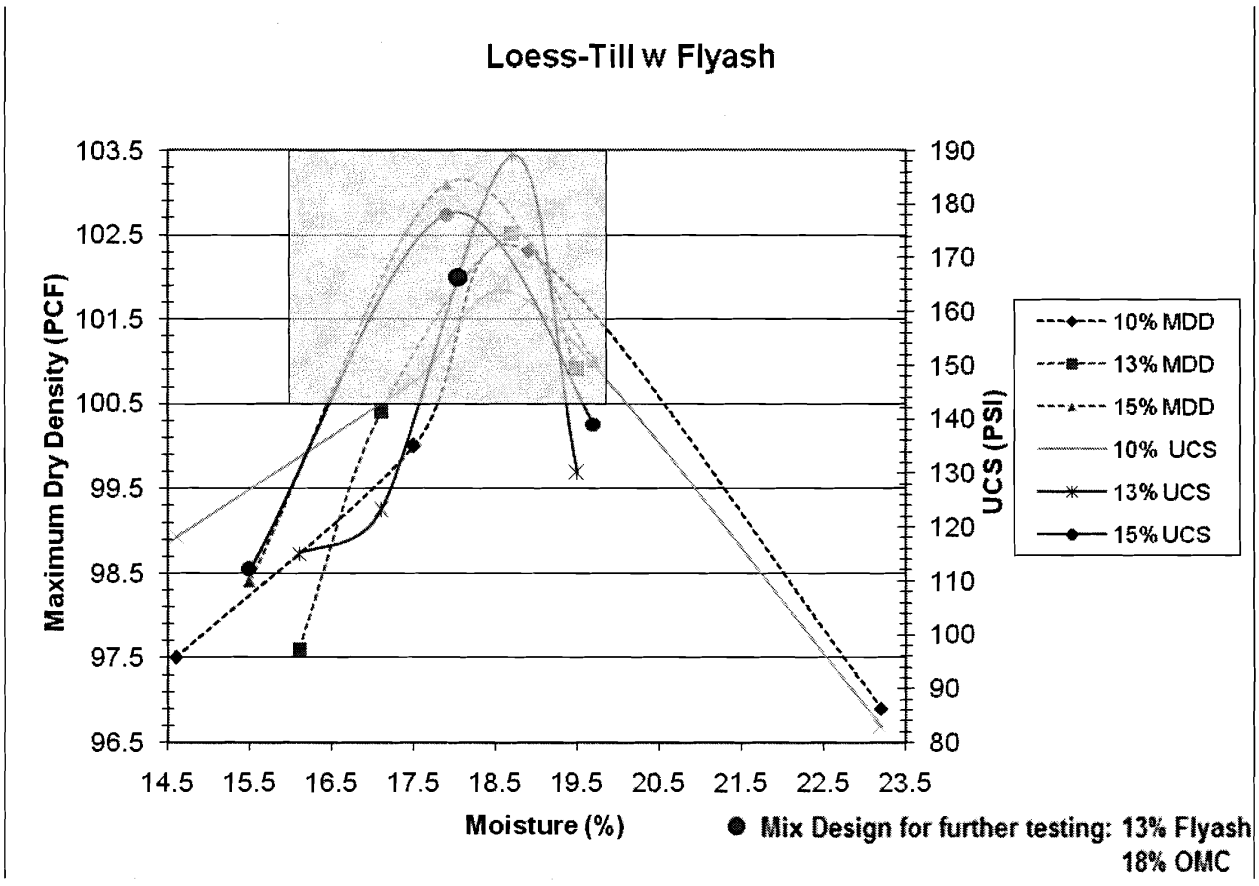

Loess w/ Hyrated Lime
Maximum Dry Density (PCF)
88.0
87.0
86.0
85.0
84.0
83.0
82.0
UCS (PSI)
75
70
65
60
55
50
45
40
35
13.0
15.0
17.0
19.0
21.0
23.0
25.0
27.0
29.0
Moisture (%
5% MDD
5% UCS
Mix Design for further testing: 5% HL
25% OMC

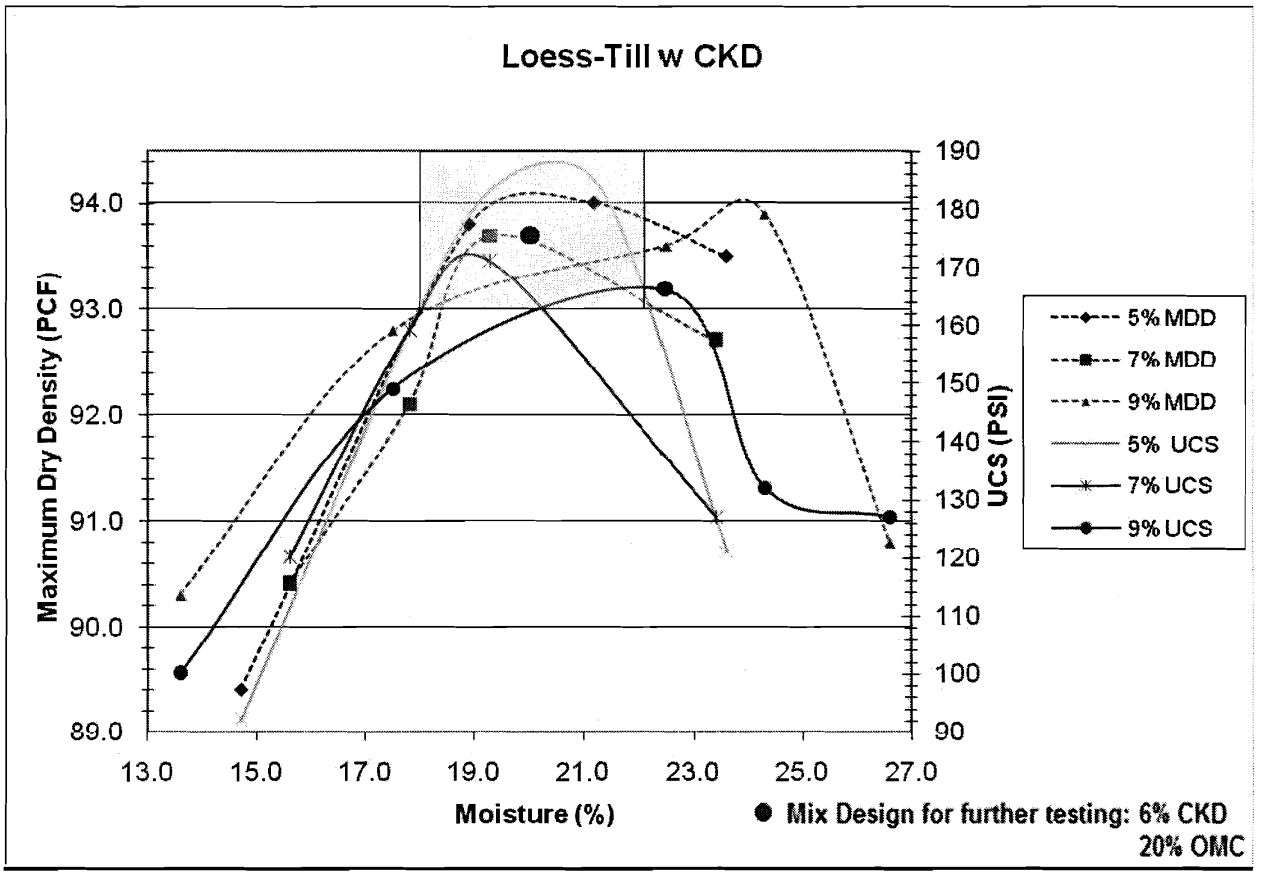
Loess/Till (NGI 13)

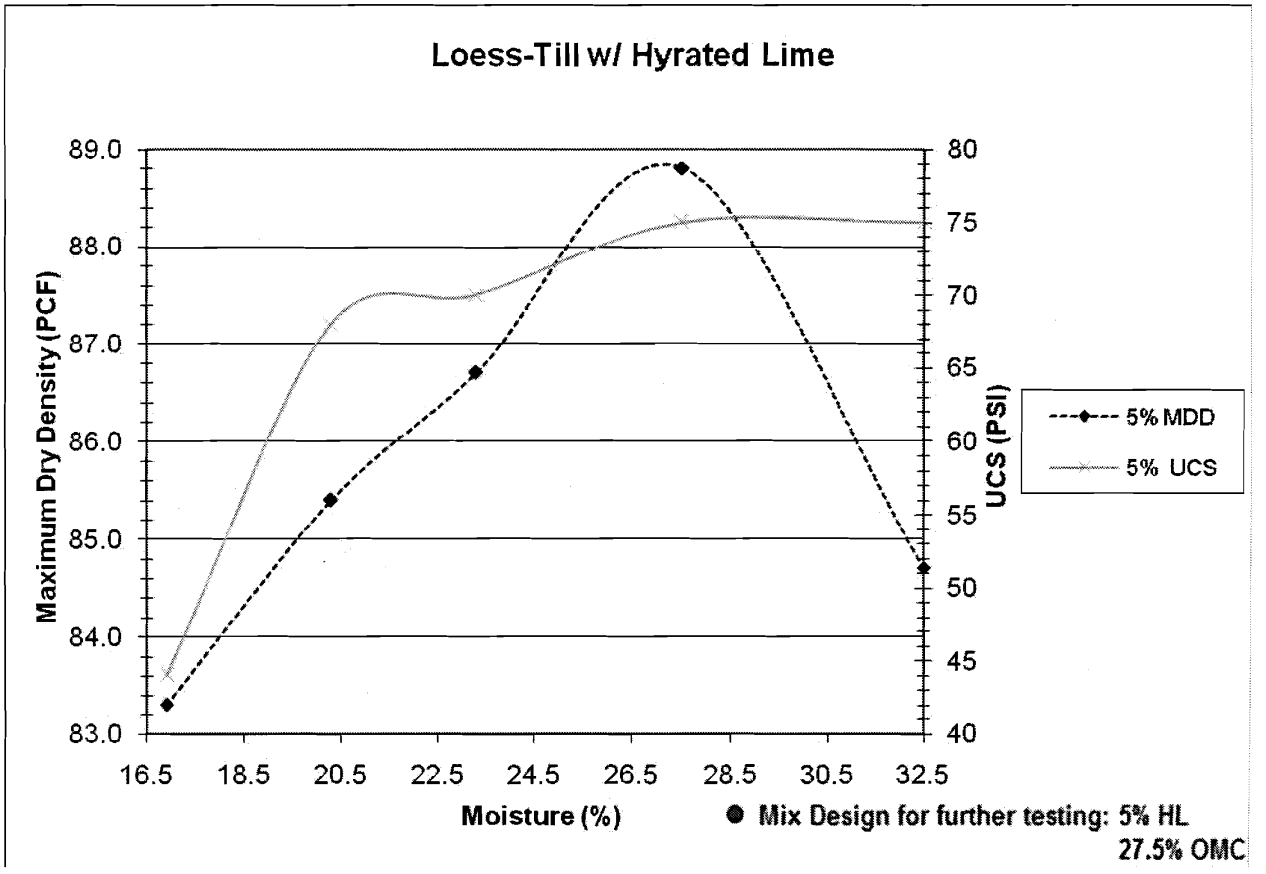
Pozzolans are often used to stabilize cohesive soils. The optimum moisture content and design mix of pozzolan to stabilize loess/till are outlined below:

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




Loess-Till w CKD
Maximum Dry Density (PCF)
94.0
93.0
92.0
91.0
90.0
89.0
UCS (PSI)
190
180
170
160
150
140
130
120
110
100
90
13.0
15.0
17.0
19.0
21.0
23.0
25.0
27.0
Moisture (%)
5% MDD
7% MDD
9% MDD
5% UCS
7% UCS
9% UCS
Mix Design for further testing: 6% CKD
20% OMC

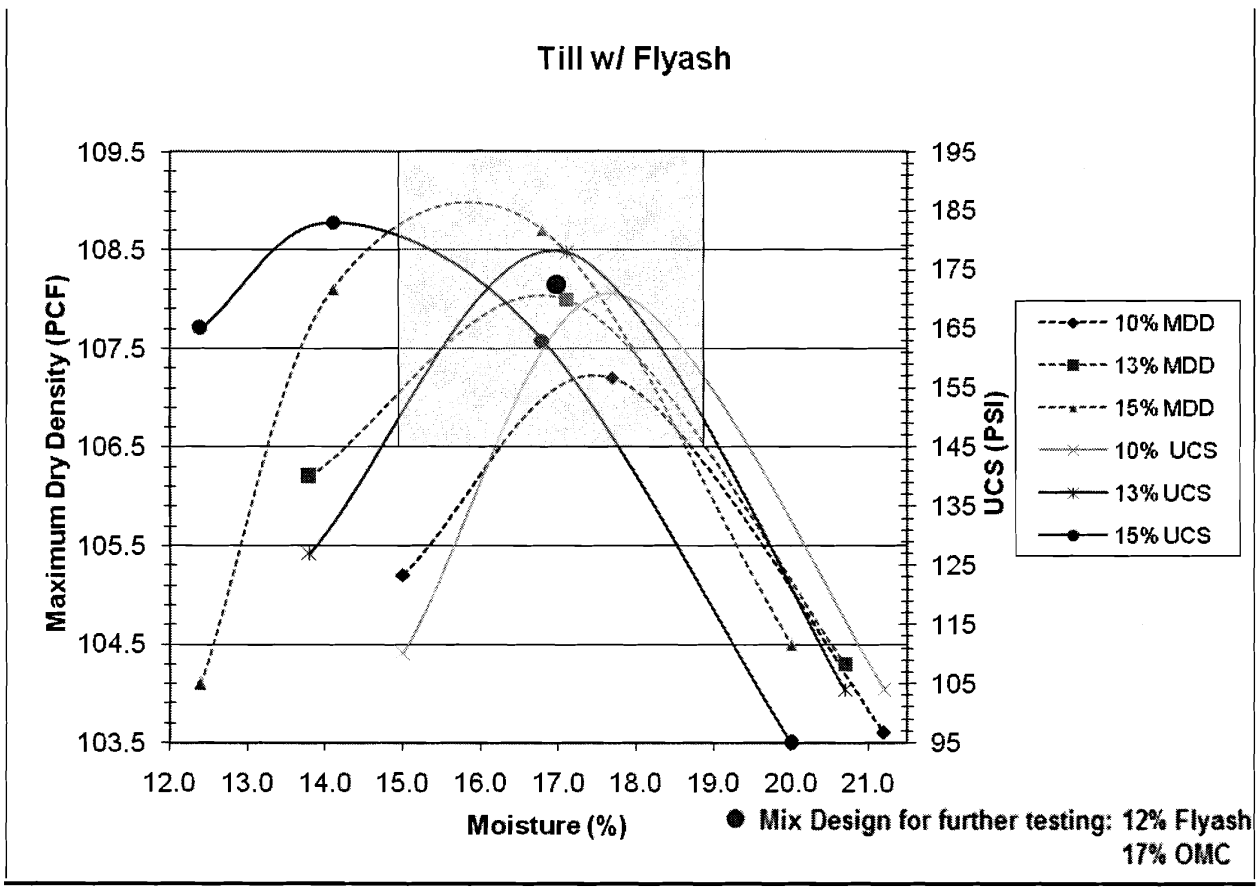

Loess-Till w/ Hyrated Lime
Maximum Dry Density (PCF)
89.0
88.0
87.0
86.0
85.0
84.0
83.0
UCS (PSI)
80
75
70
65
60
55
50
45
40
16.5
18.5
20.5
22.5
24.5
26.5
28.5
30.5
32.5
Moisture (%)
5% MDD
5% UCS
Mix Design for further testing: 5% HL
27.5% OMC

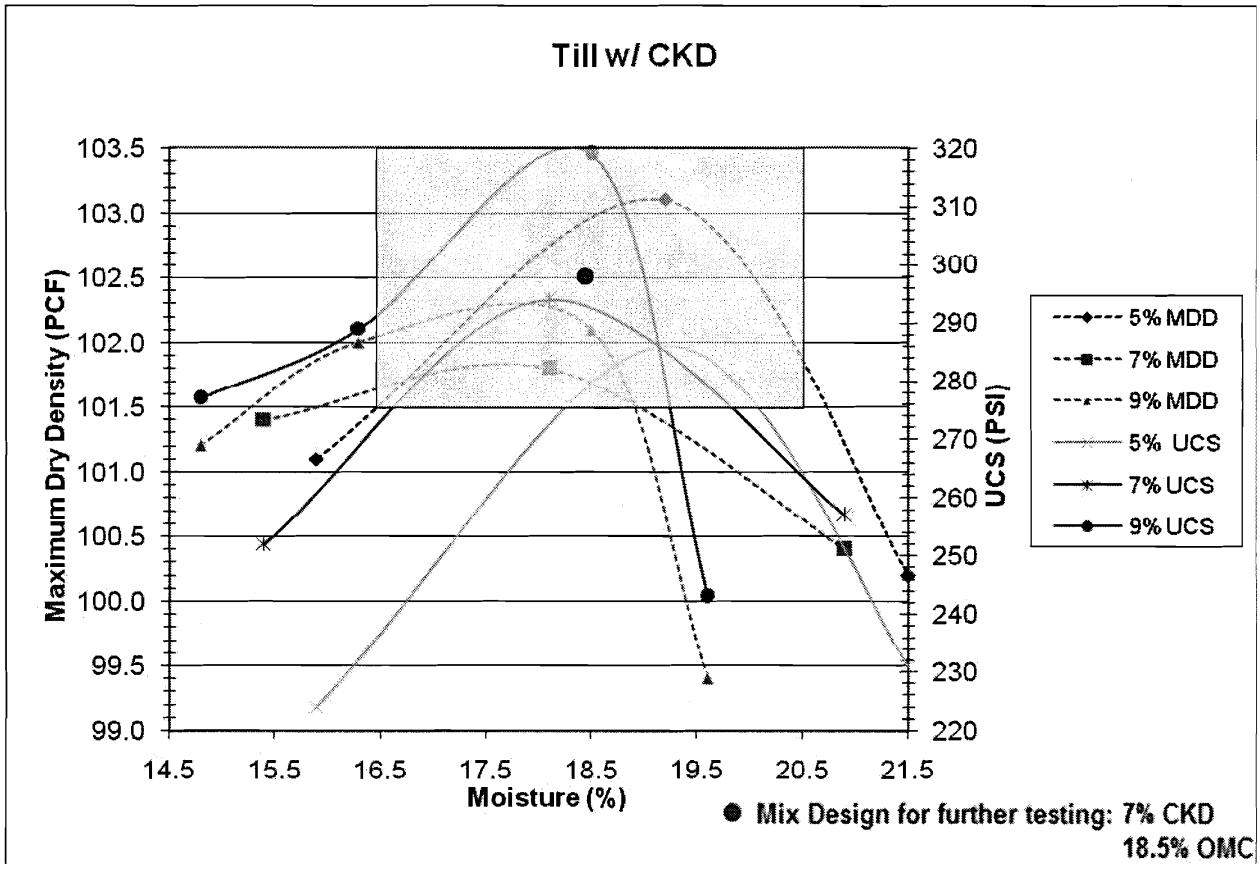
Till (NGI 15)

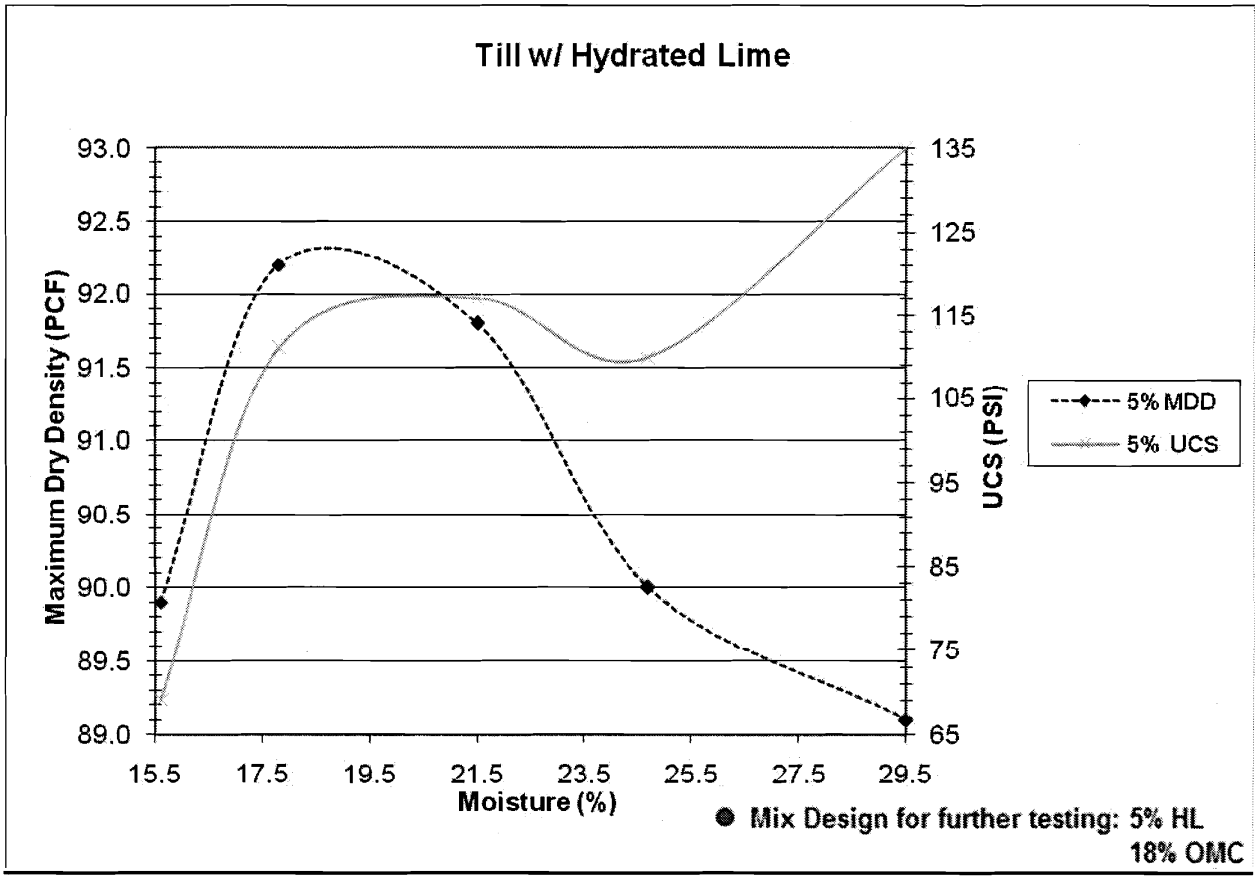
Pozzolans are often used to stabilize cohesive soils. The optimum moisture contents and the design mix of pozzolan till are outlined below:

Moisture Content and Pozzolan Percentages for Till

Till						
Pozzolan	Optimum Native Moisture	Design				
		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




Till w/ CKD
Maximum Dry Density (PCF)
103.5
103.0
102.5
102.0
101.5
101.0
100.5
100.0
99.5
99.0
UCS (PSI)
320
310
300
290
280
270
260
250
240
230
220
14.5
15.5
16.5
17.5
18.5
19.5
20.5
21.5
Moisture (%)
5% MDD
7% MDD
9% MDD
5% UCS
7% UCS
9% UCS
Mix Design for further testing: 7% CKD
18.5% OMC

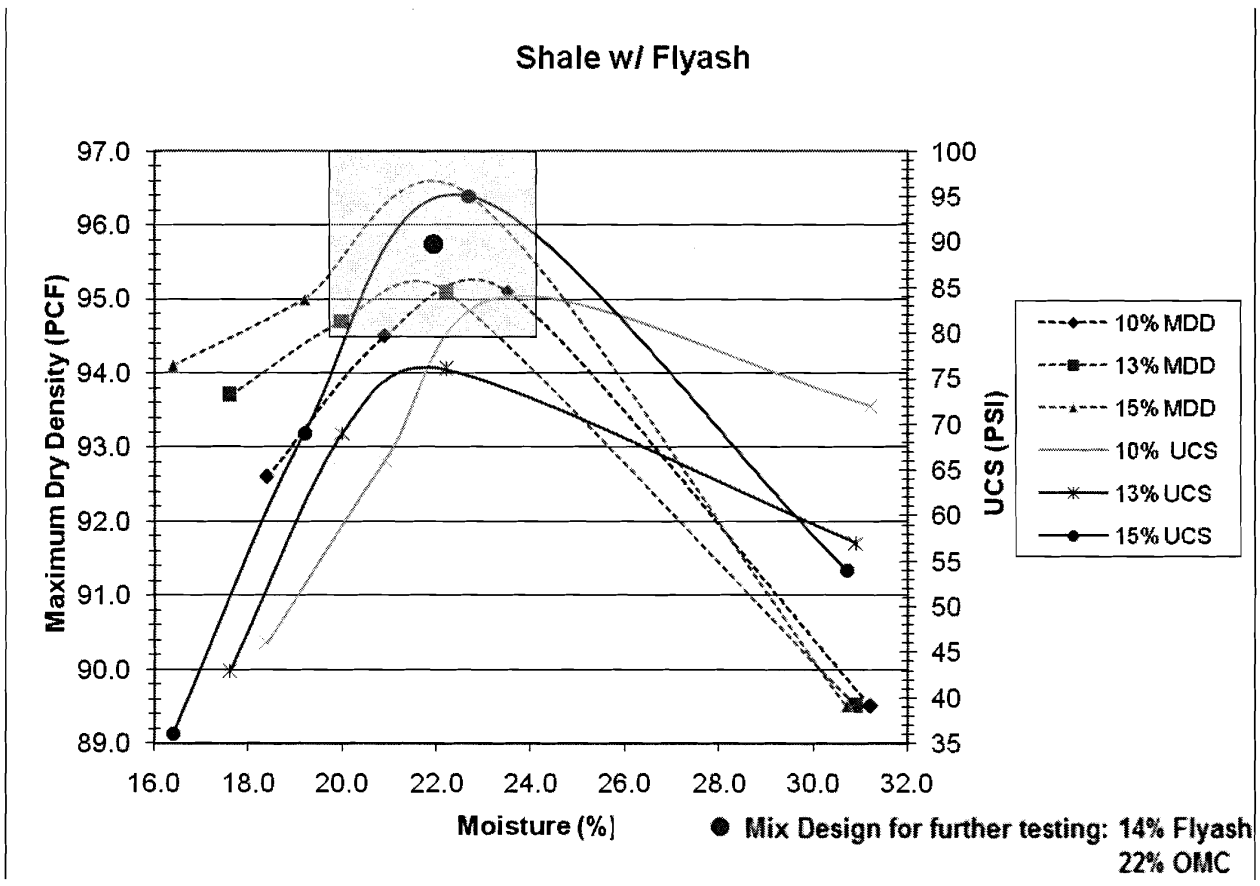

Till w/ Hydrated Lime
Maximum Dry Density (PCF)
93.0
92.5
92.0
91.5
91.0
90.5
90.0
89.5
89.0
UCS (PSI)
135
125
115
105
95
85
75
65
15.5
17.5
19.5
21.5
23.5
25.5
27.5
29.5
Moisture (%)
5% MDD
5% UCS
Mix Design for further testing: 5% HL
18% OMC

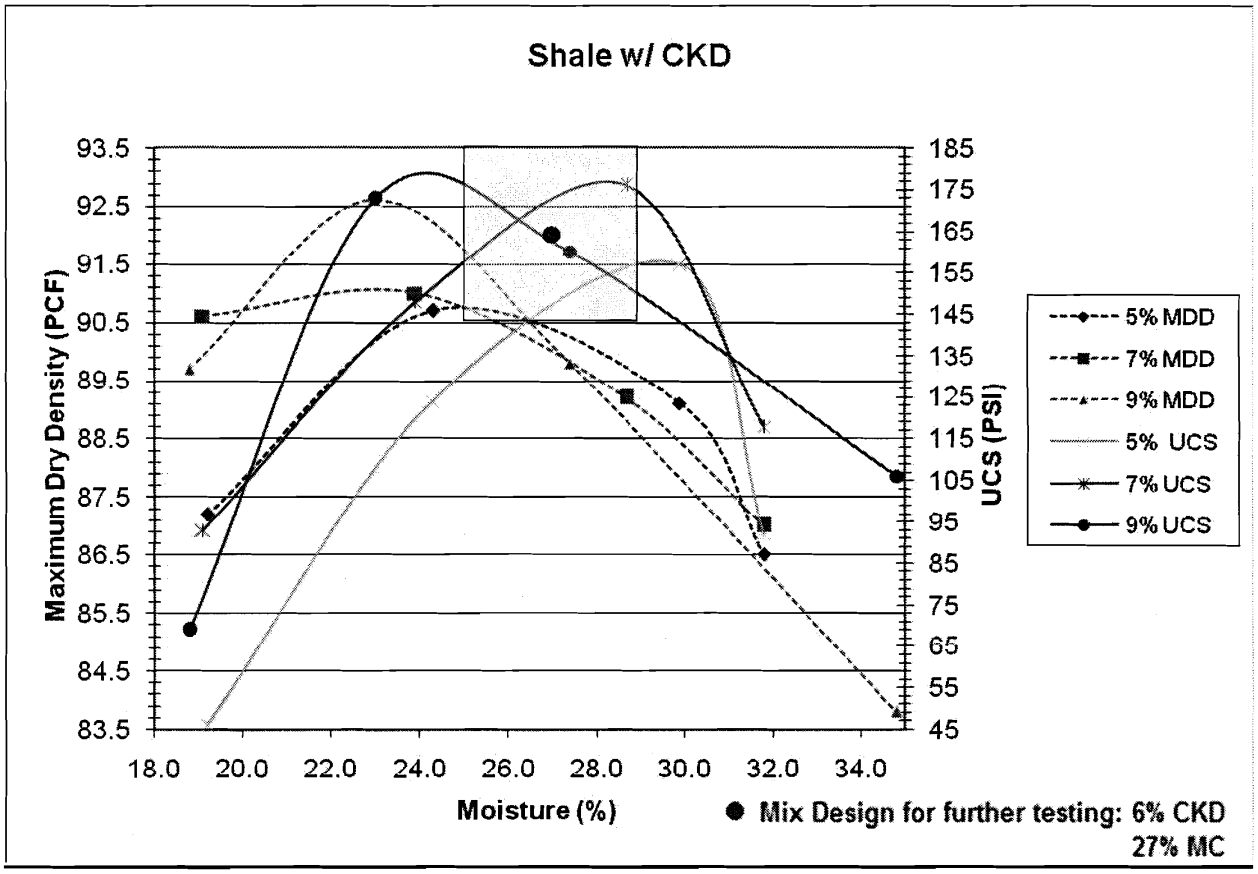
Shale (NGI 26)

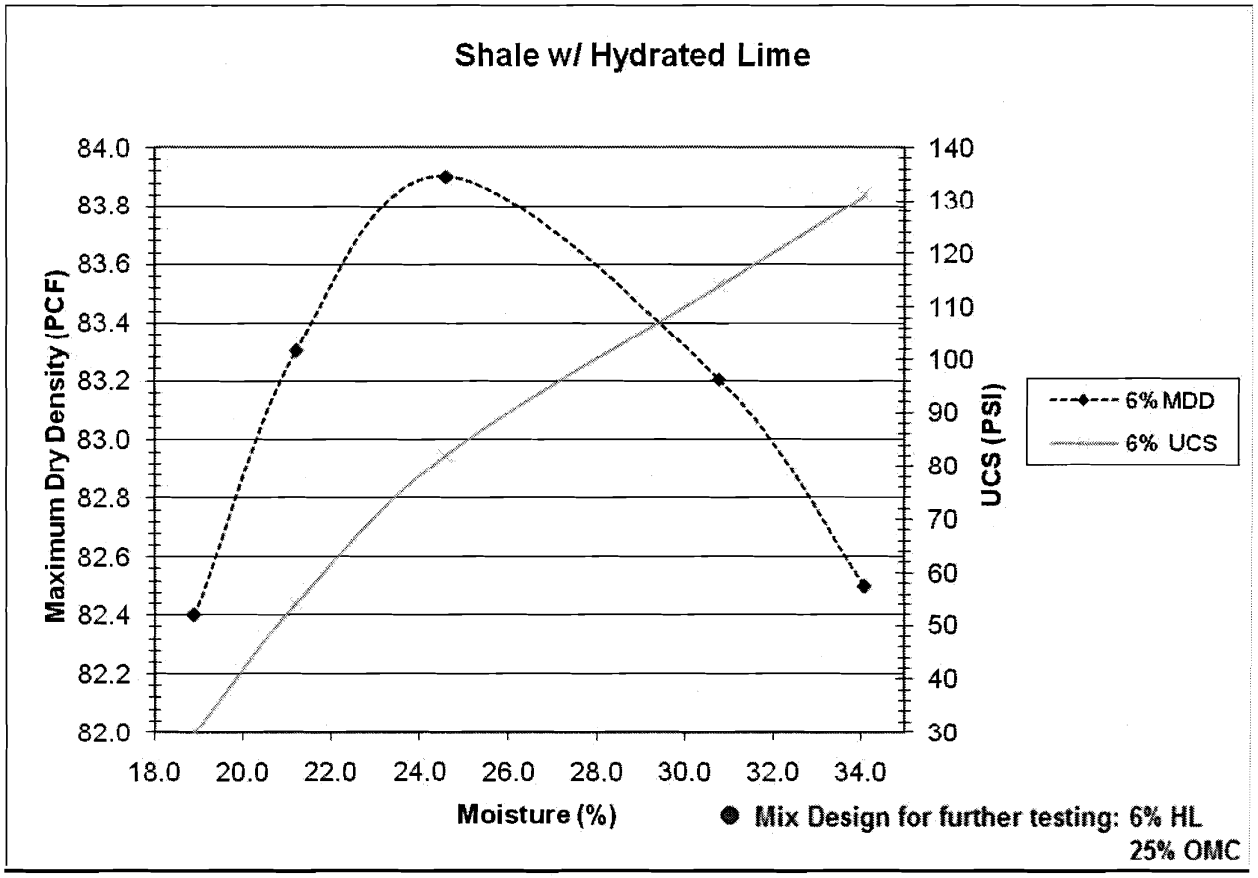
Pozzolans are often used to stabilize cohesive soils. The optimum moisture content and the design mix of pozzolan to stabilize shale are outlined below:

Moisture Content and Pozzolan Percentages for Shale

Shale						
Pozzolan	Optimum Native Moisture	Design				
		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




Shale w/ CKD
Maximum Dry Density (PCF)
93.5
92.5
91.5
90.5
89.5
88.5
87.5
86.5
85.5
84.5
83.5
UCS (PSI)
185
175
165
155
145
135
125
115
105
95
85
75
65
55
45
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
Moisture (%)
5% MDD
7% MDD
9% MDD
5% UCS
7% UCS
9% UCS
Mix Design for further testing: 6% CKD
27% MC


Shale w/ Hydrated Lime
Maximum Dry Density (PCF)
84.0
83.8
83.6
83.4
83.2
83.0
82.8
82.6
82.4
82.2
82.0
UCS (PSI)
140
130
120
110
100
90
80
70
60
50
40
30
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
Moisture (%)
6% MDD
6% UCS
Mix Design for further testing: 6% HL
25% OMC

NOTES: