EVALUATION OF LIME PRETREATMENT

FOR CEMENTITIOUS STABILIZATION

OF HIGH PLASTICITY SOIL

By

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CHAPTER I

INTRODUCTION

Subgrade soils need to have quality engineering properties in order to support pavement structures efficiently. When a subgrade soil does not have these properties, the soil does not provide adequate support for the pavement and shortens the pavements' life. Chemical additives can be used to improve a soil's engineering properties if a soil is not capable of supporting a pavement. Chemical additives modify or stabilize a soil by improving the texture, increasing the strength and reducing the swell characteristics of various soils. Chemical additives that can be used to improve a soil include: lime, Portland cement, cement kiln dust (CKD), and fly ash. These additives can be used in a variety of ways, percentages, and combinations and have diverse effects on different kinds of soils. A combination chemical additive generally describes the use of lime to pre-treat (modify) a soil before another chemical additive, like CKD or fly ash, is used to treat (stabilize) the soil. This is typically the treatment method for soils with medium to high plasticity, since the stabilizing chemical cannot be adequately mixed until the plasticity of the soil is reduced by the lime. Lime reduces the plasticity of the soil by reducing the surface chemistry force and by causing clay particles to flocculate and agglomerate. The stabilizing chemical causes cementitious pozzolanic reactions between the chemical and soil to increase the strength of the soil. This report describes the ability of CKD, fly ash, and combinations of lime and CKD, and lime and fly ash to improve the engineering properties of a moderately high plasticity soil.

Research Project Description

This research covers the effects of CKD, fly ash, lime and CKD, and lime and fly ash on a given soil. Three percentages of CKD and fly ash along with a selected percentage of lime with varying percentages of CKD and fly ash were evaluated. The evaluation of each treatment included laboratory testing to determine the plasticity, shrink-swell potential, and strength characteristics of the soil and chemical combinations. The untreated soil was evaluated to create a base line for comparison of properties. The results of the laboratory testing for each treatment (type and percentage) were compared against the untreated soil and that of other chemical additives.

Purpose of Thesis

The purpose of this thesis is to present the results of an evaluation of lime pretreatment for stabilization of high plasticity soil. A literature review was completed to determine what others know about lime pretreatment and gain a basic understanding of subgrade stabilization. A testing program was developed using standard procedures and non-standard procedures that would produce results that would be comparable against one another. The testing program focused on the plasticity, shrinkage, and strength of the soil and chemical additives mixtures. The Atterberg limits, Bar Linear Shrinkage, and Unconfined Compressive Strength were compared between the soil and chemical additive mixtures as well as between the percentages of chemical additives in the mixtures to determine the best alternatives for stabilization of a high plasticity soil.

CHAPTER II

LITERATURE REVIEW

This chapter contains a discussion of the literature reviewed during the investigation of soil stabilization with lime, cement kiln dust (CKD), and fly ash (Class C). Topics included in this chapter are: chemical modification and stabilization; reasons for stabilization; lime, CKD, and fly ash stabilization; lime pretreated stabilization; and lime pretreatment recommendations.

Background

The use of calcium based stabilizers like lime, cement kiln dust (CKD), and fly ash for improving pavement subgrade soil has been an option for decades. The design of pavement structures depends on the underlying soils having certain structural qualities to resist shear stresses and avoid excessive deformation from imposed loads. Soils do not always have these qualities and require improvement by chemical modification or stabilization to become a sufficient load-supporting material. The heterogeneity of soil properties like composition, soil structure, water interaction, and overall variability require that site specific treatments and mix designs for stabilization be developed. One such treatment alternative is the use of lime as a pretreatment for cementitious materials like CKD or fly ash. This practice is used in situations where the soil needs to be stabilized and is not suitable for treatment by CKD or fly ash alone. The soil is typically not suitable for treatment (CKD/fly ash alone) because of high plasticity.

The difference between chemical modification and stabilization of soils needs to be understood, before discussing pretreatment options. Soil modification is the incorporation of chemical additives into the subgrade to reduce the plasticity of the subgrade and improve its workability as a platform to support construction equipment (1). Soil modification takes place quickly, during and just after mixing, and results in a reduction in the plasticity index, change in texture, and improved workability, as well as, a minimal increase in shear strength. For modification, there are little or no pozzolanic or cementitious reactions, but the reduction in plasticity produces a minimal strength increase. Soil stabilization is the incorporation of chemical additives into a subgrade to increase the strength of the subgrade soils and to provide structural value for the pavement structure (1). The same physiochemical reactions occur as in modification with the additional development of pozzolanic cementing. For a soil to be considered stabilized, a significant increase in strength must occur, (e.g. 50 psi or greater increase in unconfined compressive strength) (2). Stabilization is dependent on rate of hydration, pH of the soil-additive mixture, and ambient temperature.

Reasons for Stabilization

Stabilized soils under pavements have lower deflections, distribute loads better, and resist consolidation of supporting soils. Stabilized soil subgrades provide a more stable platform for pavement structures. An unstabilized soil has lower stiffness and will deflect more, resulting in high pavement surface strains and eventual fatigue cracking of the pavement. Stabilized soils have higher stiffness, thus reducing pavement deflection, which results in smaller surface strains and extended pavement life. Stabilization will also prevent rutting because the subgrade soil will undergo much less consolidation or movement. These concepts are illustrated in Figure 2.1 from the Portland Cement Association (PCA): Guide to Cement-Treated Base, (3).

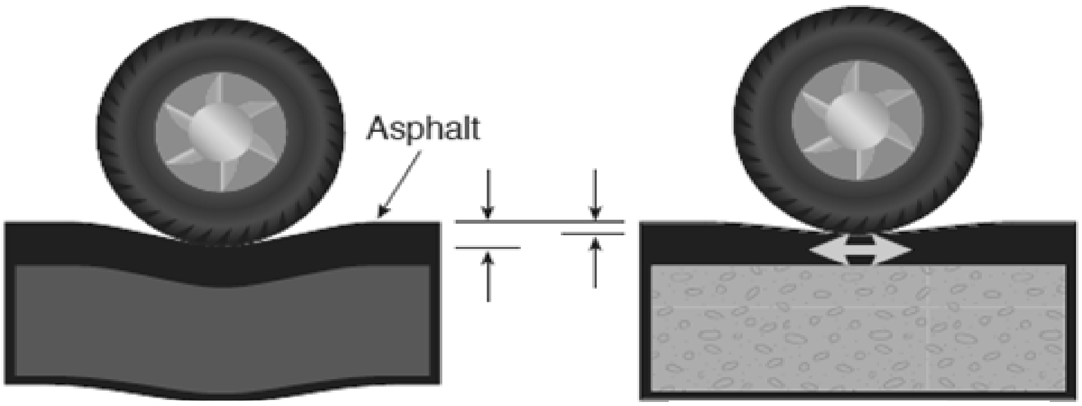
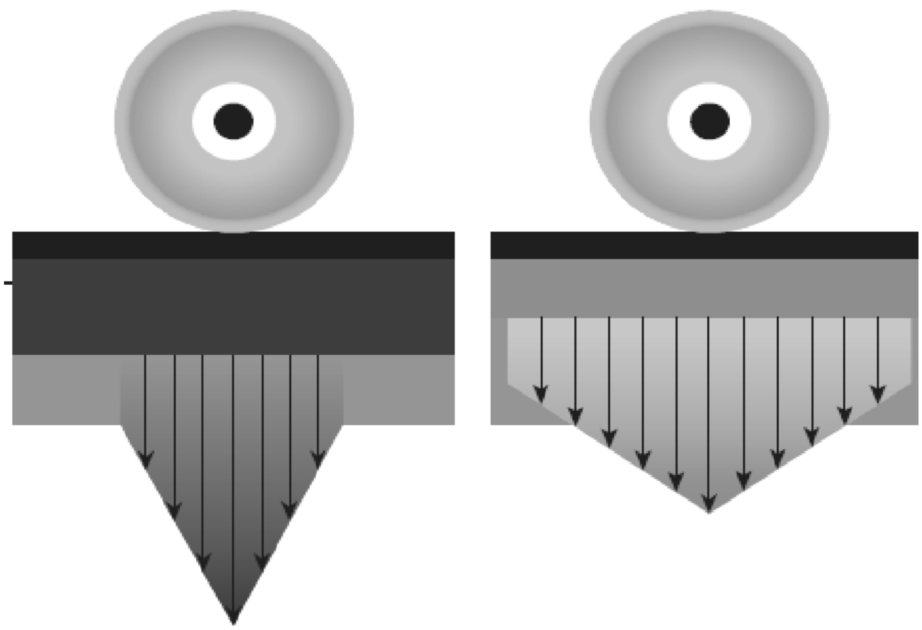


Figure 2.1 Comparison of the amount of deflection between unstabilized and stabilized subgrade soil, (3).

Imposed loads on unstabilized soils result in deep stress distribution. Stabilized soils distribute load more evenly because the stabilized layer is more rigid. This concept is illustrated in Figure 2.2, (3).



d base

Figure 2.2 Comparison of load distribution of unstabilized and stabilized subgrade soil, (3).

Methods of Stabilization

Chemical stabilization of soils is the result of physiochemical reactions between the soil and a chemical additive which means that the soil must be chemically reactive, e.g. fine grained or cohesive soil. Lime, CKD, and fly ash are common soil stabilizers and work by cation exchange, particle flocculation, and development of pozzolanic reaction products to modify and/or stabilize soil (2). Because fine-grained soils exhibit a net negative charge, they attract positively charged ions available in the soil-additive-water mixture. Calcium will substitute for monovalent cations (i.e. hydrogen and sodium) on the soil particle surface (4). This exchange results in lowering the soil particles surface chemistry force and flocculation of fine particles. Pozzolanic reaction products develop when sufficient additive is available to dissolve silica and alumina from the soil particles. The pozzolanic reaction products produce short-term and long-term shear strength increases as they "cement" the soil particles together.

Lime Stabilization

Lime, the product of the calcination of limestone, consists of calcium and magnesium oxides (5). Lime reacts with fine-grained soil in a two-step process, first cation exchange and flocculation/agglomeration result in a change in texture and plasticity. The flocculated soil particles are larger and more friable (2). Pozzolanic reactions are time dependent so little strength is gained during the initial phase, strength gains occur as the soil particles are cemented together. The pozzolanic reactions are dependent on the mineralogy of the soil. The reaction continues to occur as long as the pH is high enough to dissolve silicates and aluminates from the soil. The soluble calcium, silicates, and aluminates react together with water to form calcium-silicate-hydrate and calcium-aluminate-hydrate (6); these compounds promote strength gain. Pozzolanic reaction products typically require mellowing to begin development. This is typically twenty to twenty-four hours to ensure sufficient hydration prior to compaction (7).

CKD Stabilization

CKD is the fines or dust collected from the exhaust of cement kilns and is considered a byproduct of Portland cement production (8). CKD contains between thirty and forty percent CaO and about twenty to twenty-five percent pozzolanic material (silica, alumina, etc.) (2). Cation exchange, flocculation, and pozzolanic reactions are the primary reactions that occur when CKD, soil, and water are mixed. The free calcium hydroxide from the CKD causes clay particles to flocculate, thus reducing the plasticity of the soil. This reduction in plasticity is modification and when enough CKD is added to the soil, strength gain occurs and stabilization will take place (9). CKD contains reactive calcium, silicates, and aluminates that can support cementitious and pozzolanic reactions (2). Little mellowing time, less than two hours, is typically needed since the hydration occurs quickly and strength gain is more rapid. Hydration will continue as long as the pH of the mixture is high, e.g., excess lime is available.

Fly Ash Stabilization

Fly ash is a residue that results from the combustion of ground or powdered coal that is transported from the combustion chamber by exhaust gases of coal-fired power plants (10). The fly ash's properties vary depending on the coal used and the processes used at the power plant. Fly ash is divided into two types, Class C and Class F, dependent on the properties of the fly ash. Class C is considered to be self cementing and contains at least twenty percent Ca. Soil treated with Class C fly ash becomes more friable because the calcium ions in the fly ash cause a reduction in plasticity. This happens because of cation exchange and the crowding of additional ions around the clay particle, which changes the electrostatic charge of the clay particles. The change of electrostatic charge of the clay particles causes them to attract one another resulting in flocculation. (11) The reaction of Class C fly ash is similar to that of Portland cement, in that the hydration produces free Ca. The free Ca reacts with the silica and alumina of the soil and with the pozzolans within the fly ash creating cementitious materials (2). Class F fly ash contains less than ten percent lime and is non-self cementing. Therefore, an additional additive like lime or Portland cement is needed to activate the pozzolans. The hydration and pozzolanic reactions of fly ash require water to form the compounds that bind the soil grains together to gain strength. As with lime and CKD, a high pH is needed for long-term strength gain. The mellowing time of Class C fly ash stabilized soil is similar to that of CKD, less than two hours.

Lime Pretreated Stabilization

Lime is capable of reacting with soils that contain little clay and soils with low plastic indices. If a coarse-grained mixed soil is not sufficiently reactive, lime can be combined with an additional source of silica and alumina, (6) like CKD or fly ash. These compounds when mixed with lime and water will harden into a cementitious mass that is able to achieve high compressive strengths (12). The stabilization of granular or coarse grained materials with lime and CKD/fly ash is possible because the CKD/fly ash provide the material for the lime to react.

Fine-grained soils with high clay content and medium to high plastic indices are considered to be good candidates for lime pretreatment (6). Soil pretreated with lime will have an increase in workability and mixing characteristics as well as a reduction in plasticity. This is due to the lime intruding cation exchange and flocculation reactions (13). These reactions reduce the plasticity and improve the workability of the soil, which allows the secondary additive (CKD or fly ash) to be mixed thoroughly (6). Some pozzolanic reactions occur between the lime and soil so some strength gain is developed before the addition of the secondary treatment. When the secondary additive is mixed with the lime pretreated soil, more cation exchange and flocculation takes place. The calcium, silicates, and aluminates that are present in the secondary additive cause pozzolanic and cementitious reactions. These reactions produce strength gain and will continue to occur as long as the pH of the solution remains high enough to dissolve the silicates and aluminates. The primary mix of soil and lime is typically mellowed for twenty-four hours and the mixture with the secondary additive is mellowed for two additional hours.

Lime Pretreatment Mix Design Recommendations

Chemical Stabilization is achieved and the degree of stabilization is greatly affected by the mineralogy and the fineness of the soil (13), therefore, a complete mix design is needed to determine the exact amounts of lime and CKD/fly ash for a particular soil. The National Lime Association suggests the use of lime pretreatment on plastic clays of an application rate of two to three percent (6). The Army and Air Force (12) recommends using a mixture of lime and fly ash to treat coarse-grained soils and uses a mix design that selects the optimum lime and fly ash percentage based on unconfined compressive strengths. For fine-grained soils the Army and Air Force suggests the use of a lime and cement combination. The mix design is based on selecting a lime content that improves the workability and reduces the plasticity of the soil and the cement content is selected from the soils USCS classification and then optimized by unconfined compressive strength testing. (12) The American Coal Ash Association (ACAA) states that the typical fly ash contents vary from twelve to fourteen percent with corresponding lime contents of three to five percent (14). Oklahoma Highway Department (OHD) L-50 (15) gives the procedures for determining the stabilization practices for soils classified by American Association of State Highway and Transportation Officials (AASHTO) M145, as well as, the procedures for determining the percentage of lime for pretreatment. It recommends pre-treating A-6 soils with four percent hydrated lime and pre-treating A-7 soils with five percent hydrated lime (15). After pretreatment the percentage of CKD/fly ash is recommended based on the pretreated soils AASHTO classification.

Summary

When subgrade soil does not have the qualities to efficiently support a pavement, lime, CKD, fly ash, or combination of lime and CKD/fly ash can be used to improve the engineering properties of the soil. Stabilized soils under pavements have lower deflections, better load distributions, and resist consolidation. Stabilization with chemical additives is effective because of cation exchange, particle flocculation, and pozzolanic reactions that create cementitious compounds that decrease the plasticity and increase the strength of the soil. Soils that are not suitable for stabilization because the soil is not reactive or the soil has high plastic indices can be made suitable using the technique of pre-treating the soil with lime, followed by addition of cementitious chemical additives.

CHAPTER III

MATERIALS AND LABORATORY PROCEDURES

This chapter describes the soil, chemical additives, and testing procedures used to conduct the research. Tests were performed using standard procedures, any adjustments to standard procedures or non-standard procedures are described in detail.

Soil

The soil used in this chemical additive evaluation was classified as a CL and A-6 (19) by the Unified Soil Classification (American Society for Testing and Materials (ASTM) D 2487) and AASHTO Soil Classification (AASHTO M 145) Systems, respectively. The sample was collected from the south approach embankment of the Salt Fork River Bridge, approximately twelve miles north of Perry, Oklahoma on Highway US-77 near the junction with State Highway 15.

Additives

The chemical additives used in the evaluation were lime, cement kiln dust (CKD), and Class C fly ash. The granulated quicklime was from the Texas Lime Company in Cleburne, Texas. The CKD was produced by the rotary kiln at the Holcim US, Inc., Ada Portland Cement Plant, in Ada, Oklahoma. The fly ash was produced at the OG&E Power Plant near Red Rock, Oklahoma. The CaO of the quicklime, according to the National Lime Association is between

95-100% (5). The CKD contained between 30-40% CaO by National Cooperative Highway Research Program's definition (2). The Federal Highway Administration states that the typical CaO content of Class C fly ash 24.3% (10). A tabulation of the soil-additive mixtures used and the laboratory tests performed are shown in Table 3.1 and Table 3.2, respectively.

Table 3.1 Soil Additive Mixtures

Sample	% of Additive	Additive
Untreated	0	0
CKD Treated	10	CKD
	12	CKD
	14	CKD
Fly Ash Treated	12	Fly Ash
	15	Fly Ash
	18	Fly Ash
Pretreated	4, 10	Lime, CKD
	4, 12	Lime, CKD
	4, 14	Lime, CKD
	4, 12	Lime, Fly Ash
	4, 15	Lime, Fly Ash
	4, 18	Lime, Fly Ash

Table 3.2 Laboratory Testing Standards

Test Method	Standard
Soil Sample Preparation	AASHTO T 87
Percent Minus U.S. No. 200	AASHTO T 11
Soil-Lime pH Test	ASTM D 6276
Soil pH	ASTM D 4972 Method A
Liquid Limit	AASHTO T 89 Method A
Plastic Limit and Plastic Index	AASHTO T 90
Bar Linear Shrinkage	Tex-107-E
Moisture-Density Relationship	AASHTO T 99 Method A
Harvard Miniature Correlation	ASTM D 4609 Annex 1
Harvard Miniature Compaction	ASTN D 4609 Annex 2
Unconfined Compressive Strength	ASTM D 2166

Soil Sample Preparation

The soil was air-dried and broken up to pass a No. 4 sieve, removing any rock or organic matter from the soil. A portion was then processed further to pass a No. 40 sieve and dried at 60^{o}C for Atterberg Limits and other classification tests.

Soil and Additive Mixing and Mellowing

The soil sample and various additives were mixed together and allowed to mellow. For samples treated with lime, CKD, and fly ash separately, the additive was mixed uniformly with the dry soil and water was added without mixing. The samples were sealed and placed in a constant temperature container and mellowed. The mellowing time for the soil treated with CKD and fly ash was 2 hours and the mellowing for the soil treated with lime was twenty-four hours. After mellowing, the samples were mixed thoroughly, and then tested. Soil samples prepared with only one additive and mellowed before testing are referred to as treated. For soil sample pre-treated with lime, then treated with CKD or fly ash, the lime was added and mixed with the dry soil then water was added without mixing. The sample were sealed and mellowed for twenty-four hours. After mellowing the sample was mixed, then the second additive was added and mixed thoroughly, additional water was added to achieve the target moisture content without mixing. The soil sample was then mellowed two hours prior to testing. Soil samples that were pretreated with lime and then CKD or fly ash are referred to as pretreated.

pH Testing

The pH of each additive was determined using procedure ASTM D 4972 Method A. This was done periodically to ensure the additives were active. The optimum percentage of each additive for stabilization was estimated using Soil-Lime pH Test, ASTM D 6276.

Atterberg Limits

The Atterberg Limits of the untreated, treated, and pretreated soils were determined in accordance with AASHTO T 89 Method A and AASHTO T 90. The testing was modified slightly with the addition of the mixing and mellowing steps discussed.

Particle Size Analysis

Though a complete sieve analysis was not pertinent to the testing, it was necessary to determine the percent passing the U.S. No. 200 sieve (75 microns). One hundred grams of oven dried soil that passed the No. 4 sieve was soaked, mixed, and washed over a U.S. No. 200 sieve. The soil retained on the U.S. No. 200 sieve was collected, dried, weighed so that the percent passing the U.S. No. 200 sieve could be calculated.

Soil Classification

Using the Atterberg Limits and percent passing the U.S. No. 200 sieve of the untreated soil the classification was determined using AASHTO M145 and ASTM D 2487.

Bar Linear Shrinkage

Bar Linear Shrinkage tests were conducted on all of the soil and additive combinations. The bar linear shrinkage was determined in accordance with test method TEX-107-E.

Moisture-Density Relationships

Using the mixing and mellowing procedures discussed earlier the Moisture-Density Relationships were determined for each soil additive mix, following AASHTO T 99 Method A, to determine the maximum dry density and optimum moisture content for each of the soil additive mixtures.

Harvard Miniature Correlation

In order to prepare Unconfined Compressive Strength (UCS) test specimens, a correlation between the Standard Proctor drop hammer and the Harvard Miniature kneading foot hammer was developed. This was done by preparing the soil additive mixture at its optimum moisture content using the mixing and mellowing procedures for treated and pretreated soils. Then the number of blows required with the kneading foot hammer to achieve the maximum dry density was determined. This was done in accordance with ASTM 4609, Annex 1.

Unconfined Compressive Strength

To produce the UCS samples, the correlation for each soil additive combination was used to compact six specimens at optimum moisture content using Harvard Miniature Compaction ASTM D 4609, Annex 2, without immersed specimens. Specimens of treatments that were not completely tested (no Atterberg limits, BLS, etc, were run) were produced using the properties of the closest percentage of like additive, with the addition of two percent water to the optimum moisture content. Three specimens were cured for seven days and three specimens were cured for twenty-eight days. The specimens were cured in a constant temperature container and then tested to determine the unconfined compressive strength following ASTM D 2166.

CHAPTER IV

PRESENTATION AND DISCUSSION OF RESULTS

The results of the testing program are described in this chapter. The results include that of untreated, treated, and pretreated soil samples.

Untreated, Treated, and Pretreated Soil Properties and Additive Percentages

The untreated soil characteristics determined were Percent minus U.S. No. 200, Atterberg Limits (LL, PL, PI), Bar Linear Shrinkage (BLS), Moisture –Density Relationship (Maximum Dry Density and Optimum Moisture Content), and Unconfined Compressive Strength (UCS). A Summary of the test results is shown in Table 4.1, Untreated Soil Properties.

Table 4.1 Untreated Soil Properties

Percent Minus U.S. No. 200, %	91.0
Liquid Limit, %	37.9
Plastic Limit, %	16.6
Plastic Index, %	21.3
USCS	CL
AASHTO	A-6 (19)
Bar Linear Shrinkage, %	14.0
Maximum Dry Density, pcf	105.0
UCS, 7 Day Cure, psi	58.8
UCS, 28 Day Cure, psi	61.0

Based on the untreated soil's AASHTO classification of A-6 (19), it was determined using OHD L-50 Soil Stabilization Table (15) that the soil should be pretreated with four percent lime and then treated with ten percent CKD or twelve percent fly ash. This was done by finding the optimum lime content according to ASTM D 6276, Soil-Lime pH Test, which was eight percent, then performing Atterberg limits and determining AASHTO classification of the soil and lime mixture. The percent lime was reduced and tests repeated until the treated soil's classification returned to the untreated classification. The percent of lime just prior to the return was used as the pretreatment level. This process is shown in Table 4.2 Lime Treated Soil Atterberg Limits and AASHTO Classification.

Table 4.2 Lime Treated Soil Atterberg Limits and AASHTO Classification

Lime, %	Liquid Limit, %	Plastic Limit, %	Plastic Index, %	Classification
2	41.1	32.4	8.7	A-5 (11)
4	36.9	30.6	6.3	A-4 (8)
6	39.3	29.3	10.0	A-4 (11)
8	35.9	30.2	5.7	A-4 (7)

The results indicated two percent lime, which was adjusted for common practices for this type of soil in this region to four percent. The six percent lime results were considered to be an anomaly and not considered, since the liquid limit and plastic limit were so high. Using the pretreated soil classification of A-4, OHD L-50 Soil Stabilization Table (15) was used to determine the percentage of CKD or fly ash. For an A-4 soil, the table recommends ten percent CKD or twelve percent fly ash. Table 4.3, Pretreated Soil Properties, shows the testing results for the pretreated soils with the recommended CKD and fly ash percentages.

Table 4.3 Pretreated Soil Properties

Properties with Pretreatment	4% Lime + 10% CKD	4% Lime + 12% Fly Ash
Liquid Limit, %	37.5	36.0
Plastic Limit, %	30.8	28.3
Plastic Index, %	6.7	7.7
Bar Linear Shrinkage, %	2.69	2.09
Maximum Dry Density, pcf	99.9	102.4
Optimum Moisture Content, %	22.4	20.3
UCS, 7 Day Cure, psi	205.7	139.9
UCS, 28 Day Cure, psi	306.0	210.5

The percentages selected for the mix design evaluations were ten, twelve, and fourteen for CKD and twelve, fifteen, and eighteen for fly ash. The lowest percentages were selected from maximum recommended values given in OHD L-50, and increases were based on common steps used for the additive mix design procedures. The properties of the soil samples treated with these percentages of additives are presented in Table 4.4 Treated Soil Properties.

Table 4.4 Treated Soil Properties

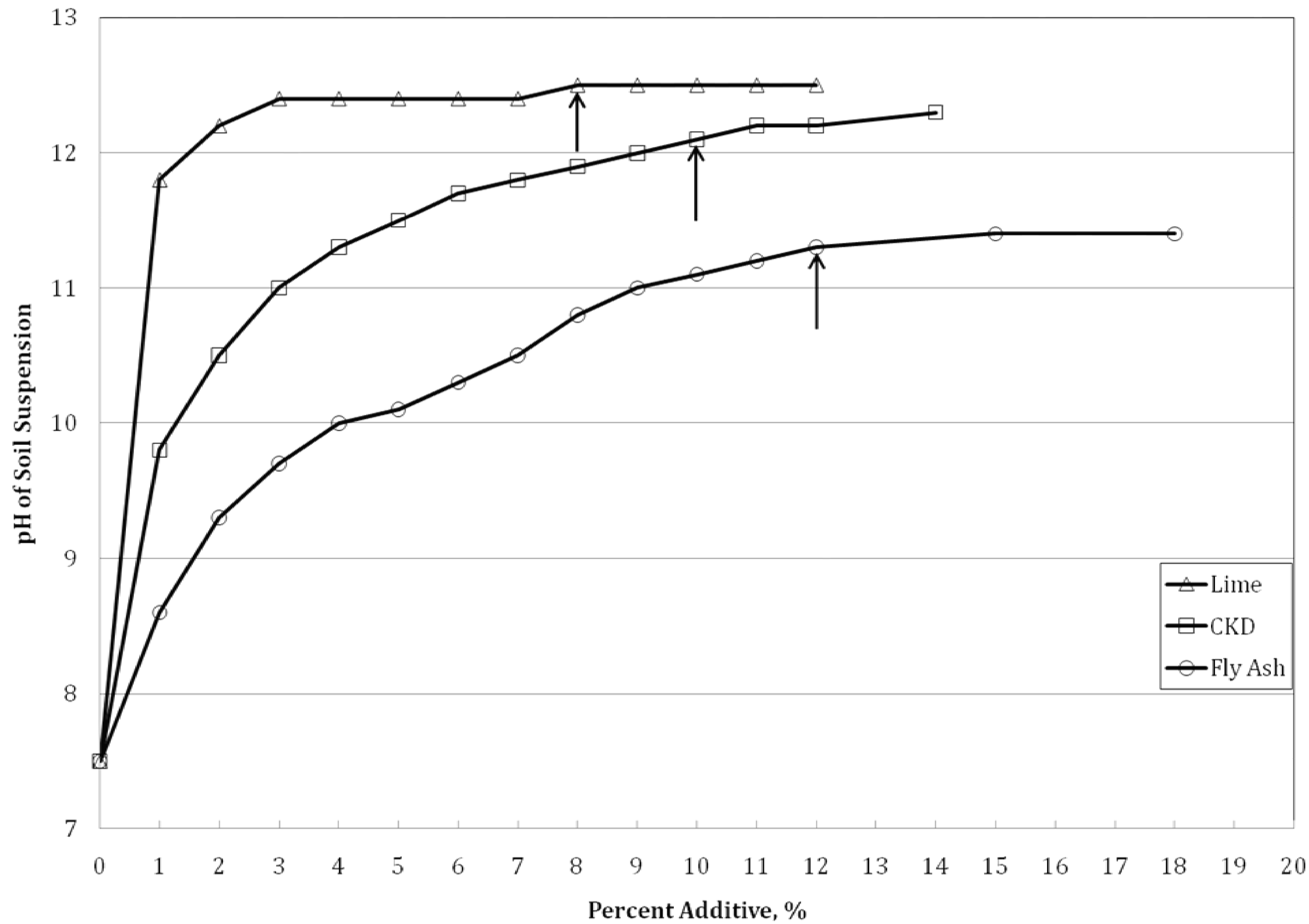
Properties with Treatment	10% CKD	12% CKD	14% CKD	12% Fly Ash	15% Fly Ash	18% Fly Ash
Liquid Limit, %	42.2	43.3	40.0	41.3	38.9	39.5
Plastic Limit, %	26.5	28.3	28.4	21.3	23.9	24.5
Plastic Index, %	15.7	15.0	11.6	20.0	15.0	15.0
Bar Linear Shrinkage, %	5.13	6.53	6.72	8.70	7.71	6.40
Maximum Dry Density, pcf	105.7	105.1	105.0	110.3	110.0	110.5
Optimum Moisture Content, %	16.9	17.8	19.8	17.0	17.1	15.5
UCS, 7 Day Cure, psi	126.2	161.0	184.7	69.7	86.4	106.3
UCS, 28 Day Cure, psi	148.7	202.9	206.1	85.0	106.8	148.8

Additional percentages for pretreatment were selected, but only the seven and twenty-eight day unconfined compressive strengths were determined. The percentages were: 4% lime + 12% CKD; 4% lime + 14% CKD; 4% lime + 15% fly Ash; and 4% lime + 18% fly ash.

pH Tests

The pH of the soil increased as the amount of additive was increased. The pH of the soil with no additive was 7.5 and increased with the addition of all of the additives. The pH values of the additives alone were: lime, 12.5; CKD, 12.7; and fly ash, 11.8. The lowest percentage of additive required to develop constant pH conditions or the modification optimum (MO) for the lime was eight percent. The MO for CKD and fly ash were ten percent and twelve percent respectively. The percentage of CaO in CKD and fly ash is less than that of lime, so higher amounts of the additives are needed to achieve modification optimum. The soil pH test curves are shown in Figure 4.1, pH of Soil Suspension Verses Percent Additive, and in Appendix A.

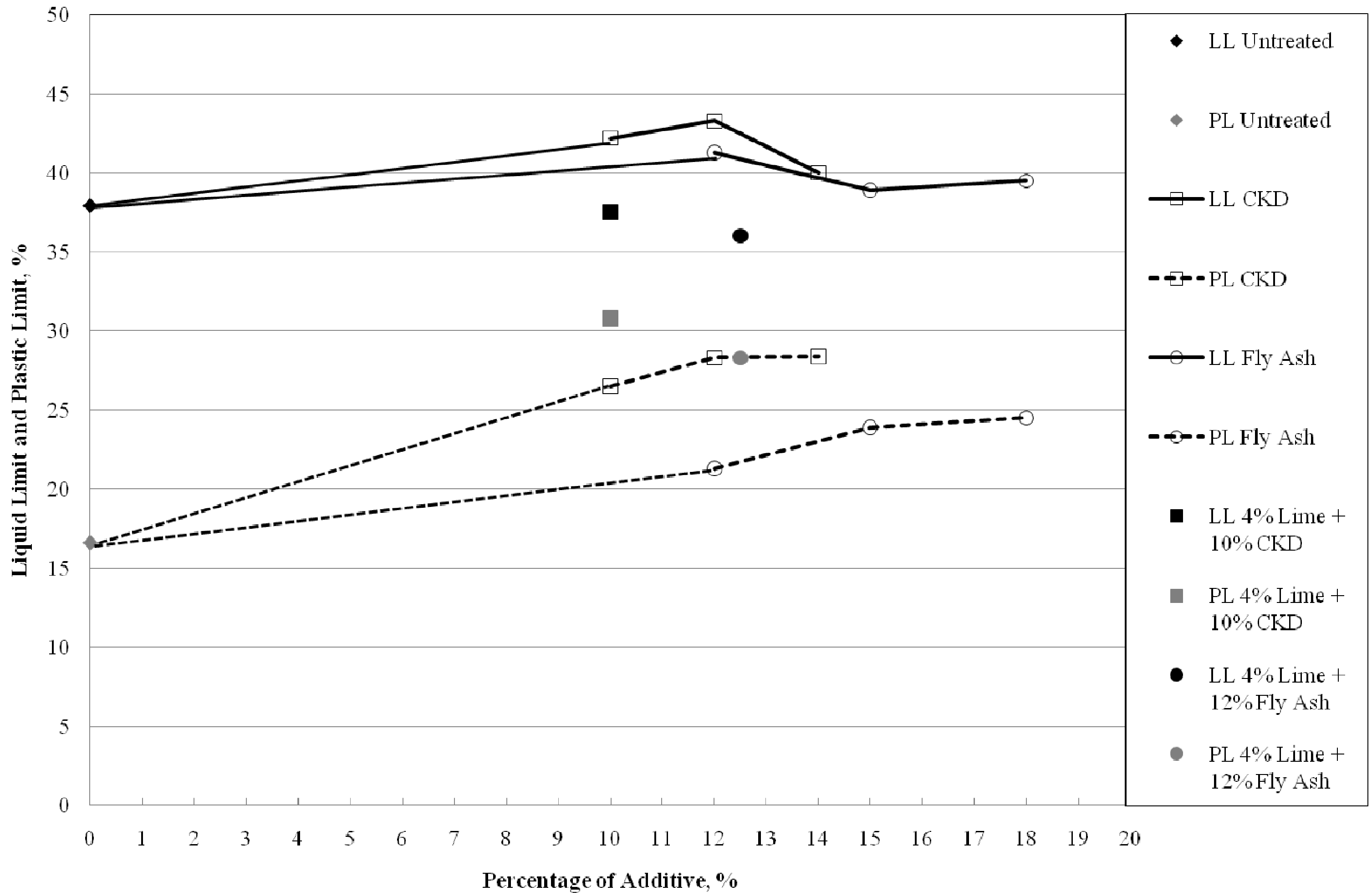
FIgure 4.1 Percent Additive Verses pH of Soil Suspension



Atterberg Limits

The addition of different additives at different percentages changed the Atterberg limits of the soil. The liquid limit for all of the treated soils increased compared to the untreated, while only the four percent lime and ten percent CKD pretreated soil increased compared to the untreated soil. Though the majority of the treatments and pretreatments generally increased the liquid limit there was no consistent relationship among the specific treatment types. The plastic limit increased across all treatment and pretreatment types. The pretreated soil experienced an almost two fold increase in the plastic limit compared to the untreated soil. The increase in the plastic limit resulted in a reduction in the plastic index for all of the treated and pretreated with the exception of the twelve percent fly ash treated soil. The plastic indexes of the pretreated soils were nearly one/third of the untreated soils plastic index. Comparing the plastic index of the additives against like additives it decreased as the percent additive increased. Figure 4.2, Liquid Limit and Plastic Limit Verses Percent Additive, shows the liquid and plastic limits of the untreated, treated, and pretreated soils, the difference between the liquid limit and plastic limit points being the plastic index.

Figure 4.2 Liqud Limit and Plastic Limit Versus Percent Additive



The Atterberg limit test results for the untreated, treated, and pretreated can be seen in Table 4.5 Atterberg Limits, with the complete Atterberg limit test data in Appendix B.

Table 4.5 Atterberg Limits

Treatment	Liquid Limit, %	Plastic Limit, %	Plastic Index, %
Untreated	37.9	16.6	21.3
Treated with:			
10% CKD	42.2	26.5	15.7
12% CKD	43.3	28.3	15.0
14% CKD	40.0	28.4	11.6
12% Fly Ash	41.3	21.3	20.0
15% Fly Ash	38.9	23.9	15.0
18% Fly Ash	39.5	24.5	15.0
Pretreated with:			
4% Lime + 10% CKD	37.5	30.8	6.7
4% Lime + 12% Fly Ash	36.0	28.3	7.7

Soil Classification

The untreated soil classified as a CL according to the Unified Soil Classification System. According to AASHTO Soil Classification the soil was an A-6 (19). These classifications were used to determine the appropriate additive percentages as discussed earlier. The classification of the soil samples treated with CKD were: 10% CKD, A-7-6 (16); 12% CKD, A-7-6 (19); and 14% CKD, A-6 (12). The classification of the soil samples treated with fly ash were: 12% fly ash, A-7-6 (19); 15% fly ash, A-6 (15); and 18% fly ash, A-6 (15). The lime pretreated soil samples were both classified as A-4 (8).

Bar Linear Shrinkage

With addition of an additive, the Bar Linear Shrinkage (BLS) generally decreased. The treated and pretreated soils experienced a significant decrease in BLS, when compared to the untreated soil. The BLS of the CKD and fly ash treated soil were consistent with the increase in additives, with the BLS of the CKD and fly ash treated soils around six percent. The pretreated samples saw a reduction in the BLS with no real difference between the CKD or fly ash treated soil, which was expected since the soils were pretreated with lime. The BLS percentages for the untreated, treated, and pretreated soils are presented in Table 4.6 Bar Linear Shrinkage.

Table 4.6 Bar Linear Shrinkage

Treatment	BLS, %
Untreated	14.0
Treated with:	
10% CKD	5.13
12% CKD	6.53
14% CKD	6.72
12% Fly Ash	6.70
15% Fly Ash	7.71
18% Fly Ash	6.40
Pretreated with:	
4% Lime + 10% CKD	2.69
4% Lime + 12% Fly Ash	2.09

Maximum Dry Density and Optimum Moisture Content

Slight changes occurred in the maximum dry density and moderate changes occurred in the optimum moisture content when the soil was treated and pretreated. The soil treated with CKD experienced little or no change in the maximum dry density, less than one pcf, with an increase in the optimum moisture when compared to the untreated soil. The optimum moisture content increase as the percentage of CKD increased. For the fly ash treated soils compared to the untreated soil an increase of five pcf was developed and a minimal increase of the optimum water content was noted. There was no difference in the maximum dry density over the range of fly ash percents but the optimum moisture content decreased as the percentage of fly ash increased. The maximum dry densities and optimum water contents of the treated soils are shown in Table 4.7 Maximum Dry Density and Optimum Moisture Content. The pretreated soil's maximum dry densities and optimum moisture contents are also present in Table 4.7 Maximum Dry Density and Optimum Moisture Content. A reduction in the maximum dry density and an increase in optimum moisture content were noted in the pretreated soils when compared to the untreated soils. A plot of the compaction produced for each treatment type is shown in Figure

4.3.A Compaction Curve for Untreated Soil, Figure 4.3.B Compaction Curves for CKD Treated Soils, and Figure 4.3.C Compaction Curves for Fly Ash Treated Soils.

Table 4.7 Maximum Dry Density and Optimum Moisture Content

Treatment	Maximum Dry Density, pcf	Optimum Moisture Content, %
Untreated	105.0	14.5
Treated with:		
10% CKD	105.7	16.9
12% CKD	105.1	17.8
14% CKD	105.0	19.8
12% Fly Ash	110.3	17.0
15% Fly Ash	110.0	17.1
18% Fly Ash	110.5	15.5
Pretreated with:		
4% Lime + 10% CKD	99.9	22.4
4% Lime + 12% Fly Ash	102.4	20.3

Figure 4.3.A Compaction Curve for Untreated Soil

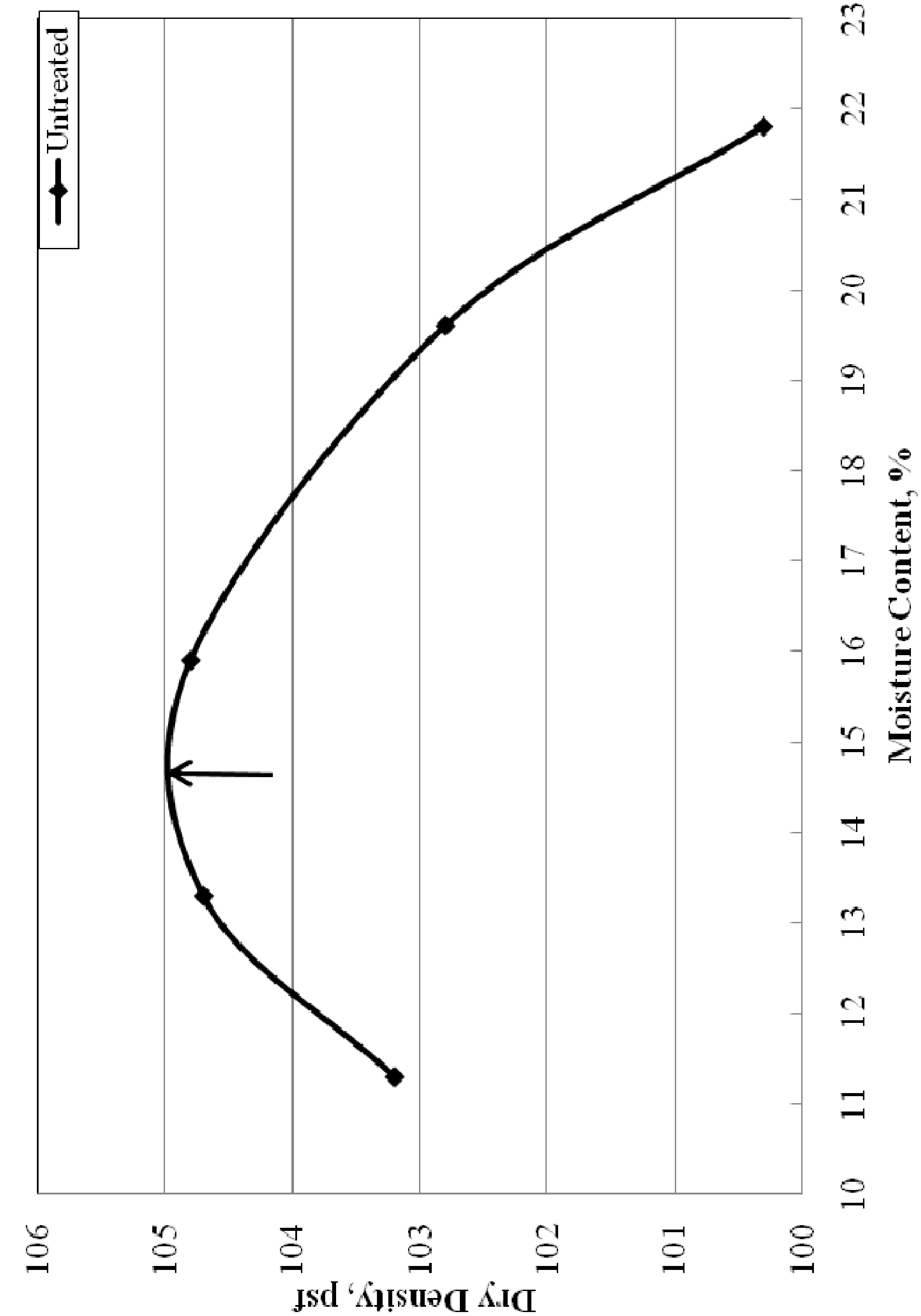


Figure 4.3.B Compaction Curves for CKD Treated Soils

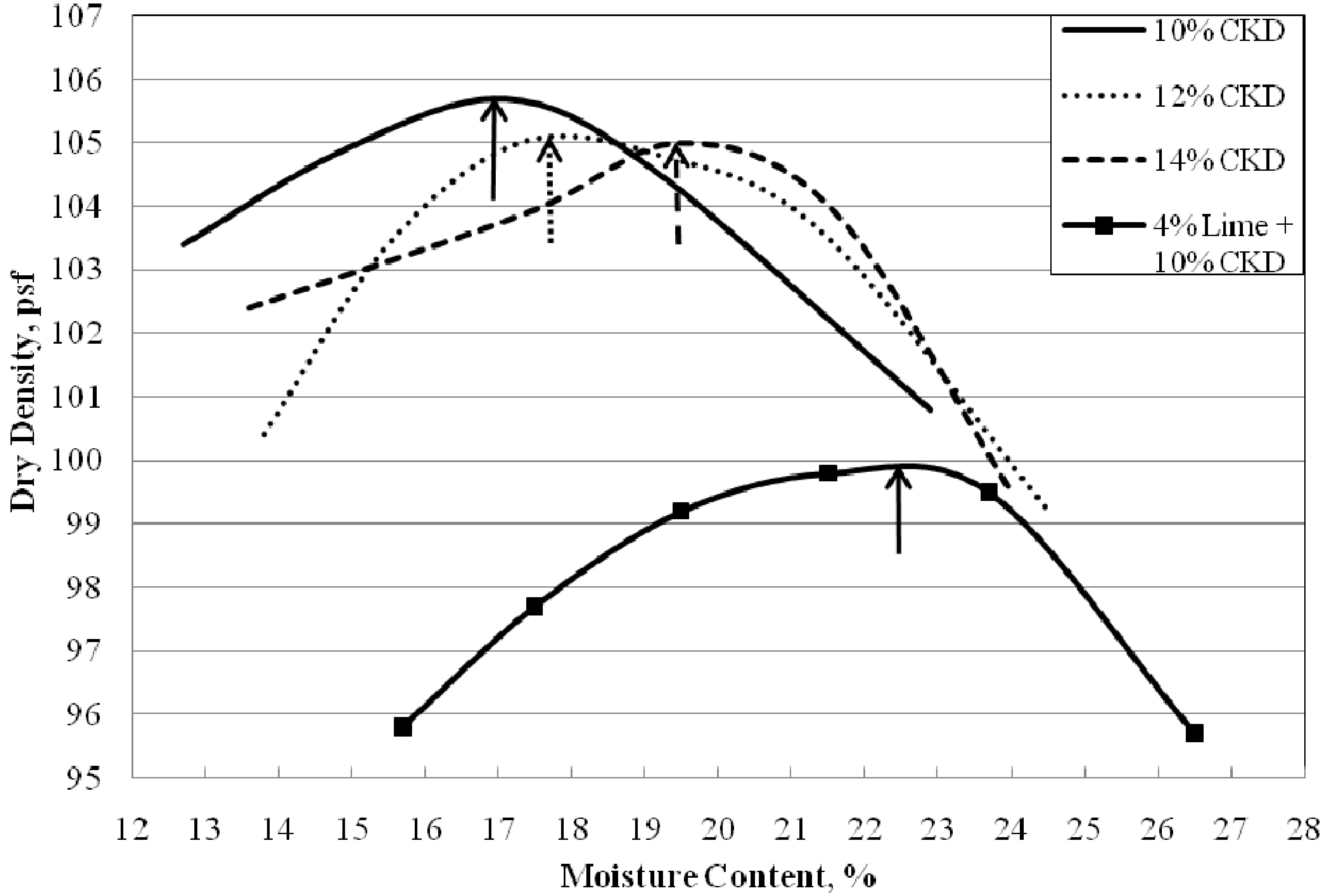
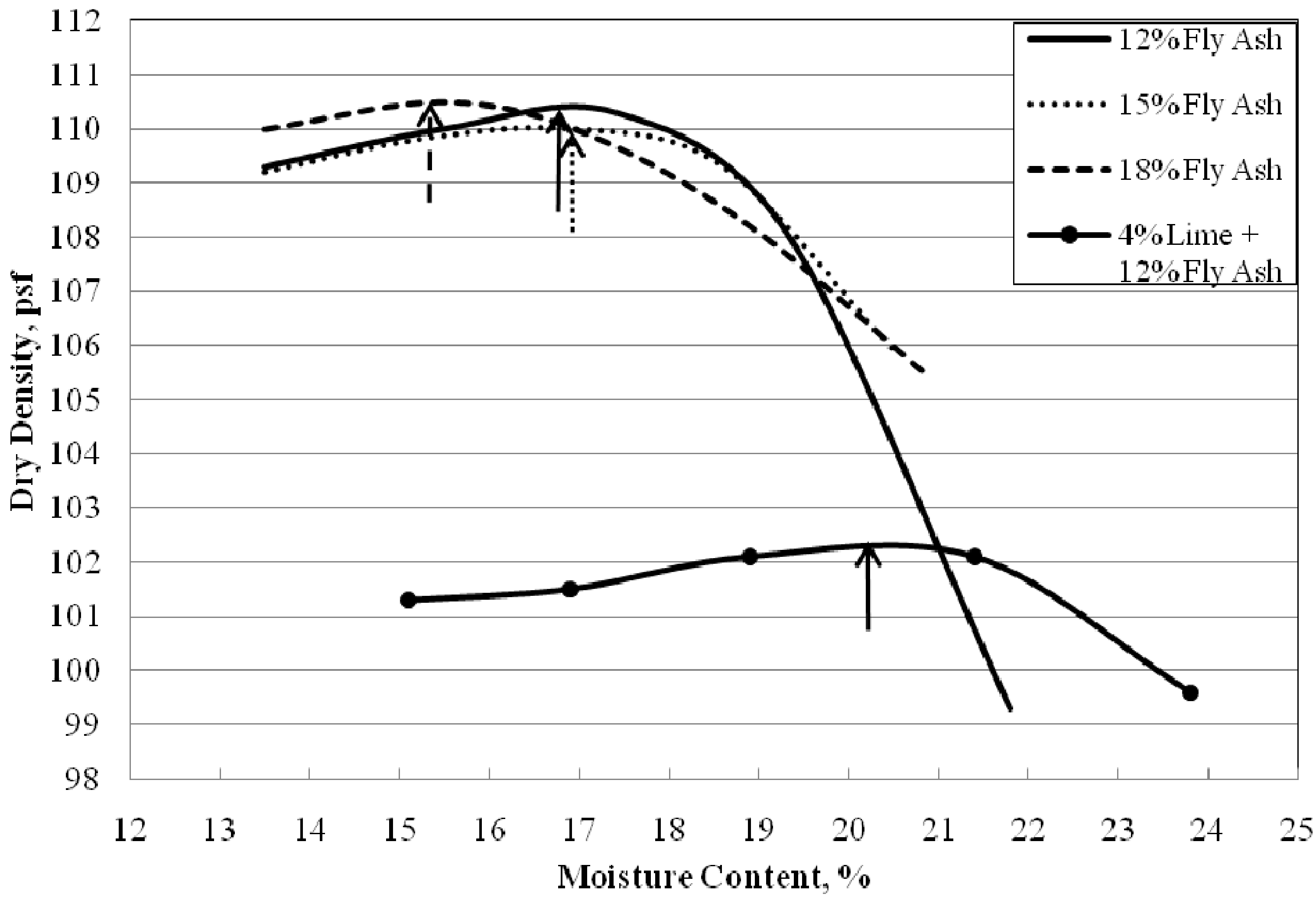


Figure 4.3.C Compaction Curves for Fly AshTreated Soils



Harvard Miniature Correlation

With the maximum dry density and optimum moisture content known from the Standard Proctor compaction test, a correlation or calibration of the Harvard miniature kneading foot hammer was conducted. An increase in the number of blows between the untreated and treated was experienced as well as an increase between the untreated and pretreated. The number of blows, the achieved densities, and moisture contents of the kneading foot hammer are shown in Table 4.8 Harvard Miniature Correlation Results.

Table 4.8 Harvard Miniature Correlation Results

Treatment	Number of Blows	Achieved Dry Density, pcf	Moisture Content, %
Untreated	12	105.4	15.0
Treated with:			
10% CKD	25	105.5	17.4
12% CKD	22	104.8	17.7
14% CKD	30	104.2	19.5
12% Fly Ash	25	109.5	17.5
15% Fly Ash	30	109.5	16.5
18% Fly Ash	30	109.2	15.8
Pretreated with:			
4% Lime + 10% CKD	30	98.6	20.4
4% Lime + 12% Fly Ash	25	101.6	19.7

Unconfined Compressive Strength

The unconfined compressive strength (UCS) was found for each of the untreated, treated, and pretreated soil conditions at seven and twenty-eight days and the results are shown in Table 4.9 Unconfined Compressive Strength.

Table 4.9 Unconfined Compressive Strength

Treatment	7 Day UCS, psi	28 Day UCS, psi
Untreated	58.8	61.0
Treated with:		
10% CKD	126.2	148.7
12% CKD	161.0	202.9
14% CKD	184.7	206.1
12% Fly Ash	69.7	85.0
15% Fly Ash	86.4	106.8
18% Fly Ash	106.2	148.8
Pretreated with:		
4% Lime + 10% CKD	205.7	306.0
4% Lime + 12% CKD	249.4	344.8
4% Lime + 14% CKD	244.6	355.0
4% Lime + 12% Fly Ash	139.9	210.5
4% Lime + 15% Fly Ash	132.8	223.2
4% Lime + 18% Fly Ash	129.5	223.0

The UCS of all of the treated and pretreated soils increased, some slightly and other significantly with the addition of additive. The soils treated with CKD experienced larger increases than the soils treated with fly ash compared to the untreated soil. With an increase in the percentage of additive the treated soil experienced an increase in seven day and twenty-eight day UCS when compared against the lesser percentages of the same additive. The twenty-eight day UCS of the soil treated with CKD began to level between the twelve and fourteen percentages. All of the pretreated soils UCS for seven and twenty-eight days were higher than those of the soils with the same additive. The seven day pretreated CKD samples experienced an increase in UCS between ten and twelve percent CKD but the UCS decreased slightly between twelve and fourteen percent. The decrease between pretreated twelve and fourteen percent CKD samples was probably due to weak samples or the maximum seven day strength was met at twelve percent. This can be assumed since the twenty-eight day UCS of the pretreated fourteen percent CKD was greater than the twenty-eight day UCS of the pretreated twelve percent CKD. A slight decrease in UCS was produced in the seven day pretreated fly ash samples as the percentage of fly ash increase. As the percentage of CKD increased in the pretreated CKD sample the twenty-eight day UCS increased, more so between ten and twelve percent CKD than between twelve and fourteen percent CKD. For the pretreated fly ash samples the UCS increased between twelve and fifteen percent fly ash and remained constant between the fifteen and eighteen percentages. All of the samples had higher twenty-eight day UCS's than seven day UCS's. Figure 4.4 and 4.5 depict the UCS versus the percent of additive for the seven day and twenty-eight day curing times. The Stress-Strain plots are presented in Appendix C.

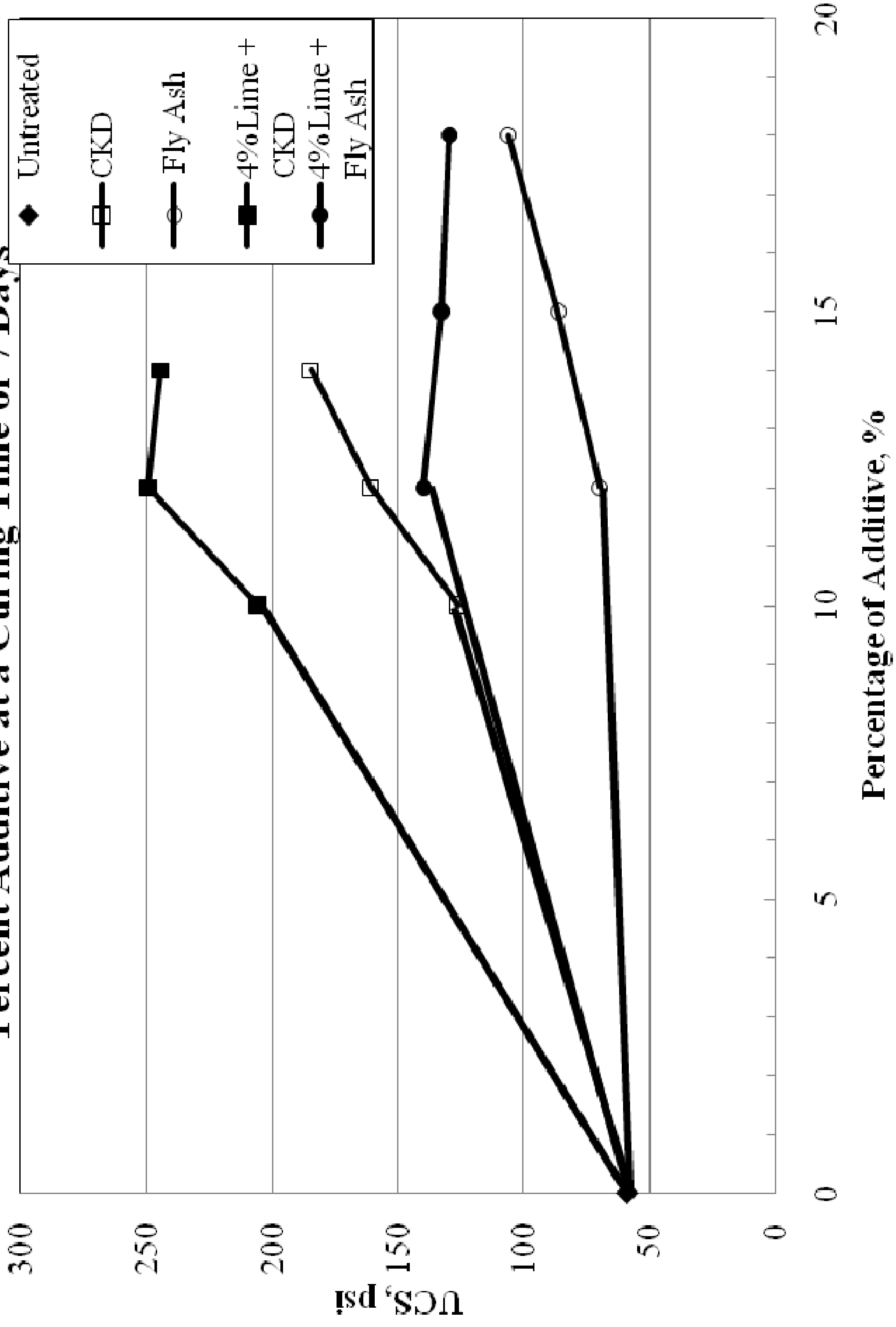
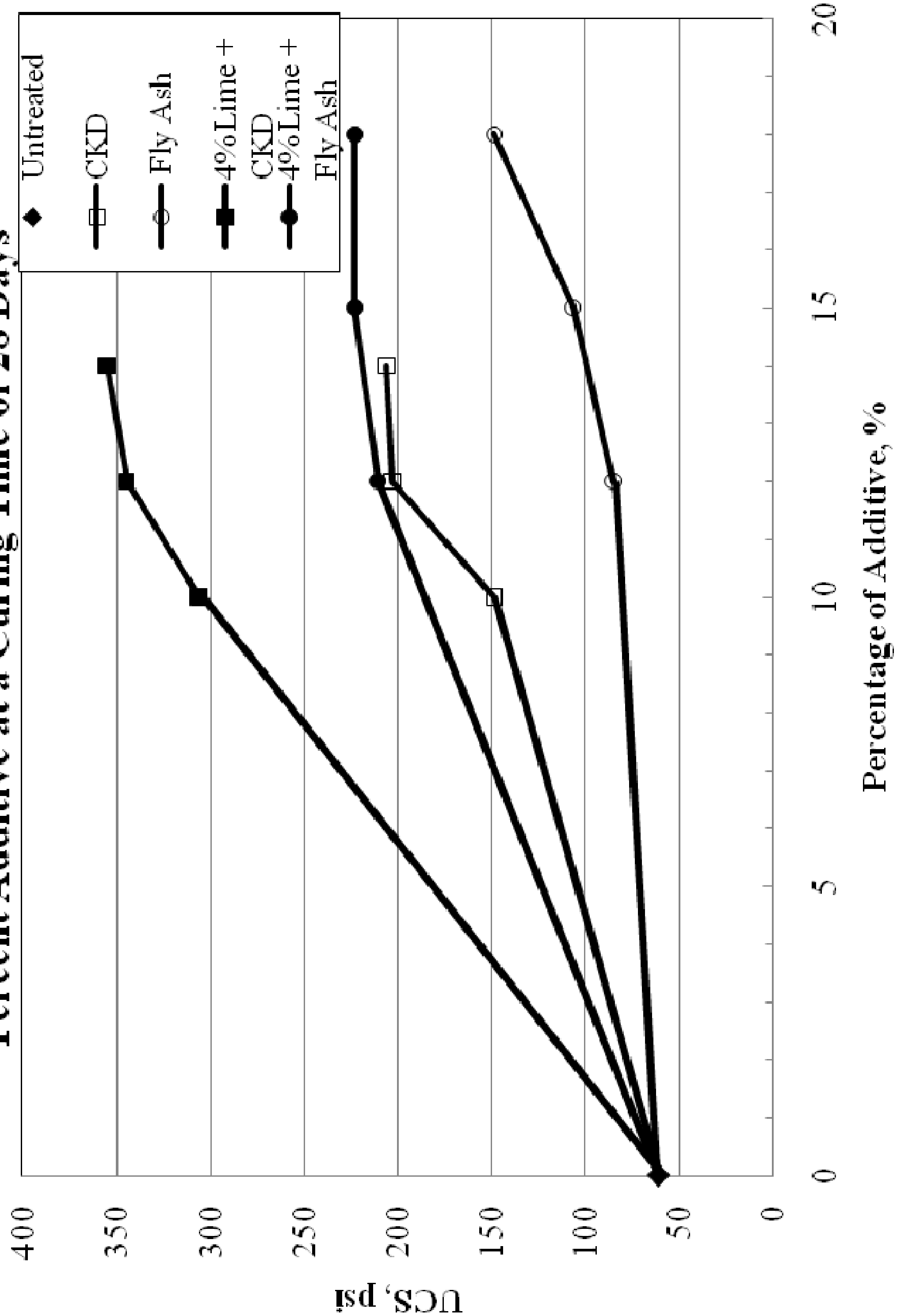


Figure 4.4 Unconfined Compressive Strength Versus Percent Additive at a Curing Time of 7 Days

Figure 4.5 Unconfined Compressive Strength Versus Percent Additive at a Curing Time of 28 Days



CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

This chapter discusses the conclusions developed from the chemical additive evaluation and presents recommendations for implementation of these conclusions, as well as recommendations for further testing.

Pretreatment Usage

The treatment of a soil with lime prior to treatment with a cementitious stabilizer is considered pretreatment. Pretreatment of an A-6 soil resulted in a reduction of plasticity, Bar Linear Shrinkage, and maximum dry density, as well as, an increase in the unconfined compressive strength. It is recommended that pretreatment be used for the stabilization of sub-grade soils with A-6 or A-7 classifications.

Atterberg Limits

The Atterberg limits of a soil are used to determine the plasticity of the soil and along with the percentage of the soil passing the U.S. No. 200 sieve are used to determine the soil's classification. The soil's classification and the plasticity can be used to estimate a soil's engineering properties, like permeability, compressibility, and strength. Pretreatment reduces the plastic index of soils; therefore, a change in the soil's classification and engineering properties occurs. Lime pretreatment along with CKD or fly ash reduces the plasticity of an A-6 soil more effectively than the same percentage of CKD or fly ash alone. Increasing the percentage of CKD or fly ash reduces the plasticity of an A-6 soil, but even the highest percentage of CKD or fly ash tested did not equal the reduction achieved by pretreatment.

Bar Linear Shrinkage

Bar Linear Shrinkage (BLS) test was used to determine the shrink-swell potential of the soil. CKD and fly ash alone reduced the BLS of the A-6 soil, however; pretreatment with lime more effectively decreased the BLS.

Unconfined Compressive Strength

The twenty-eight day unconfined compressive strength (UCS) of the A-6 soil was increased more with pretreatment than CKD or fly ash treatment alone. The CKD treated A-6 soil had significant increases in seven and twenty-eight day UCS between ten and twelve percent, but minimal increases in UCS between twelve and fourteen percent. The fly ash treated A-6 soil had consistent increases in seven and twenty-eight day UCS between each of the increasing percentages. Pretreated CKD soil samples had higher seven and twenty-eight day UCS than all percentages of pretreated fly ash soil samples. Pretreated CKD soil samples and the treated CKD soil samples had similar increases in UCS as the percentage of CKD increased. No significant strength gain occurred from increasing the percentage of fly ash for pretreated fly ash soil samples.

Summary

Stabilization of high plasticity soils with lime as a pretreatment and CKD or fly ash as a cementitious additive was more effective for improving the engineering properties of a soil than using a single treatment like CKD or fly ash alone. Pretreatment of an A-6 soil improves the soil by: decreasing the plasticity; decreasing the BLS; and increasing the UCS.

Other Considerations

Some other considerations that should be taken into account include the sulfate content of the soil being treated, the loss on ignition (LOI) of the additive, and cost/availability. Soils stabilized with any chemical that contains lime should be checked for the presence of sulfate, generally in the form of gypsum. Soils with enough sulfates that are being stabilized using a lime based stabilizer will react adversely, due to formation of expansive mineral compounds. LOI is a measurement of the amount of unburned carbon present in the CKD or fly ash. The unburned carbon will hamper the stabilization process by not allowing the soil and additive to react because the carbon effectively blocks reaction with the silicates and aluminates. A complete cost analysis of all available chemical stabilization processes should be considered when planning a project. Lime generally costs roughly three to four times as much as CKD and fly ash, that is why pretreatment came to existence, as a way to reduce the amount lime used. Some chemical stabilizers may not be available for use in some areas due to the haul distance of the chemical from the production site to the construction site. Other possible stabilization alternatives or combinations include: Portland cement, Portland cement-fly ash combination; lime-Portland cement combination; asphalt; and lime-asphalt combination.

Testing Recommendations

For future research in the area of pretreatment as an alternative to stabilize sub-grade soil the following recommendations are made:

1. More high plasticity soils should be tested to gain understanding of the effects of pretreatment on the engineering properties of different soils.
2. Additional percentages and combinations of lime, CKD, and fly ash should be tested to ensure completeness of the evaluation.

3. Future testing programs should include resilient modulus testing and field testing at selected construction sites.
4. Lime, CKD, and fly ash are the most common chemical stabilizing agents in this region, but additional additives could be evaluated to test their effectiveness as a soil stabilizer (e.g. Portland cement, lime kiln dust, and asphalt).

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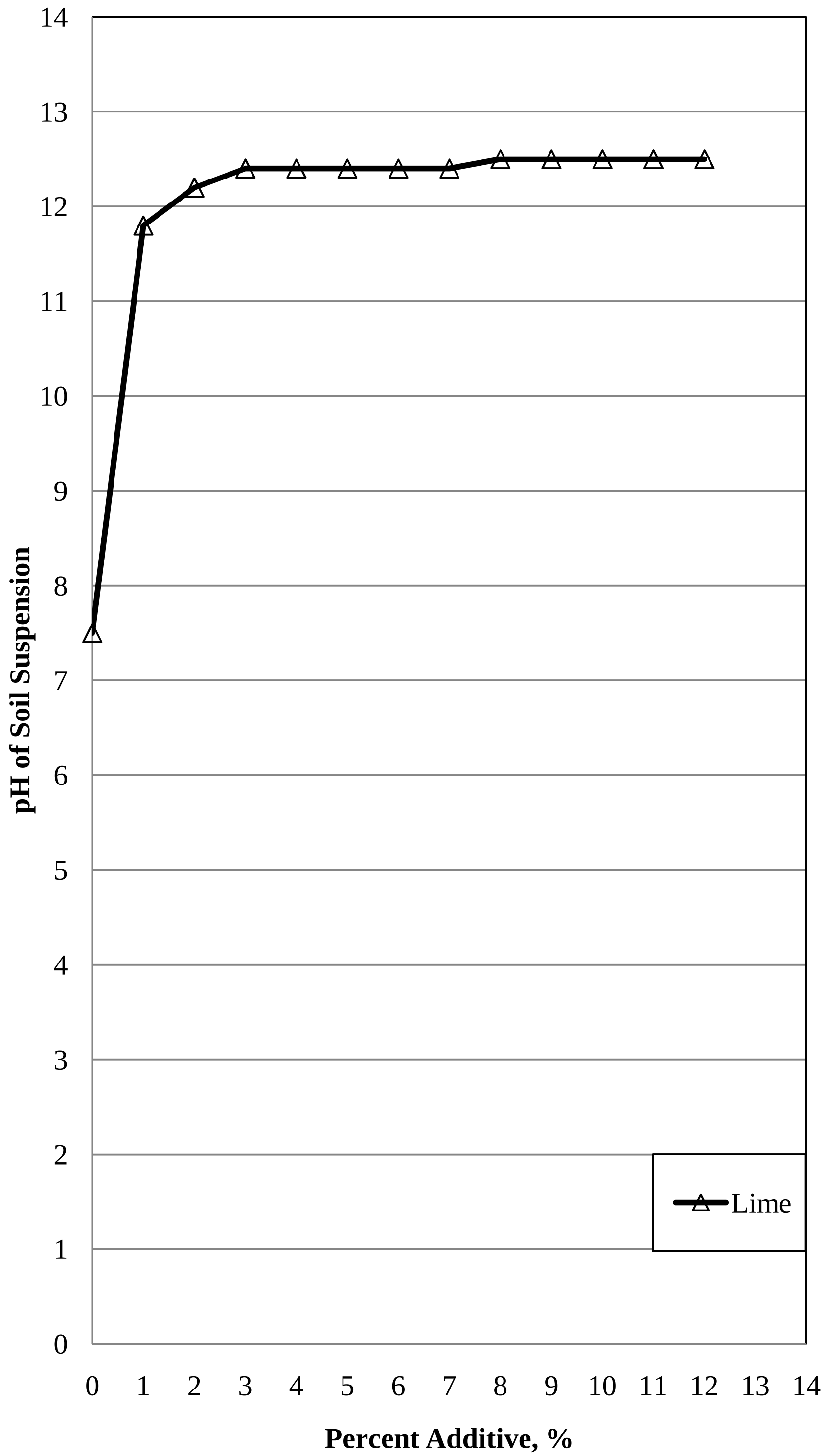
14. American Coal Ash Association, “Fly Ash Facts for Highway Engineers”, Federal Highway Administration, FHWA-IF-03-019. Washington D.C., June 2003.
15. “OHD L-50 Soil Stabilization Mix Design Procedure”, Oklahoma Department of Transportation, October 2006.

APPEDIX A

Soil-pH Test Data

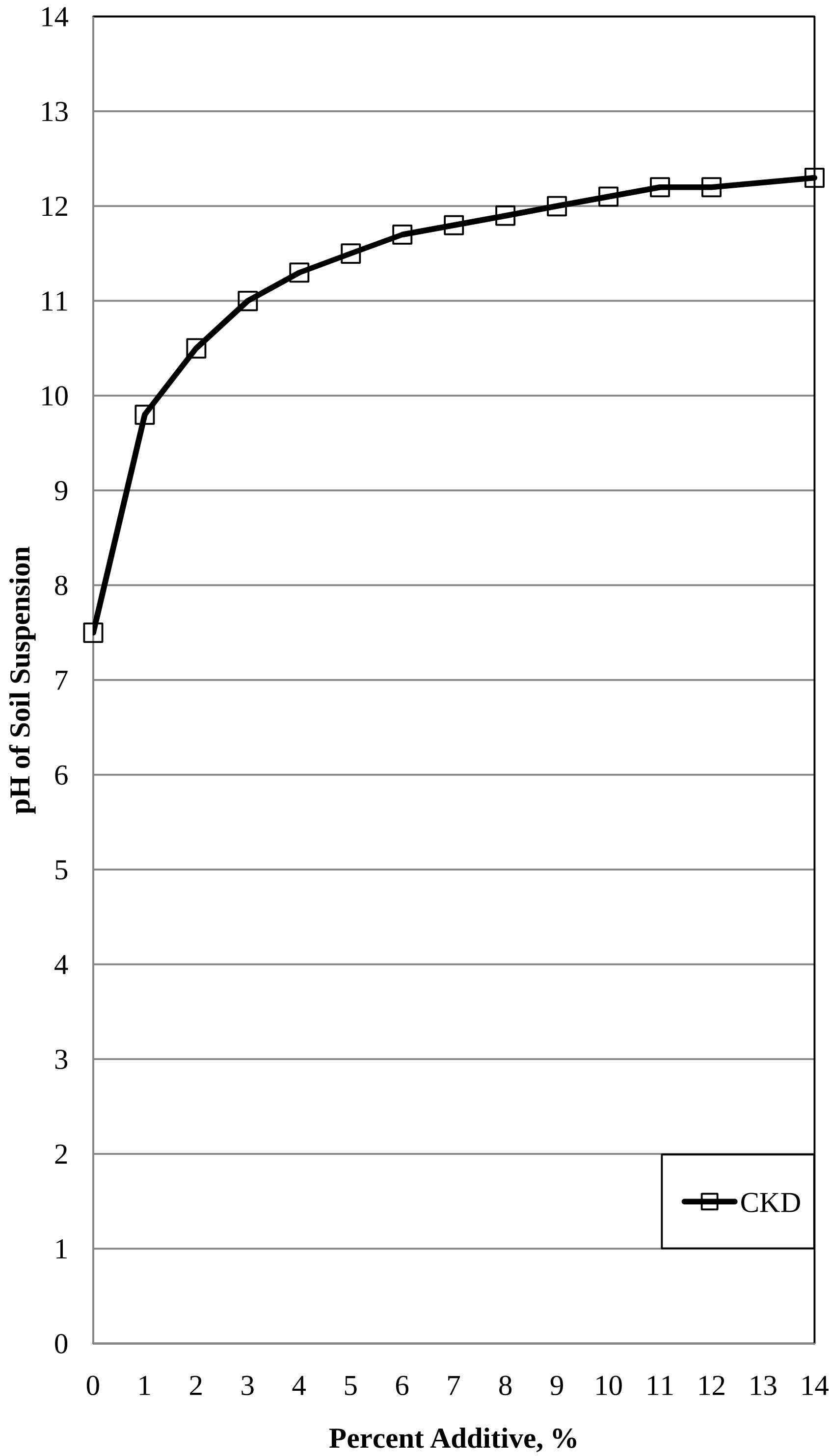
Lime	
Additive, %	pH
0	7.5
1	11.8
2	12.2
3	12.4
4	12.4
5	12.4
6	12.4
7	12.4
8	12.5
9	12.5
10	12.5
11	12.5
12	12.5

Figure A.1 Percent Lime Verses pH of Soil Suspension



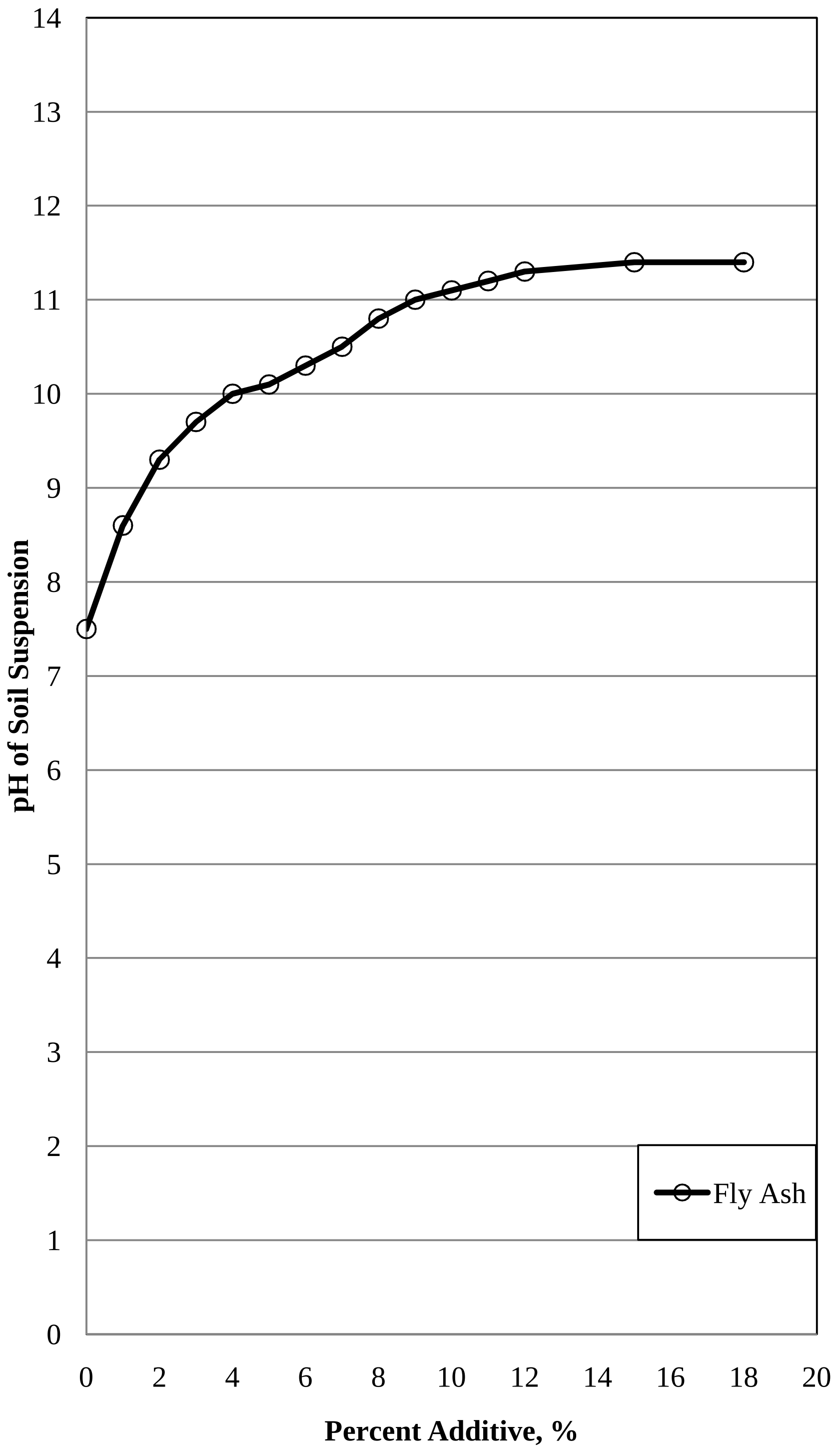
CKD	
Additive, %	pH
0	7.5
1	9.8
2	10.5
3	11.0
4	11.3
5	11.5
6	11.7
7	11.8
8	11.9
9	12.0
10	12.1
11	12.2
12	12.2
14	12.3

Figure A.2 Percent CKD Verses pH of Soil Suspension



Fly Ash	
Additive, %	pH
0	7.5
1	8.6
2	9.3
3	9.7
4	10.0
5	10.1
6	10.3
7	10.5
8	10.8
9	11.0
10	11.1
11	11.2
12	11.3
15	11.4
18	11.4

FIgure A.3 Percent Fly Ash Verses pH of Soil Suspension



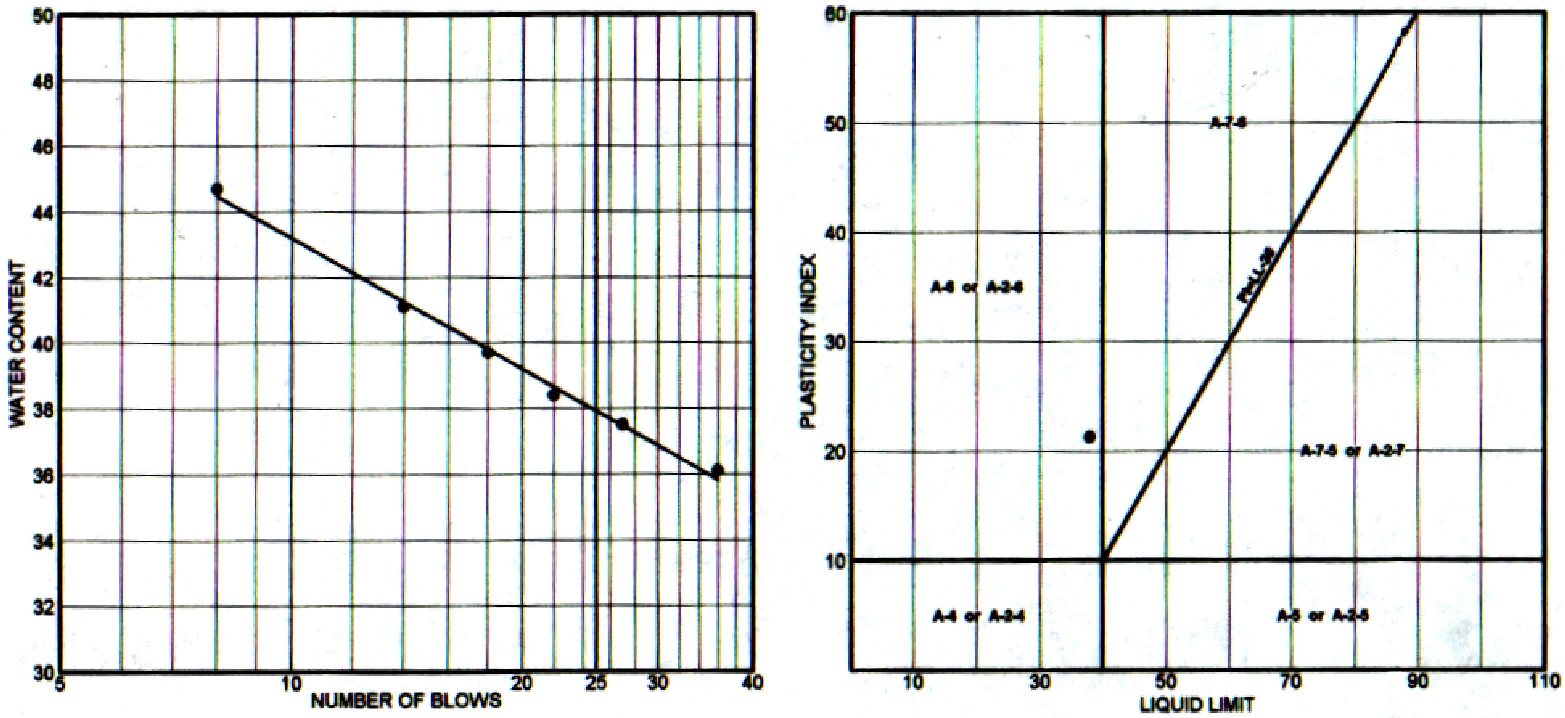
APPEDIX B

Atterberg Limits Test Data

Appendix B1

Untreated Atterberg Limits Test Data

Figure B.1 Liquid and Plastic Limits Test Report for Untreated Soil



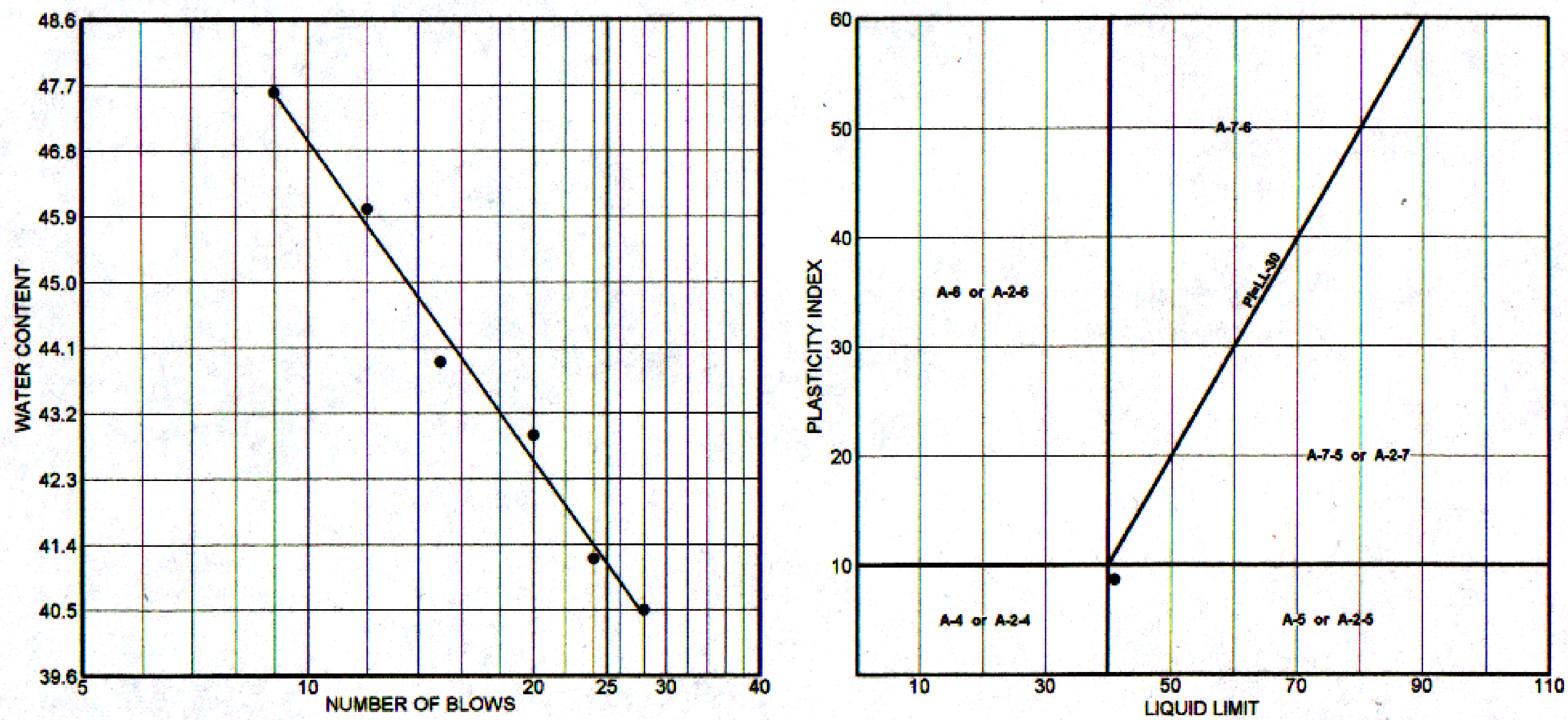
	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	Untreated	1		6/22/10	A-6 (19)	Untreated Soil		37.9	21.3

Client Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil Project No.	**Oklahoma State University**	● Untreated Soil

Appendix B2

Lime Treated Atterberg Limits Test Data

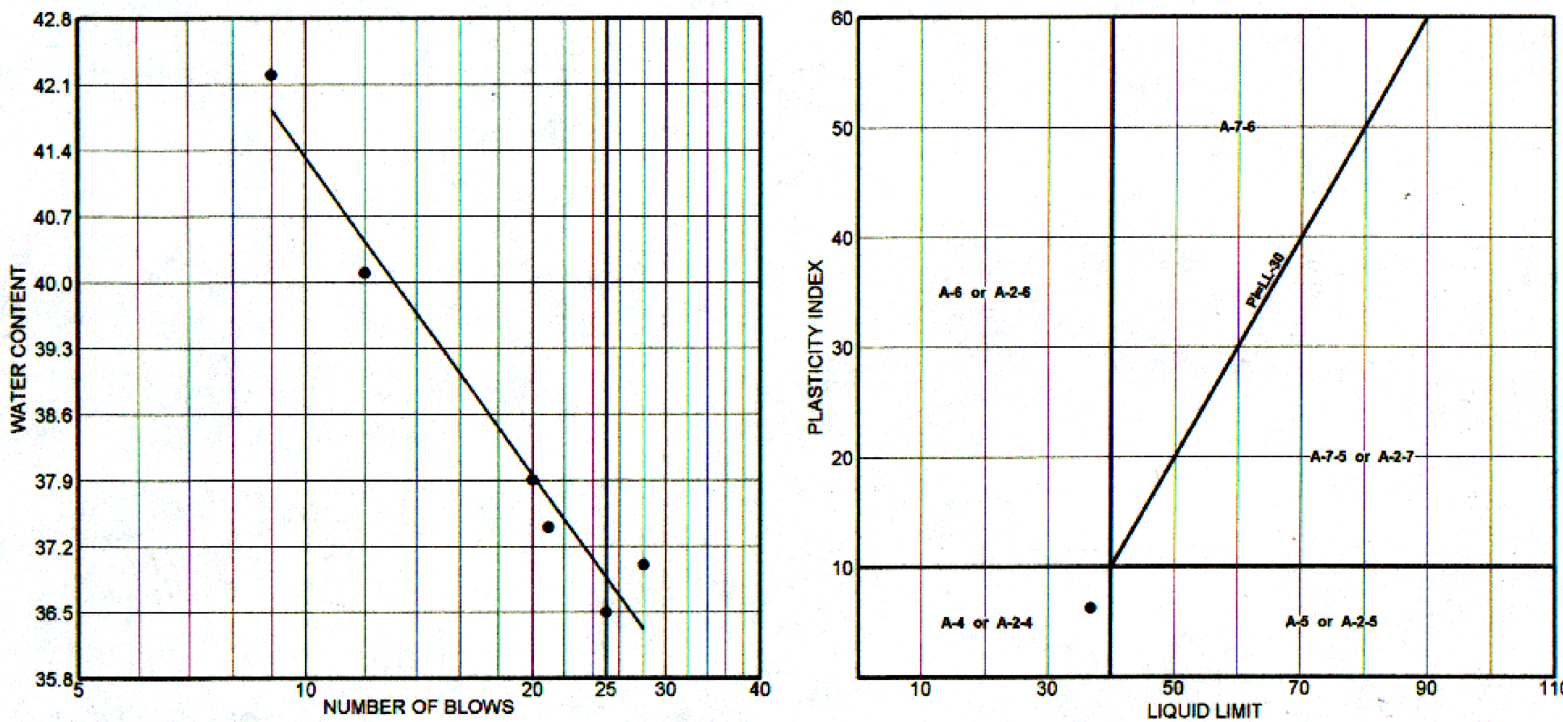
Figure B.2 Liquid and Plastic Limits Test Report for 2% Lime Treated Soil



	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	Lime	2% Lime		07/08/09	A-5 (11)	2% Lime		41.1	8.7

Client Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil Project No.	**Oklahoma State University**	● 2% Lime

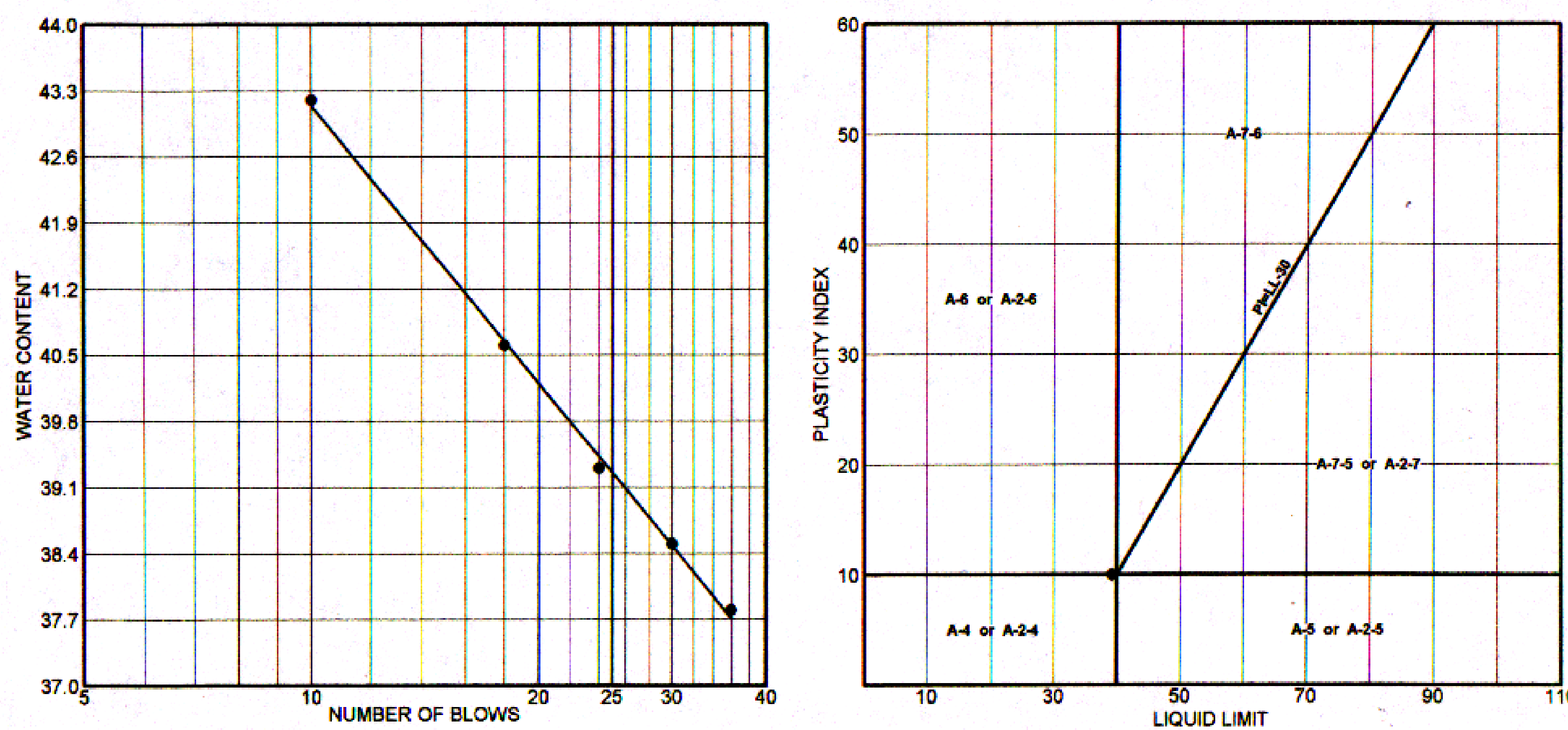
Figure B.3 Liquid and Plastic Limits Test Report for 4% Lime Treated Soil



	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	Lime	4% Lime		06/09/09	A-4 (8)	4% Lime		36.9	6.3

Client	Oklahoma State University	● 4% Lime
Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil		
Project No.		

Figure B.4 Liquid and Plastic Limits Test Report for 6% Lime Treated Soil



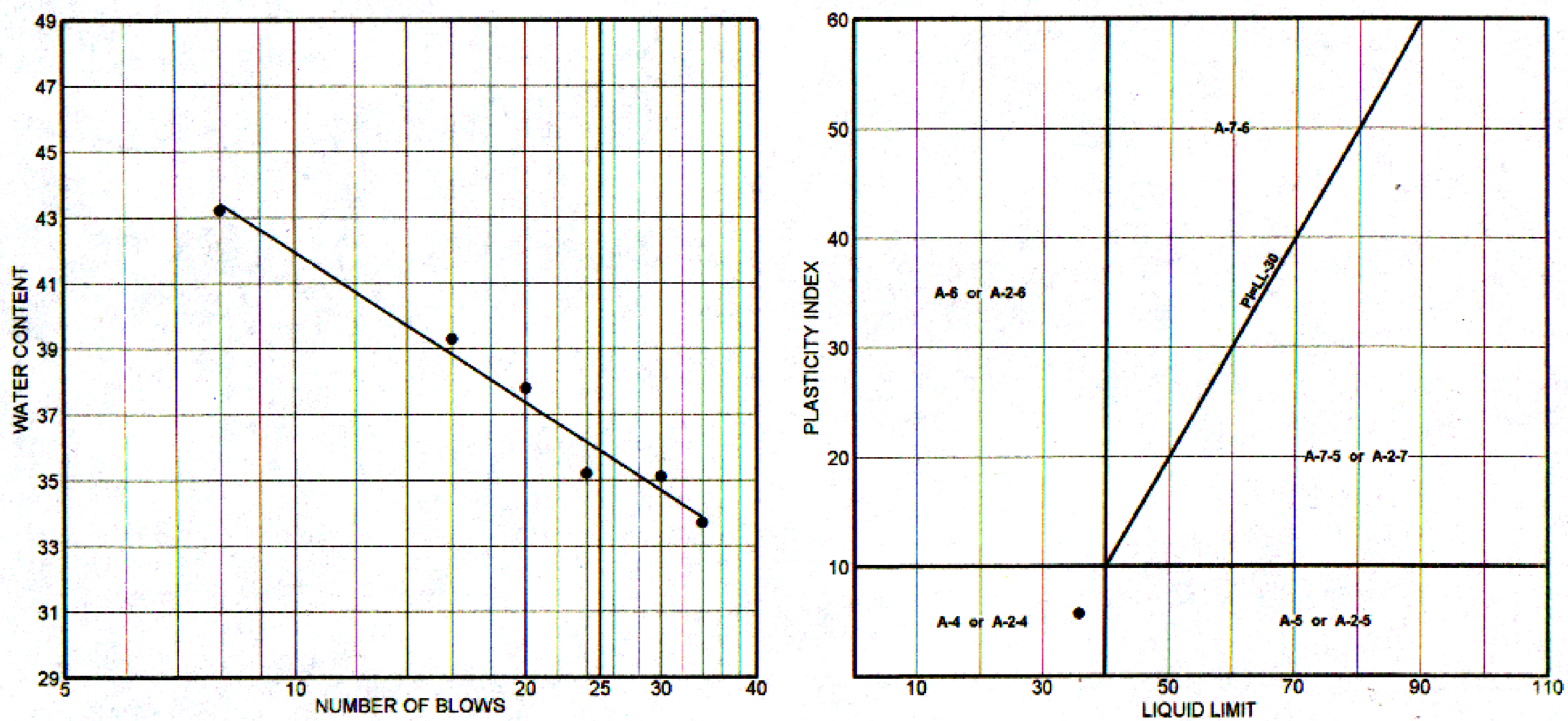
	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	Lime	6% Lime		06/11/09	A-4 (11)	6% Lime		39.3	10.0

Client
Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil
Project No.

Oklahoma State University

● 6% Lime

Figure B.5 Liquid and Plastic Limits Test Report for 8% Lime Treated Soil



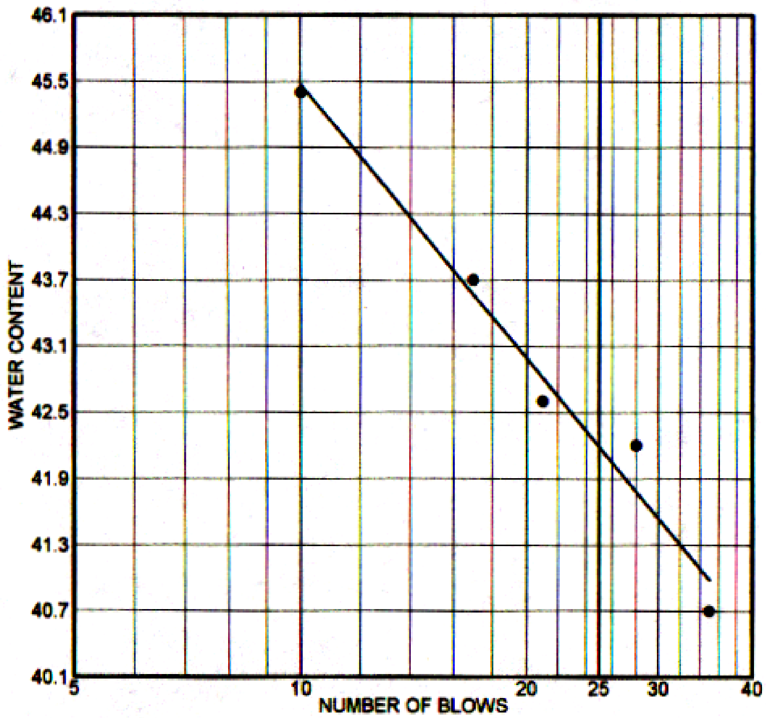
	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	Lime	8% Lime		06/15/09	A-4 (7)	8% Lime		35.9	5.7

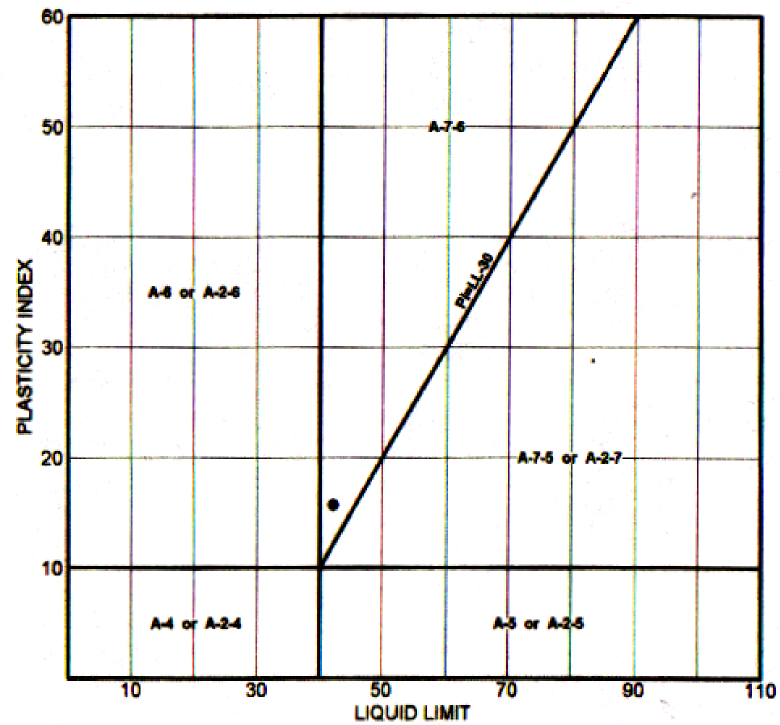
Client Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil Project No.	**Oklahoma State University**	● 8% Lime

Appendix B3

Treated Atterberg Limits Test Data

Figure B.6 Liquid and Plastic Limits Test Report for 10% CKD Treated Soil

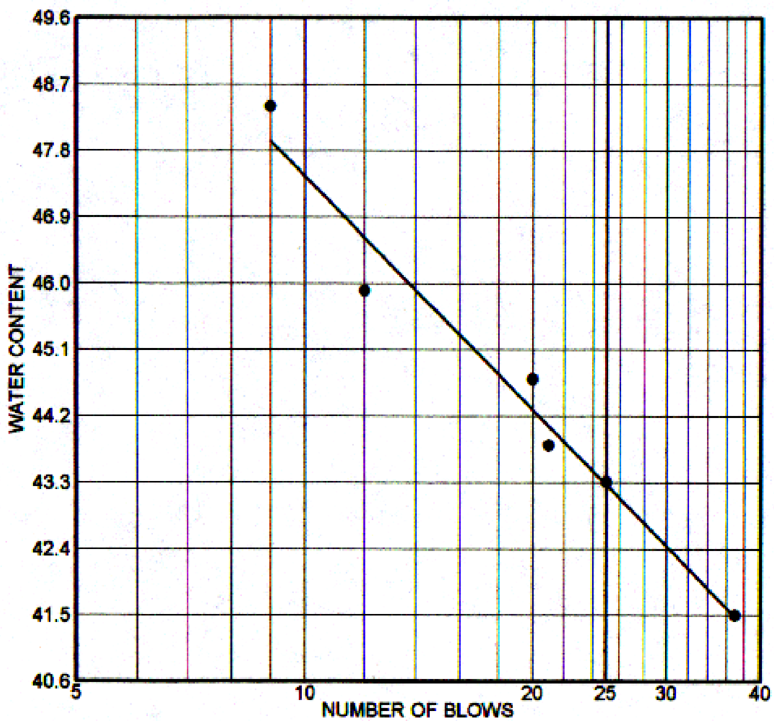


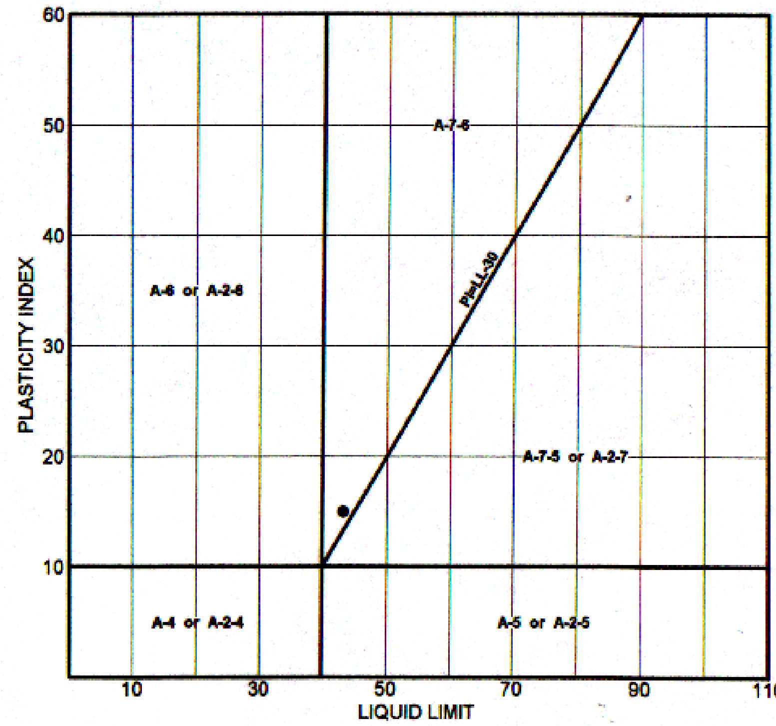


	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	CKD	3		06/11/09	A-7-6 (16)	10% CKD		42.2	15.7

Client Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil Project No.	**Oklahoma State University**	● Treated 10% CKD

Figure B.7 Liquid and Plastic Limits Test Report for 12% CKD Treated Soil





	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	CKD	5		03/15/10	A-7-6 (16)	12% CKD		43.3	15.0

Client

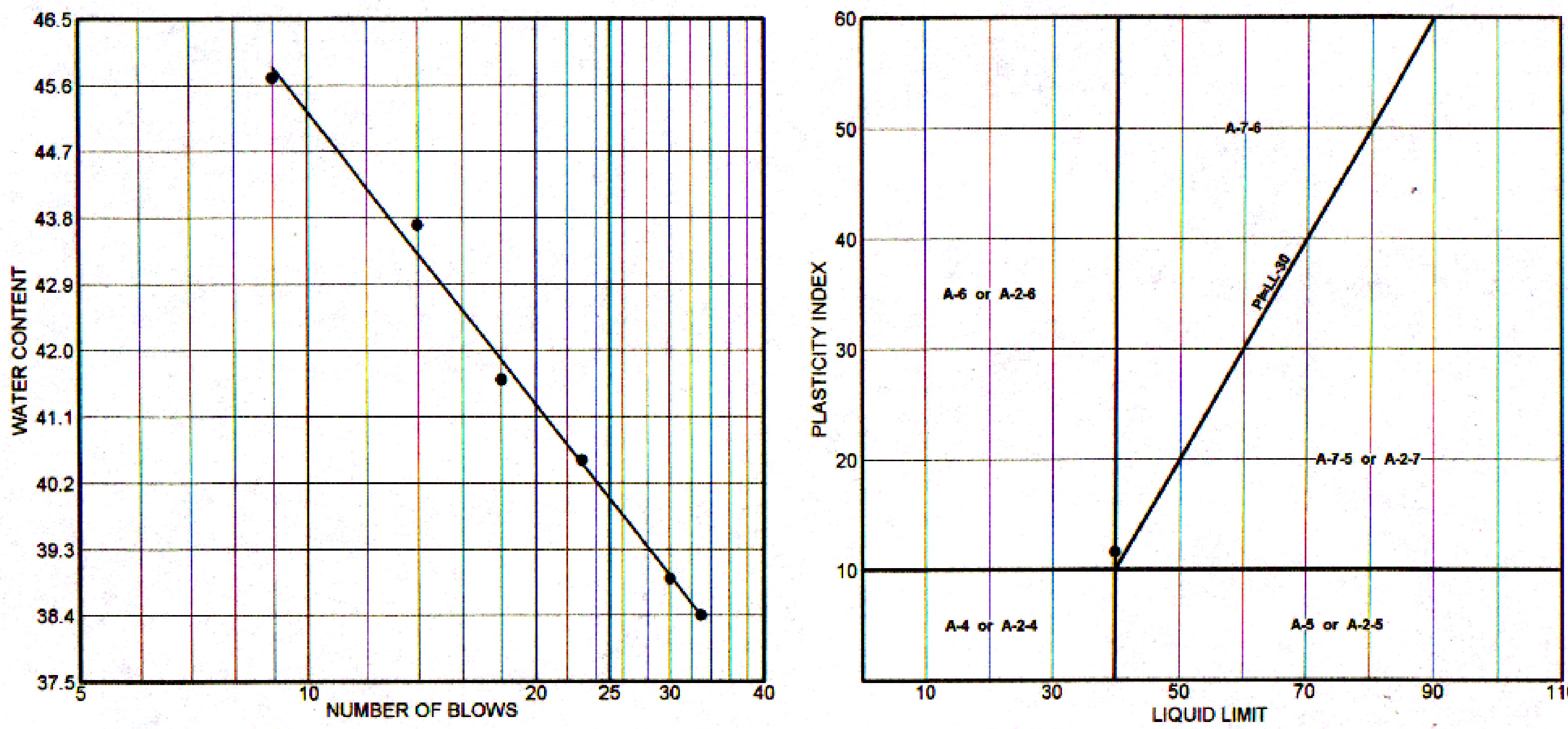
Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Project No.

Oklahoma State University

● Treated 12% CKD

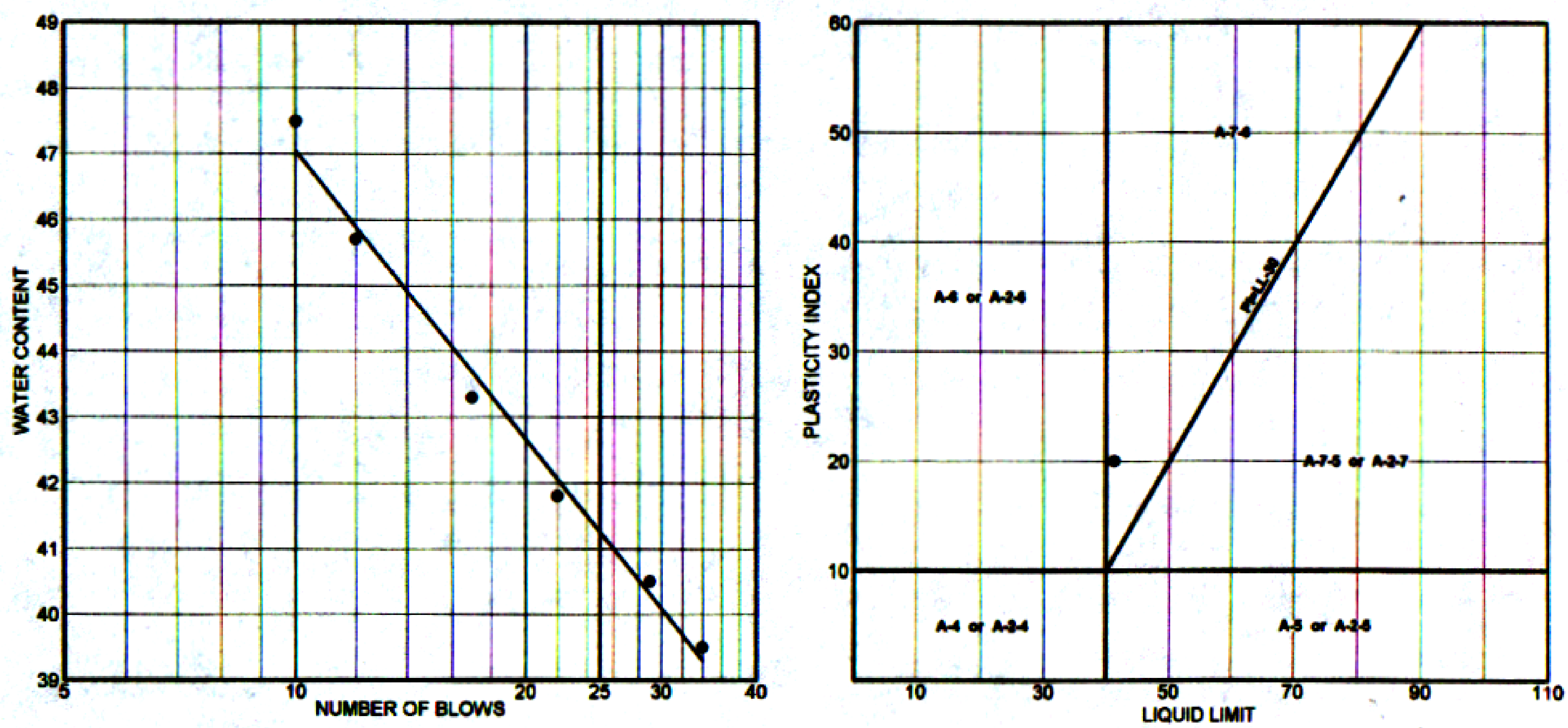
Figure B.8 Liquid and Plastic Limits Test Report for 14% CKD Treated Soil



	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	CKD	7		03/15/10	A-6 (12)	14% CKD		40.0	11.6

Client Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil Project No.	**Oklahoma State University**	● Treated 14% CKD

Figure B.9 Liquid and Plastic Limits Test Report for 12% Fly Ash Treated Soil



	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	Fly Ash	9		08/04/10	A-7-6 (19)	12% Fly Ash		41.3	20.0

Client

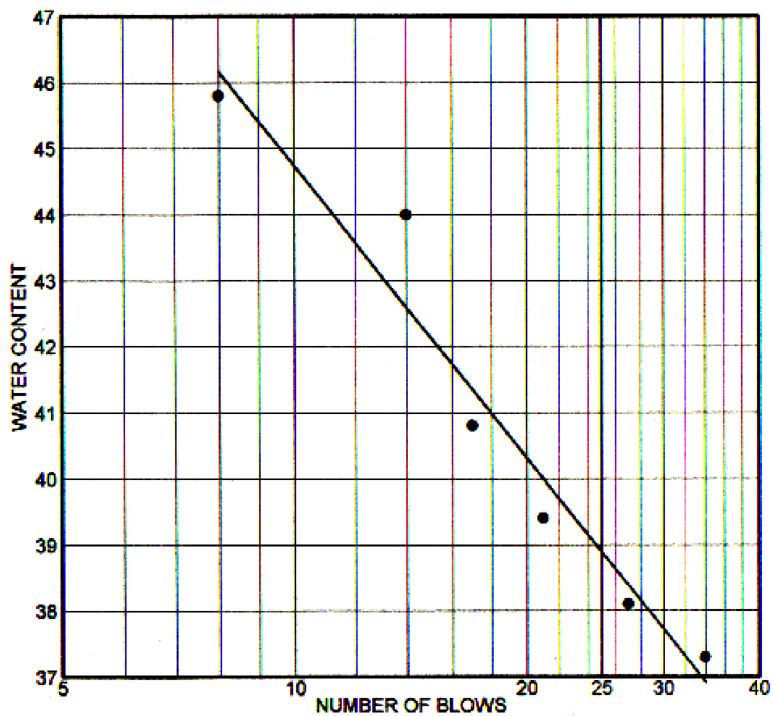
Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

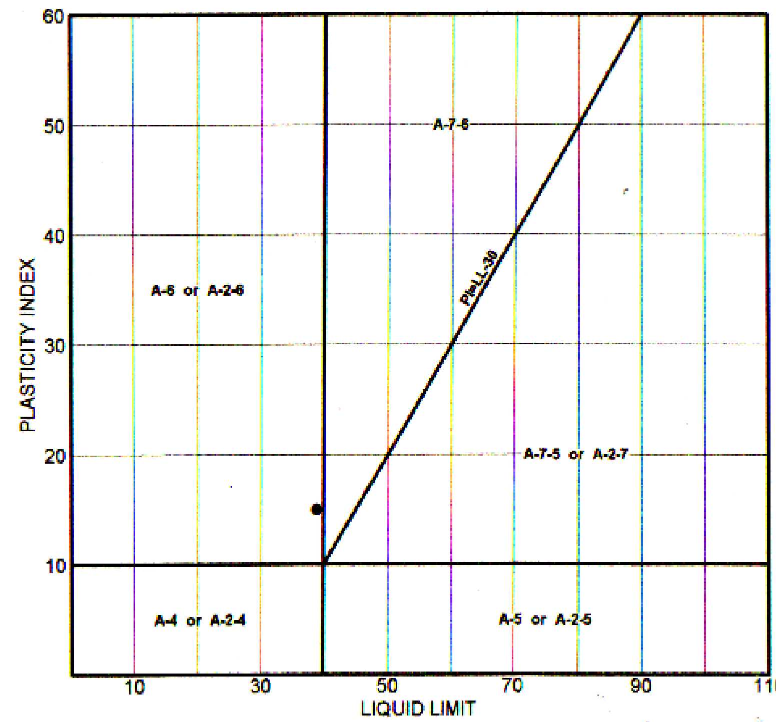
Project No.

Oklahoma State University

● Treated
12% Fly Ash

Figure B.10 Liquid and Plastic Limits Test Report for 15% Fly Ash Treated Soil





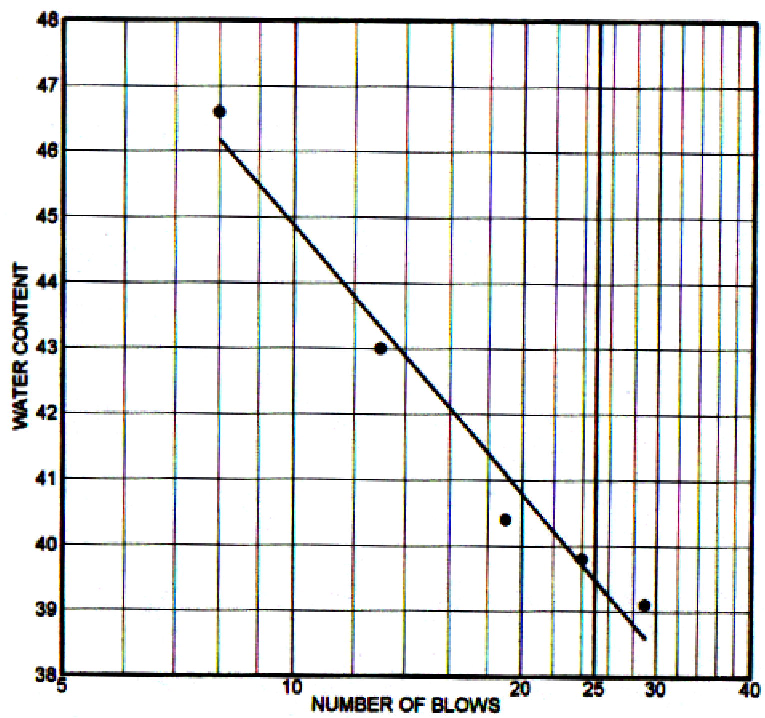
	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	Fly Ash	11		03/16/10	A-6 (15)	15% Fly Ash		38.9	15.0

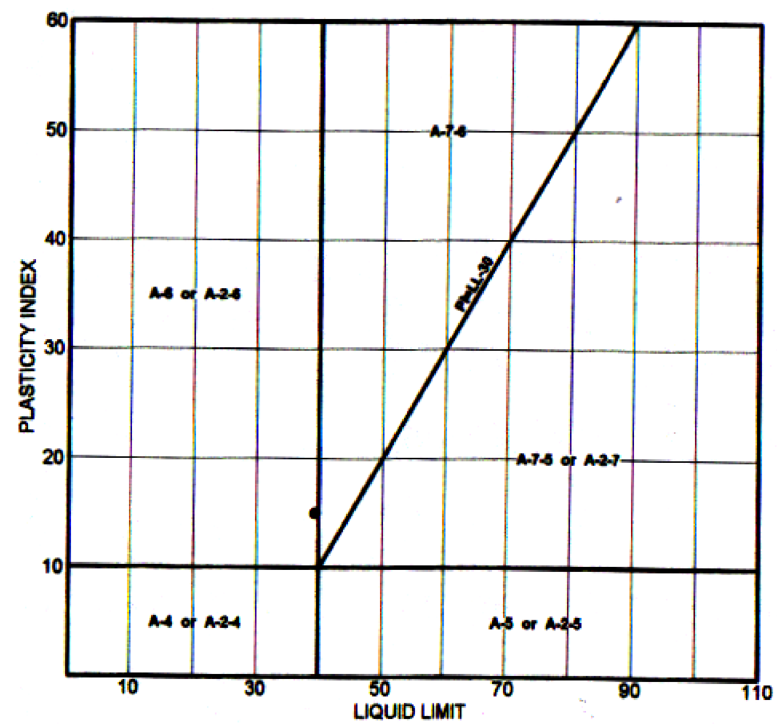
Client
Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil
Project No.

Oklahoma State University

● Treated
15% Fly Ash

Figure B.11 Liquid and Plastic Limits Test Report for 18% Fly Ash Treated Soil





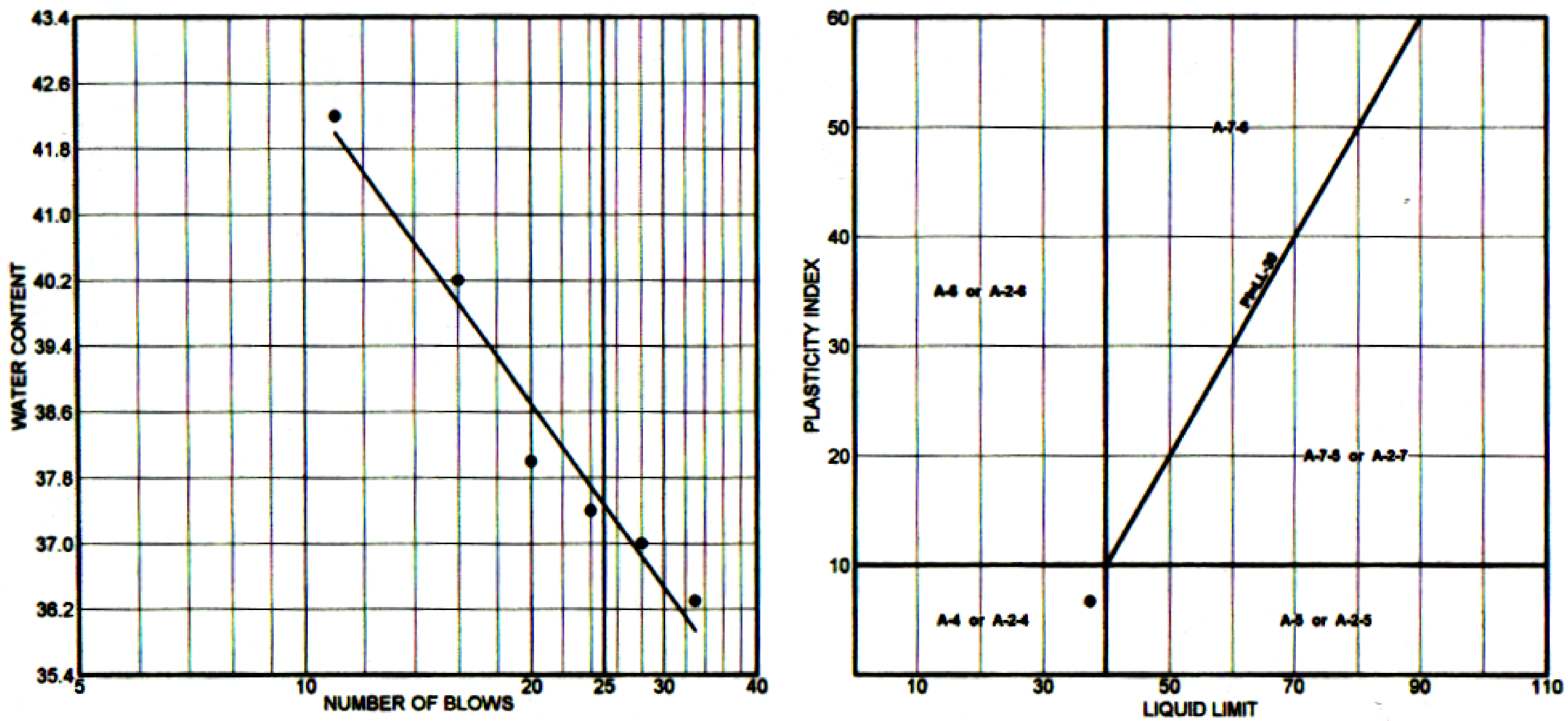
	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	Fly Ash	13		03/15/10	A-6 (15)	18% Fly Ash		39.5	15.0

Client Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil Project No.	Oklahoma State University	● Treated 18% Fly Ash

Appendix B4

Pretreated Atterberg Limits Test Data

Figure B.12 Liquid and Plastic Limits Test Report for 4% Lime + 10% CKD Treated Soil



	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	Lime + CKD/Fly Ash	15		06/12/09	A-4 (8)	4% Lime + 10% CKD		37.5	6.7

Client

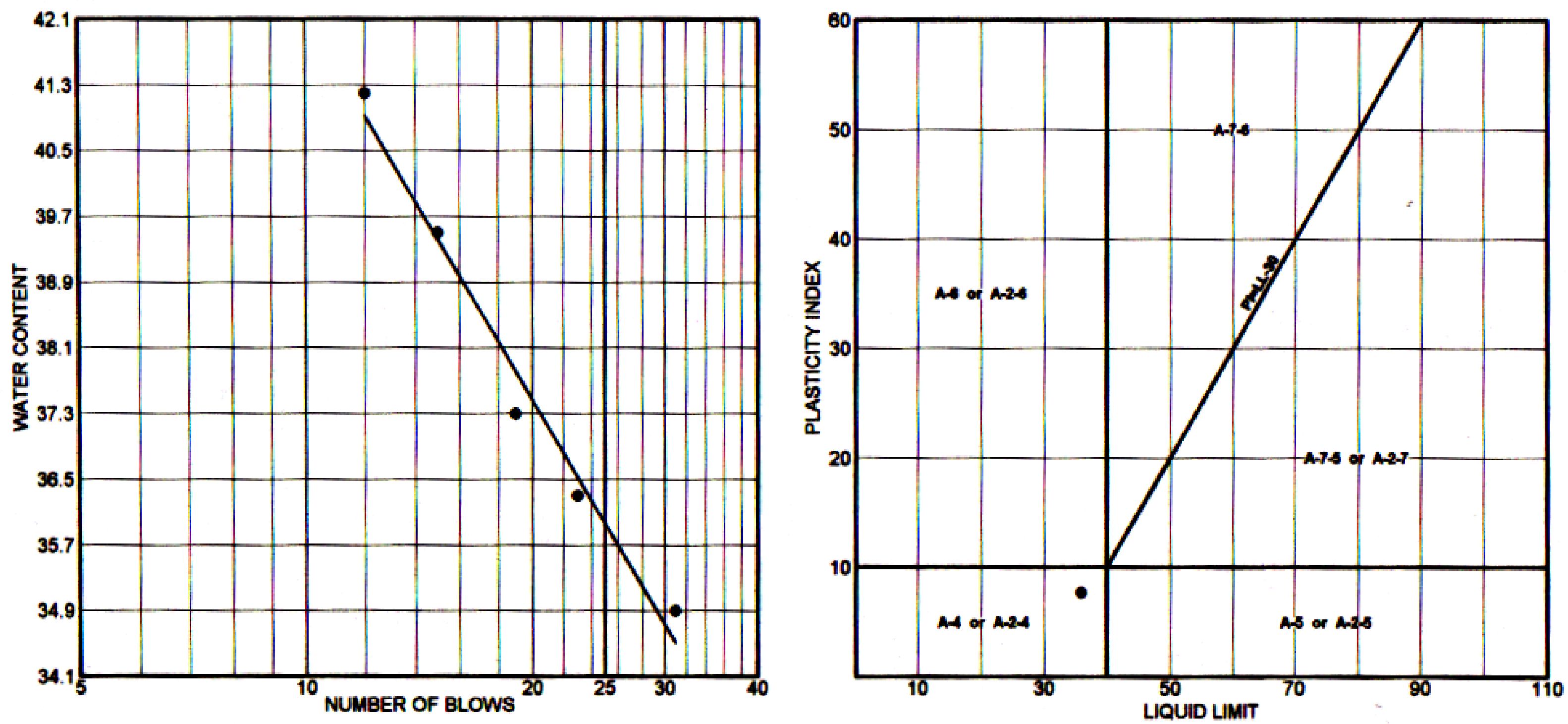
Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Project No.

Oklahoma State University

● Pretreated
4% Lime + 10% CKD

Figure B.13 Liquid and Plastic Limits Test Report for 4% Lime + 12% Fly Ash Treated



	SOURCE	SAMPLE #	DEPTH/ELEV.	DATE SAMPLED	AASHTO	MATERIAL DESCRIPTION	NM %	LL	PI
●	Lime + CKD/Fly Ash	21		06/12/10	A-4 (8)	4% Lime + 12% Fly Ash		36.0	7.7

Client

Project Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Project No.

Oklahoma State University

● Pretreated
4% Lime + 12% Fly Ash

APPENDIX C

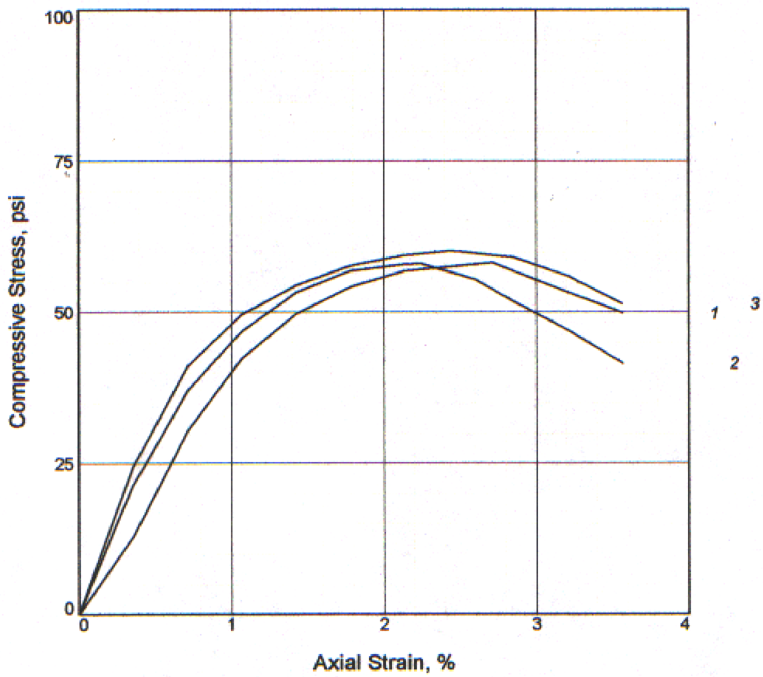
Unconfined Compressive Strength Test Data

Appendix C1

Untreated Unconfined Compressive Strength Test Data

Figure C.1 Untreated, 7 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3	
Unconfined strength, psi	58.18	58.03	60.04	
Undrained shear strength, psi	29.09	29.01	30.02	
Failure strain,	2.7	2.2	2.4	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	14.4	13.9	14.4	
Wet density, pcf	123.4	123.9	124.6	
Dry density, pcf	107.8	108.8	109.0	
Saturation, %	67.0	66.2	68.6	
Void ratio	0.5920	0.5781	0.5756	
Specimen diameter, in.	1.31	1.30	1.30	
Specimen height, in.	2.80	2.81	2.81	
Height/diameter ratio	2.14	2.15	2.15	

Description: Untreated Soil, 7 Day Cure

LL = 37.9 | **PL =** 16.6 | **PI =** 21.3 | **Assumed GS=** 2.75 | **Type:** Untreated

Project No.:

Date: 6/22/10

Remarks:
Figure C.1 Untreated, 7 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 1

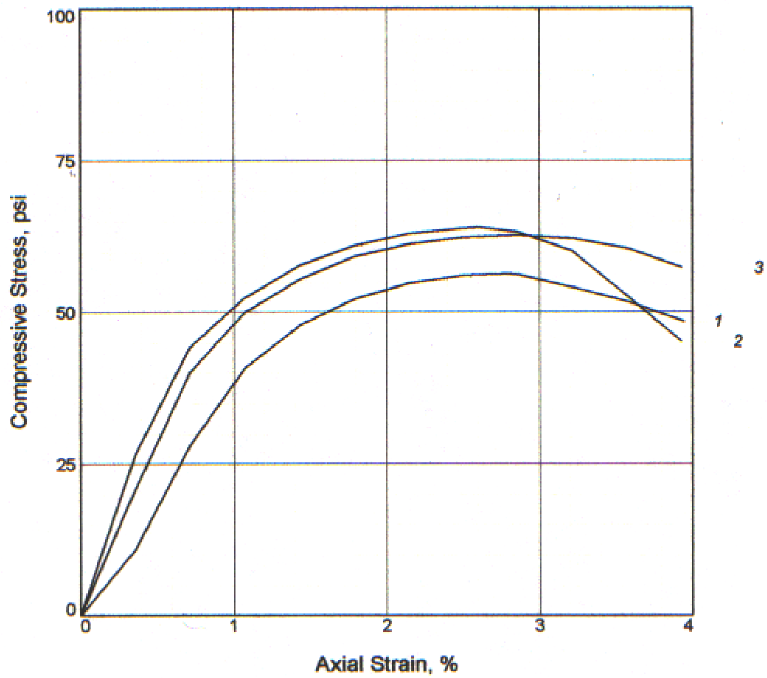
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.2 Untreated, 28 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3	
Unconfined strength, psi	56.35	63.89	62.65	
Undrained shear strength, psi	28.17	31.94	31.32	
Failure strain,	2.8	2.6	2.9	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	15.2	14.9	15.0	
Wet density, pcf	127.2	129.0	127.8	
Dry density, pcf	110.4	112.3	111.1	
Saturation, %	75.4	77.4	75.9	
Void ratio	0.5554	0.5284	0.5452	
Specimen diameter, in.	1.30	1.29	1.30	
Specimen height, in.	2.79	2.80	2.80	
Height/diameter ratio	2.14	2.16	2.15	

Description: Untreated Soil, 28 Day Cure

LL = 37.9	**PL =** 16.6	**PI =** 21.3	**Assumed GS=** 2.75	**Type:** Untreated

Project No.:
Date: 06/13/10
Remarks:
Figure C.2 Untreated, 28 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil
Location: US 77
Sample Number: 2

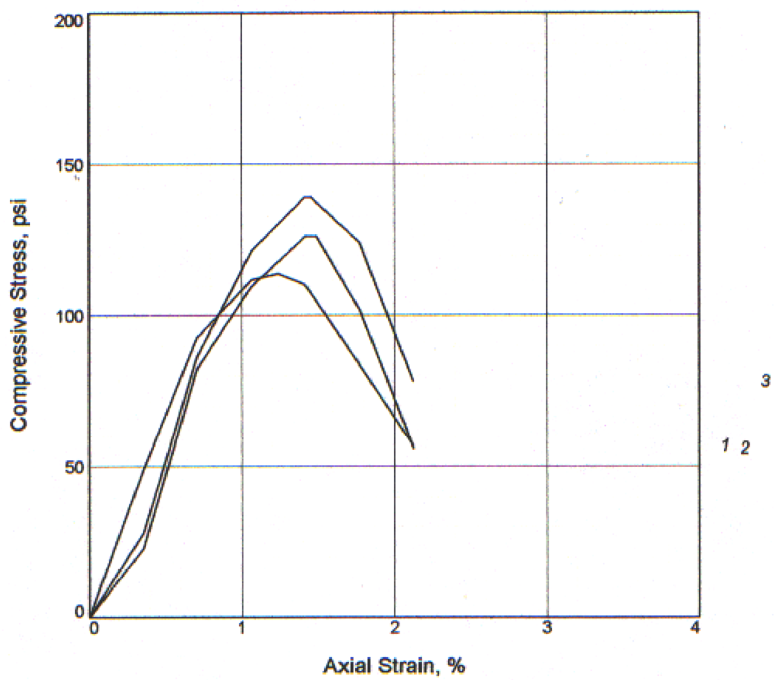
UNCONFINED COMPRESSION TEST
Oklahoma State University

Tested By: JU

Appendix C2

Treated Unconfined Compressive Strength Test Data

Figure C.3 10% CKD, 7 Day Cure



Sample No.	1	2	3	
Unconfined strength, psi	113.74	126.08	138.90	
Undrained shear strength, psi	56.87	63.04	69.45	
Failure strain,	1.2	1.4	1.5	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	17.9	17.9	17.6	
Wet density, pcf	124.1	124.3	124.5	
Dry density, pcf	105.2	105.5	105.8	
Saturation, %	78.0	78.3	78.0	
Void ratio	0.6317	0.6280	0.6221	
Specimen diameter, in.	1.31	1.31	1.32	
Specimen height, in.	2.83	2.82	2.83	
Height/diameter ratio	2.15	2.15	2.15	

Description: 10% CKD, 7 Day Cure

LL = 42.2	**PL =** 26.5	**PI =** 15.7	**Assumed GS=** 2.75	**Type:** CKD Treated

Project No.:
Date: 06/11/09
Remarks:
Figure C.3 10% CKD, 7 Day Cure
Unconfined Compression Test

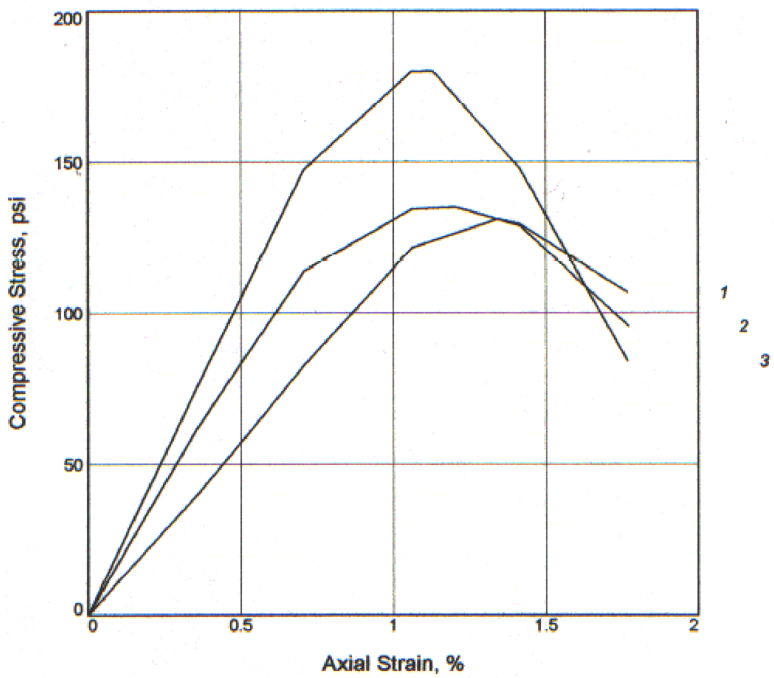
Client:
Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil
Location: US 77
Sample Number: 3

UNCONFINED COMPRESSION TEST
Oklahoma State University

Tested By: JU

Figure C.4 10% CKD, 28 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3
Unconfined strength, psi	131.10	134.95	180.16
Undrained shear strength, psi	65.55	67.47	90.08
Failure strain,	1.3	1.2	1.1
Strain rate, in./min.	0.03	0.03	0.03
Water content, %	17.1	16.9	17.2
Wet density, pcf	122.9	124.0	124.2
Dry density, pcf	105.0	106.0	106.0
Saturation, %	74.0	75.2	76.4
Void ratio	0.6350	0.6195	0.6200
Specimen diameter, in.	1.31	1.31	1.31
Specimen height, in.	2.83	2.83	2.83
Height/diameter ratio	2.16	2.16	2.16

Description: 10% CKD, 28 Day Cure

LL = 42.2 | **PL =** 26.5 | **PI =** 15.7 | **Assumed GS=** 2.75 | **Type:** CKD Treated

Project No.:

Date: 07/19/10

Remarks:
Figure C.4 10% CKD, 28 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 4

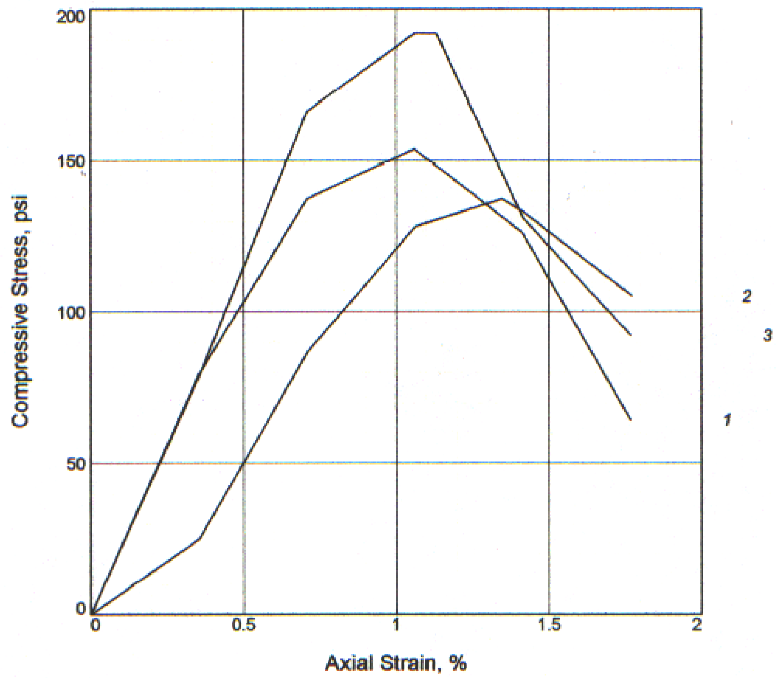
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.5 12% CKD, 7 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3
Unconfined strength, psi	153.69	137.26	191.97
Undrained shear strength, psi	76.84	68.63	95.98
Failure strain,	1.1	1.3	1.1
Strain rate, in./min.	0.03	0.03	0.03
Water content, %	17.1	17.1	17.1
Wet density, pcf	122.9	123.7	122.7
Dry density, pcf	105.0	105.6	104.7
Saturation, %	74.1	75.2	73.7
Void ratio	0.6357	0.6257	0.6391
Specimen diameter, in.	1.31	1.31	1.31
Specimen height, in.	2.83	2.82	2.83
Height/diameter ratio	2.16	2.15	2.15

Description: 12% CKD, 7 Day Cure

LL = 43.3 | **PL =** 28.3 | **PI =** 15.0 | **Assumed GS=** 2.75 | **Type:** CKD Treated

Project No.:
Date: 03/15/10
Remarks:
Figure C.5 12% CKD, 7 Day Cure
Unconfined Compression Test

Client:

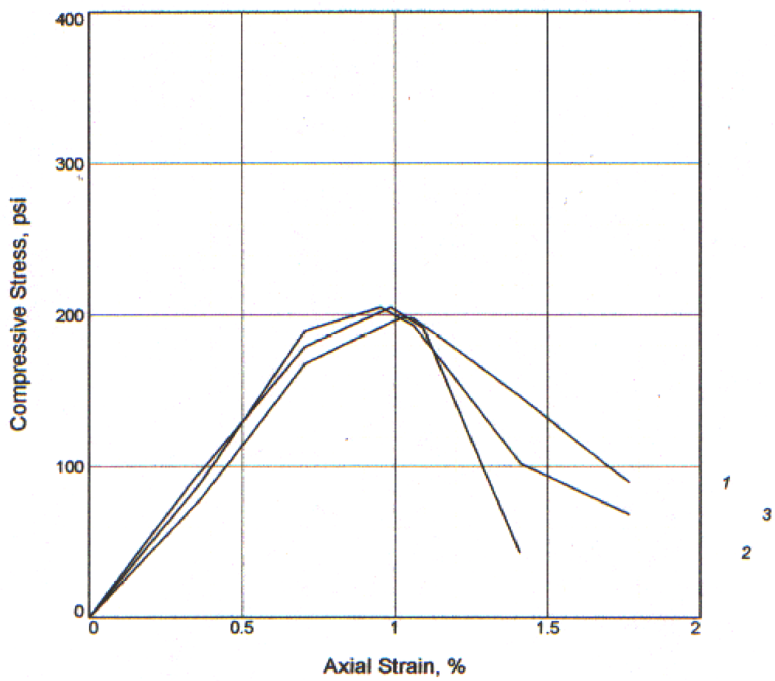
Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil
Location: US 77
Sample Number: 5

UNCONFINED COMPRESSION TEST
Oklahoma State University

Tested By: JU

Figure C.6 12% CKD, 28 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3	
Unconfined strength, psi	198.37	205.15	205.08	
Undrained shear strength, psi	99.19	102.58	102.54	
Failure strain,	1.0	1.0	1.0	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	16.8	16.7	16.9	
Wet density, pcf	121.8	121.5	122.3	
Dry density, pcf	104.3	104.1	104.6	
Saturation, %	71.5	70.8	72.3	
Void ratio	0.6459	0.6492	0.6407	
Specimen diameter, in.	1.31	1.31	1.31	
Specimen height, in.	2.83	2.84	2.83	
Height/diameter ratio	2.15	2.16	2.15	

Description: 12% CKD, 28 Day Cure

LL = 43.3	**PL =** 28.3	**PI =** 15.0	**Assumed GS=** 2.75	**Type:** CKD Treated

Project No.:
Date: 07/20/10
Remarks:
Figure C.6 12% CKD, 28 Day Cure
Unconfined Compression Test

Client:

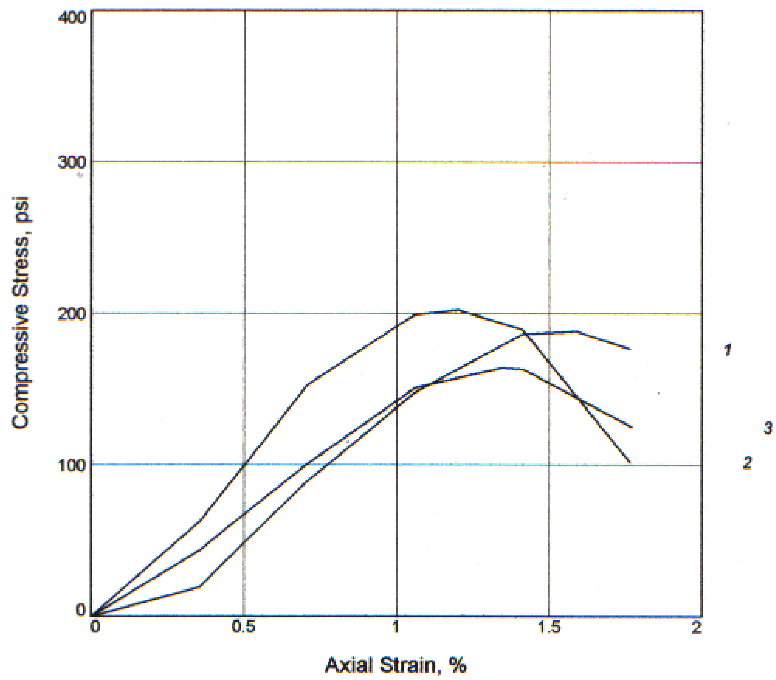
Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil
Location: US 77
Sample Number: 6

UNCONFINED COMPRESSION TEST
Oklahoma State University

Tested By: JU

Figure C.7 14% CKD, 7 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3	
Unconfined strength, psi	187.90	202.35	163.73	
Undrained shear strength, psi	93.95	101.17	81.87	
Failure strain,	1.6	1.2	1.3	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	19.1	19.2	19.2	
Wet density, pcf	124.2	124.1	124.6	
Dry density, pcf	104.3	104.1	104.5	
Saturation, %	81.3	81.3	82.2	
Void ratio	0.6463	0.6499	0.6427	
Specimen diameter, in.	1.32	1.32	1.31	
Specimen height, in.	2.83	2.83	2.83	
Height/diameter ratio	2.15	2.15	2.15	

Description: 14% CKD, 7 Day Cure

LL = 40.0 | **PL =** 28.4 | **PI =** 11.6 | **Assumed GS=** 2.75 | **Type:** CKD Treated

Project No.:

Date: 03/15/10

Remarks:
Figure C.7 14% CKD, 7 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 7

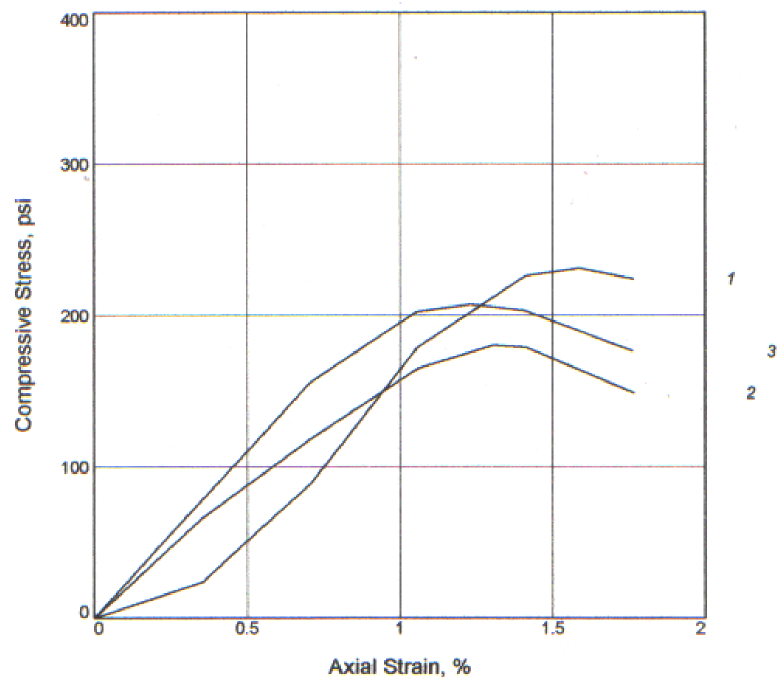
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.8 14% CKD, 28 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3	
Unconfined strength, psi	231.37	179.93	207.04	
Undrained shear strength, psi	115.68	89.96	103.52	
Failure strain,	1.6	1.3	1.2	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	19.8	19.6	19.6	
Wet density, pcf	124.8	124.2	124.0	
Dry density, pcf	104.2	103.8	103.7	
Saturation, %	84.1	82.6	82.3	
Void ratio	0.6482	0.6534	0.6557	
Specimen diameter, in.	1.31	1.31	1.31	
Specimen height, in.	2.83	2.83	2.84	
Height/diameter ratio	2.16	2.15	2.16	

Description: 14% CKD, 28 Day Cure

LL = 40.0 | **PL =** 28.4 | **PI =** 11.6 | **Assumed GS=** 2.75 | **Type:** CKD Treated

Project No.:

Date: 07/20/10

Remarks:
Figure C.8 14% CKD, 28 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 8

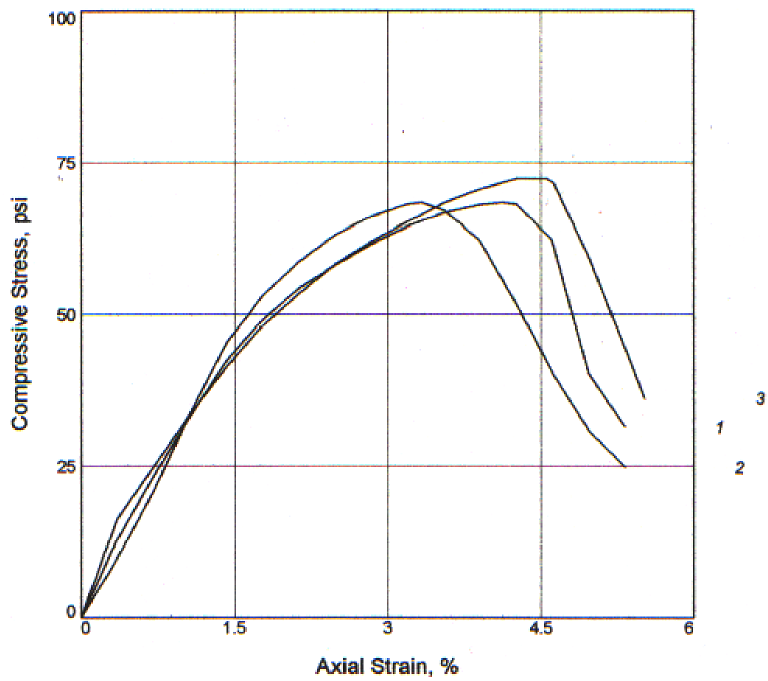
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.9 12% Fly Ash, 7 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3	
Unconfined strength, psi	68.43	68.40	72.32	
Undrained shear strength, psi	34.21	34.20	36.16	
Failure strain,	4.1	3.3	4.3	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	18.1	18.0	18.0	
Wet density, pcf	130.1	130.0	130.0	
Dry density, pcf	110.1	110.1	110.2	
Saturation, %	89.2	88.6	88.8	
Void ratio	0.5590	0.5586	0.5582	
Specimen diameter, in.	1.31	1.31	1.31	
Specimen height, in.	2.82	2.82	2.81	
Height/diameter ratio	2.16	2.16	2.15	

Description: 12% Fly Ash, 7 Day Cure

LL = 41.3	**PL =** 21.3	**PI =** 20.0	**Assumed GS=** 2.75	**Type:** Fly Ash Treated

Project No.:

Date: 08/04/10

Remarks:
Figure C.9 12% Fly Ash, 7 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

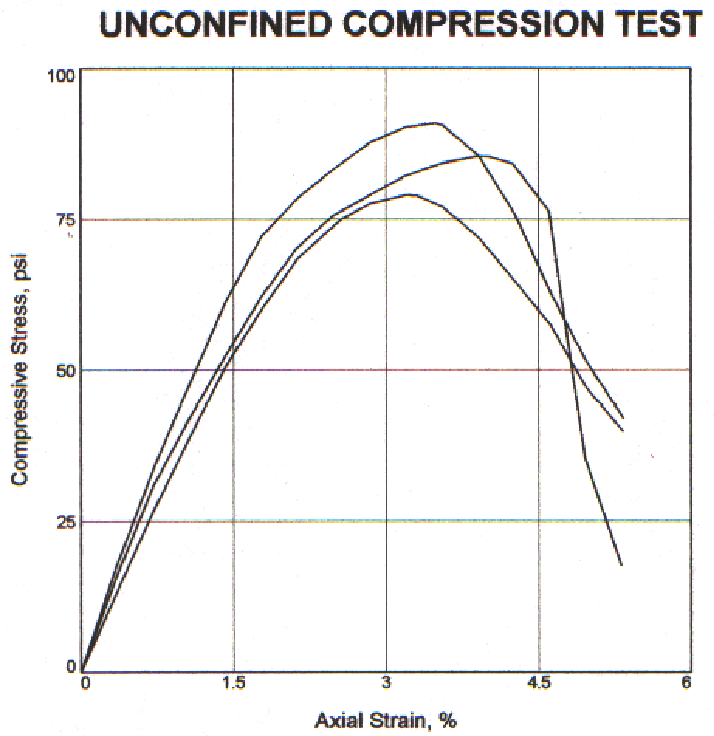
Sample Number: 9

UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.10 12% Fly Ash, 28 Day Cure



Sample No.	1	2	3	
Unconfined strength, psi	90.92	85.50	78.96	
Undrained shear strength, psi	45.46	42.75	39.48	
Failure strain,	3.5	3.9	3.2	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	17.4	17.9	17.7	
Wet density, pcf	130.6	130.0	130.3	
Dry density, pcf	111.2	110.3	110.7	
Saturation, %	88.2	88.4	88.6	
Void ratio	0.5436	0.5562	0.5508	
Specimen diameter, in.	1.30	1.30	1.30	
Specimen height, in.	2.81	2.83	2.81	
Height/diameter ratio	2.16	2.16	2.16	

Description: 12% Fly Ash, 28 Day Cure

LL = 41.3	**PL** = 21.3	**PI** = 20.0	**Assumed GS=** 2.75	**Type:** Fly Ash Treated

Project No.:
Date: 07/14/10
Remarks:
Figure C.10 12% Fly Ash, 28 Day Cure
Unconfined Compression Test

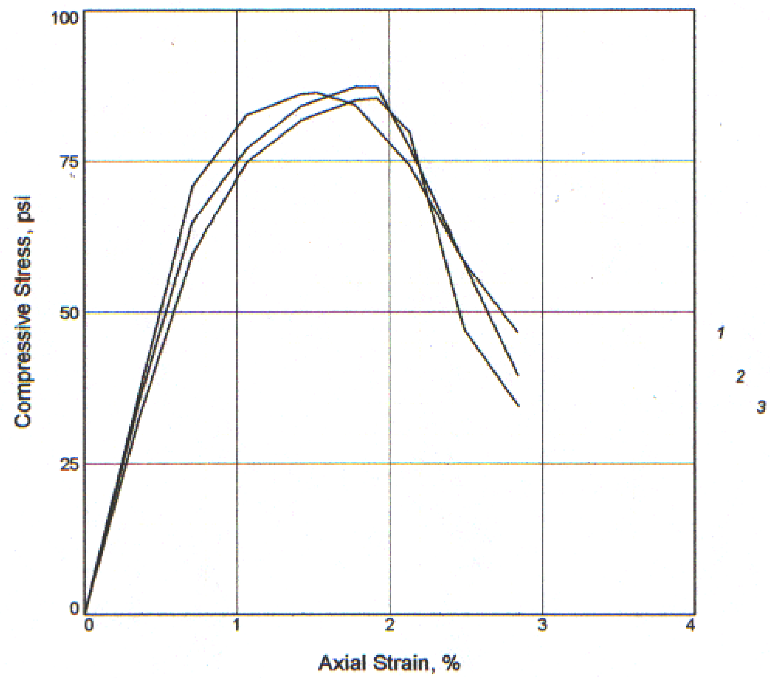
Client:
Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil
Location: US 77
Sample Number: 10

UNCONFINED COMPRESSION TEST
Oklahoma State University

Tested By: JU

Figure C.11 15% Fly Ash, 7 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3	
Unconfined strength, psi	86.38	87.37	85.43	
Undrained shear strength, psi	43.19	43.69	42.72	
Failure strain,	1.5	1.9	1.9	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	16.3	16.8	16.8	
Wet density, pcf	129.8	129.8	129.8	
Dry density, pcf	111.6	111.2	111.1	
Saturation, %	83.2	84.8	84.9	
Void ratio	0.5382	0.5444	0.5459	
Specimen diameter, in.	1.31	1.31	1.31	
Specimen height, in.	2.82	2.81	2.81	
Height/diameter ratio	2.16	2.15	2.15	

Description: 15% Fly Ash, 7 Day Cure

LL = 38.9	**PL =** 23.9	**PI =** 15.0	**Assumed GS=** 2.75	**Type:** Fly Ash Treated

Project No.:

Date: 03/16/10

Remarks:
Figure C.11 15% Fly Ash, 7 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 11

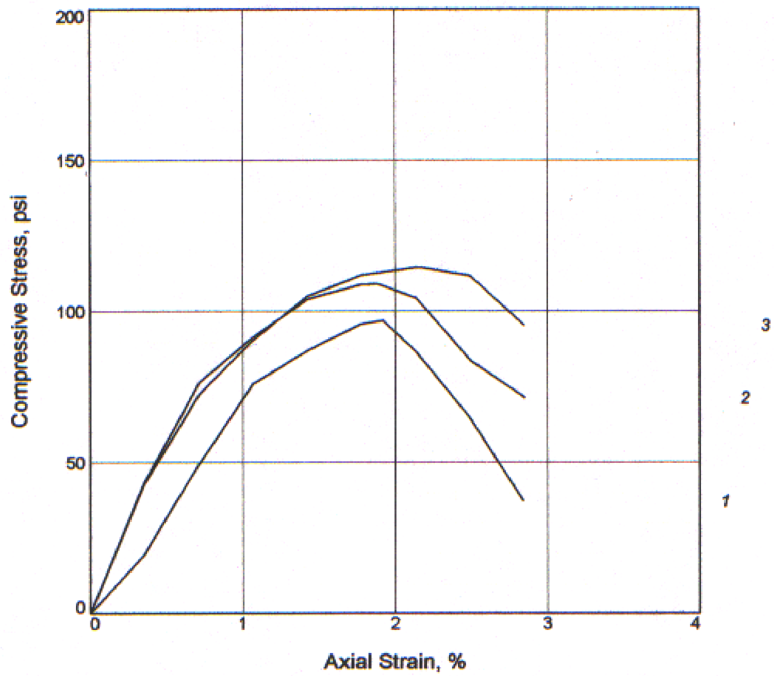
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.12 15% Fly Ash, 28 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3	
Unconfined strength, psi	96.71	109.12	114.46	
Undrained shear strength, psi	48.36	54.56	57.23	
Failure strain,	1.9	1.9	2.2	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	16.9	16.8	16.6	
Wet density, pcf	129.9	130.3	131.8	
Dry density, pcf	111.1	111.5	113.0	
Saturation, %	85.2	85.8	88.0	
Void ratio	0.5454	0.5397	0.5195	
Specimen diameter, in.	1.31	1.31	1.30	
Specimen height, in.	2.81	2.81	2.81	
Height/diameter ratio	2.15	2.14	2.15	

Description: 15% Fly Ash, 28 Day Cure

LL = 38.9	**PL =** 23.9	**PI =** 15.0	**Assumed GS=** 2.75	**Type:** Fly Ash Treated

Project No.:

Date: 07/16/10

Remarks:
Figure C.12 15% Fly Ash, 28 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 12

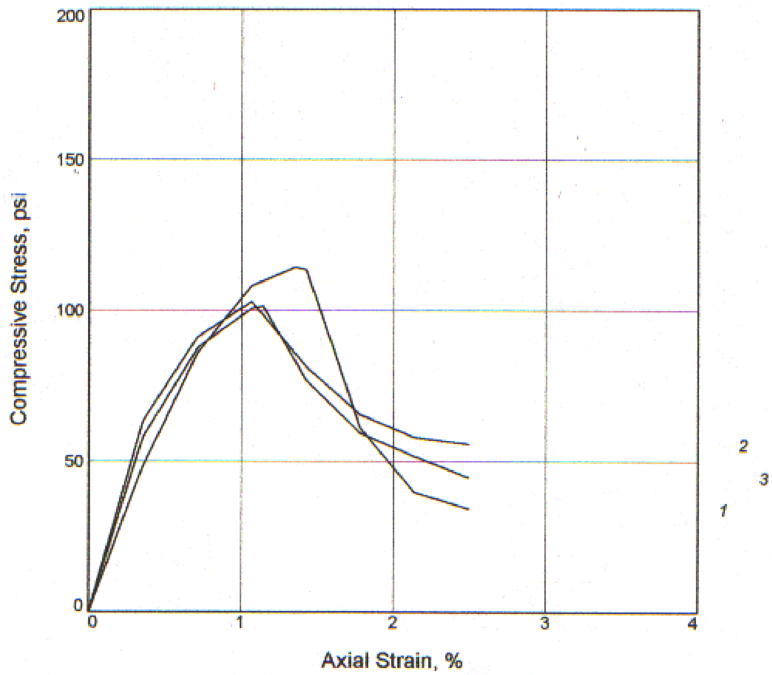
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.13 18% Fly Ash, 7 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3	
Unconfined strength, psi	114.45	102.87	101.38	
Undrained shear strength, psi	57.23	51.43	50.69	
Failure strain,	1.4	1.1	1.1	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	15.5	15.5	15.6	
Wet density, pcf	128.8	128.9	128.4	
Dry density, pcf	111.5	111.6	111.1	
Saturation, %	79.1	79.2	78.7	
Void ratio	0.5398	0.5382	0.5456	
Specimen diameter, in.	1.31	1.31	1.31	
Specimen height, in.	2.81	2.81	2.81	
Height/diameter ratio	2.15	2.15	2.15	

Description: 18% Fly Ash, 7 Day Cure

LL = 39.5 | **PL =** 24.5 | **PI =** 15.0 | **Assumed GS=** 2.75 | **Type:** Fly Ash Treated

Project No.:

Date: 03/15/10

Remarks:
Figure C.13 18% Fly Ash, 7 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

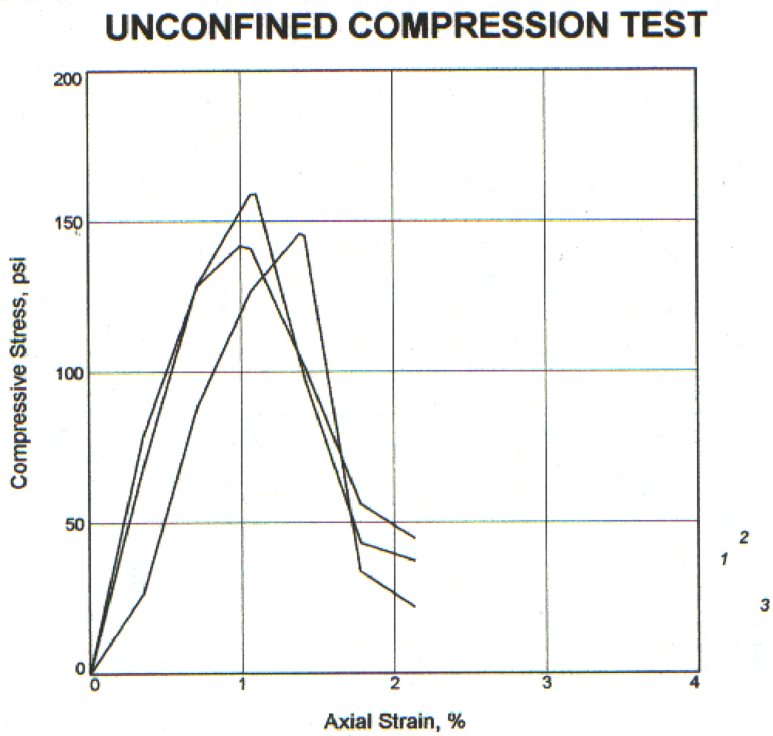
Sample Number: 13

UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.14 18% Fly Ash, 28 Day Cure



Sample No.	1	2	3	
Unconfined strength, psi	158.98	141.84	145.67	
Undrained shear strength, psi	79.49	70.92	72.84	
Failure strain,	1.1	1.0	1.4	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	14.9	15.1	15.0	
Wet density, pcf	128.4	127.7	128.4	
Dry density, pcf	111.8	110.9	111.7	
Saturation, %	76.3	75.8	76.7	
Void ratio	0.5362	0.5475	0.5368	
Specimen diameter, in.	1.31	1.31	1.31	
Specimen height, in.	2.81	2.81	2.81	
Height/diameter ratio	2.14	2.14	2.15	

Description: 18% Fly Ash, 28 Day Cure

LL = 39.5	**PL =** 24.5	**PI =** 15.0	**Assumed GS=** 2.75	**Type:** Fly Ash Treated

Project No.:

Date: 07/19/10

Remarks:
Figure C.14 18% Fly Ash, 28 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 14

UNCONFINED COMPRESSION TEST

Oklahoma State University

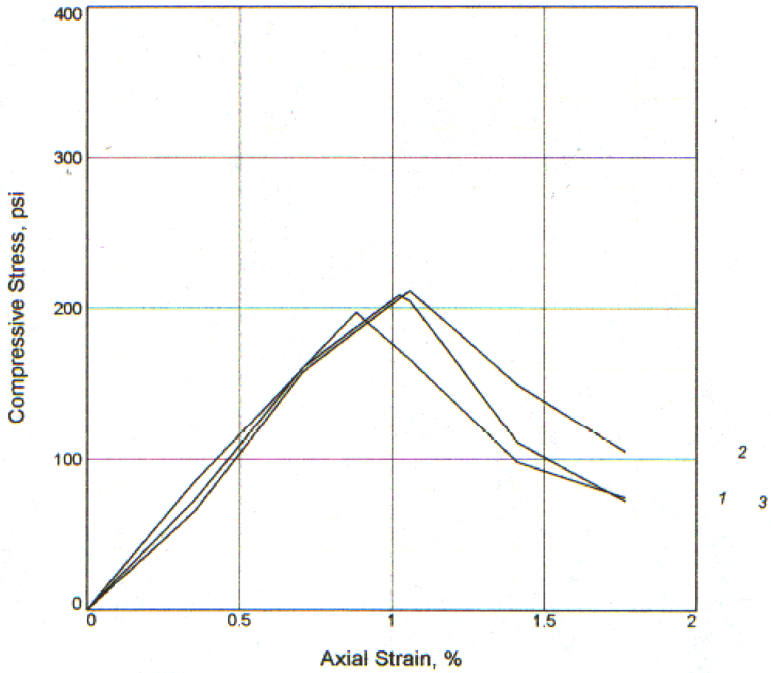
Tested By: JU

Appendix C3

Pretreated Unconfined Compressive Strength Test Data

Figure C.15 4% Lime + 10% CKD, 7 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3
Unconfined strength, psi	196.78	211.63	208.72
Undrained shear strength, psi	98.39	105.82	104.36
Failure strain,	0.9	1.1	1.0
Strain rate, in./min.	0.03	0.03	0.03
Water content, %	20.0	20.6	20.7
Wet density, pcf	118.1	117.5	117.8
Dry density, pcf	98.4	97.4	97.6
Saturation, %	74.0	74.3	74.9
Void ratio	0.7448	0.7623	0.7585
Specimen diameter, in.	1.31	1.31	1.31
Specimen height, in.	2.83	2.83	2.83
Height/diameter ratio	2.16	2.16	2.15

Description: 4% Lime + 10% CKD, 7 Day Cure

LL = 37.5	**PL =** 30.8	**PI =** 6.7	**Assumed GS=** 2.75	**Type:** Lime Pretreated / CKD Treated

Project No.:

Date: 06/12/09

Remarks:
Figure C.15 4% Lime + 10% CKD,
7 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 15

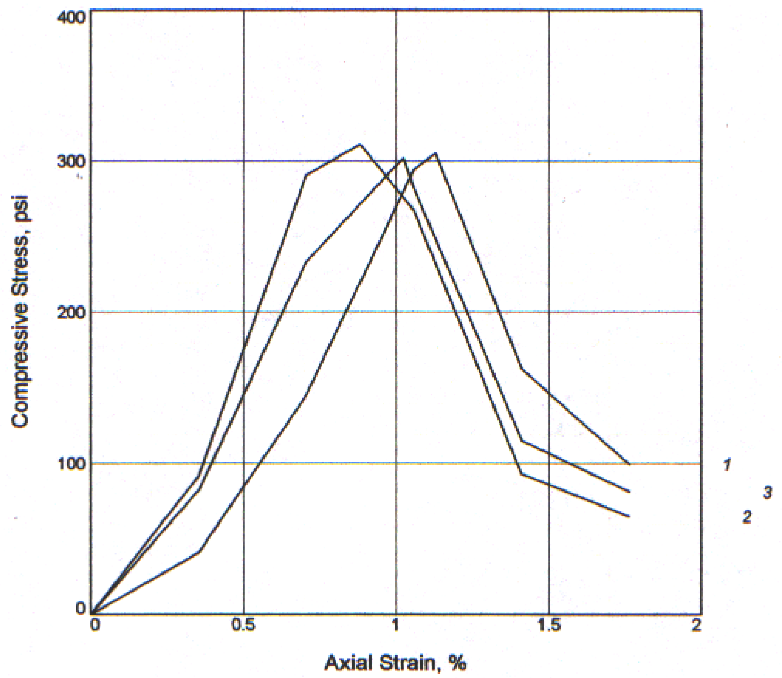
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.16 4% Lime + 10% CKD, 28 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3	
Unconfined strength, psi	305.18	310.76	302.07	
Undrained shear strength, psi	152.59	155.38	151.03	
Failure strain,	1.1	0.9	1.0	
Strain rate, in./min.	0.03	0.03	0.03	
Water content, %	20.5	20.0	19.7	
Wet density, pcf	118.2	118.0	118.4	
Dry density, pcf	98.1	98.3	98.9	
Saturation, %	75.3	73.6	73.7	
Void ratio	0.7504	0.7459	0.7357	
Specimen diameter, in.	1.31	1.31	1.31	
Specimen height, in.	2.83	2.84	2.83	
Height/diameter ratio	2.16	2.16	2.16	

Description: 4% Lime + 10% CKD, 28 Day Cure

LL = 37.5	**PL =** 30.8	**PI =** 6.7	**Assumed GS=** 2.75	**Type:** Lime Pretreated / CKD Treated

Project No.:
Date: 07/21/10
Remarks:
Figure C.16 4% Lime + 10% CKD,
28 Day Cure
Unconfined Compression Test

Client:

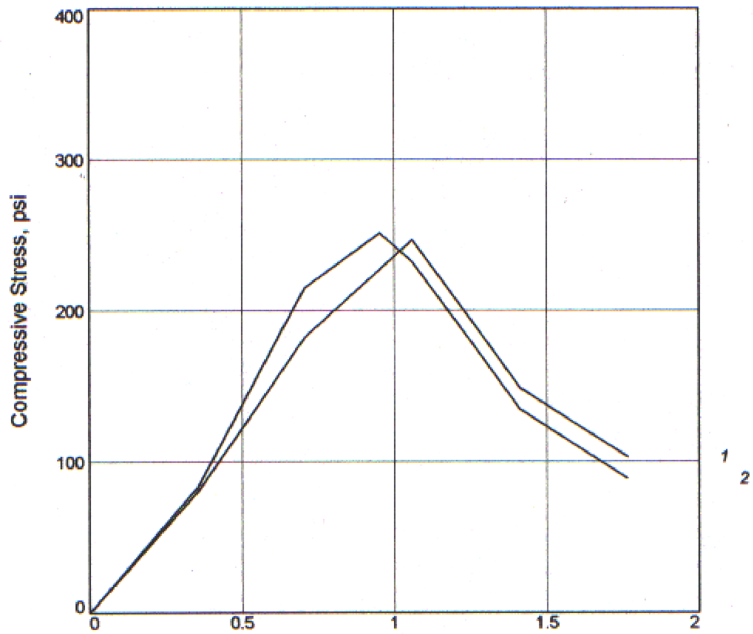
Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil
Location: US 77
Sample Number: 16

UNCONFINED COMPRESSION TEST
Oklahoma State University

Tested By: JU

Figure C.17 4% Lime + 12% CKD, 7 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2		
Unconfined strength, psi	247.11	251.59		
Undrained shear strength, psi	123.55	125.79		
Failure strain,	1.1	1.0		
Strain rate, in./min.	0.03	0.03		
Water content, %	21.4	21.0		
Wet density, pcf	118.2	118.0		
Dry density, pcf	97.3	97.5		
Saturation, %	77.1	76.0		
Void ratio	0.7639	0.7616		
Specimen diameter, in.	1.31	1.32		
Specimen height, in.	2.83	2.83		
Height/diameter ratio	2.15	2.15		

Description: 4% Lime + 12% CKD, 7 Day Cure

LL =	**PL =**	**PI =**	**Assumed GS=** 2.75	**Type:** Lime Pretreated / CKD Treated

Project No.:

Date: 08/25/10

Remarks:
Figure C.17 4% Lime + 12% CKD,
7 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 17

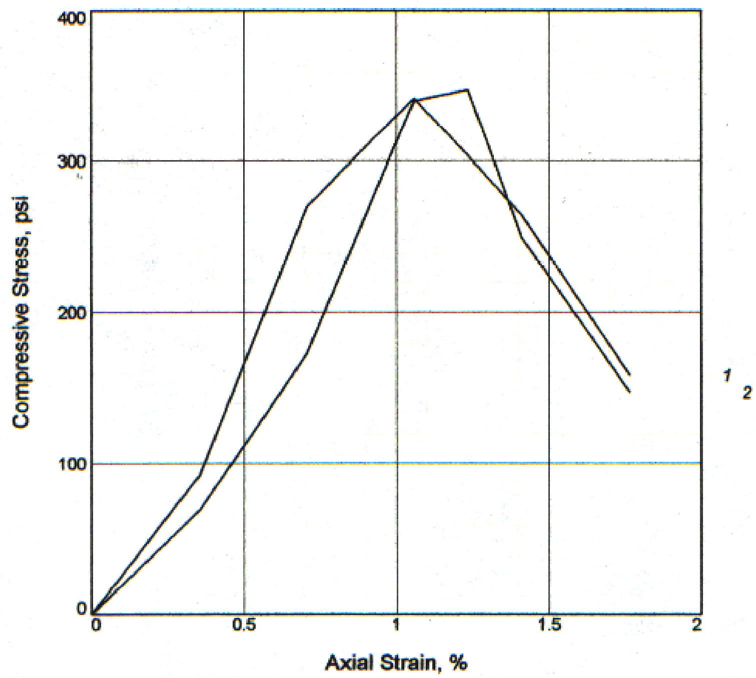
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.18 4% Lime + 12% CKD, 28 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2		
Unconfined strength, psi	342.04	347.64		
Undrained shear strength, psi	171.02	173.82		
Failure strain,	1.1	1.2		
Strain rate, in./min.	0.03	0.03		
Water content, %	21.6	21.6		
Wet density, pcf	118.5	117.4		
Dry density, pcf	97.5	96.6		
Saturation, %	77.9	76.2		
Void ratio	0.7616	0.7777		
Specimen diameter, in.	1.31	1.32		
Specimen height, in.	2.83	2.83		
Height/diameter ratio	2.16	2.15		

Description: 4% Lime + 12% CKD, 28 Day Cure

LL =	PL =	PI =	Assumed GS= 2.75	Type: Lime Pretreated / CKD Treated

Project No.:

Date: 09/15/10

Remarks:
Figure C.18 4% Lime + 12% CKD,
28 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 18

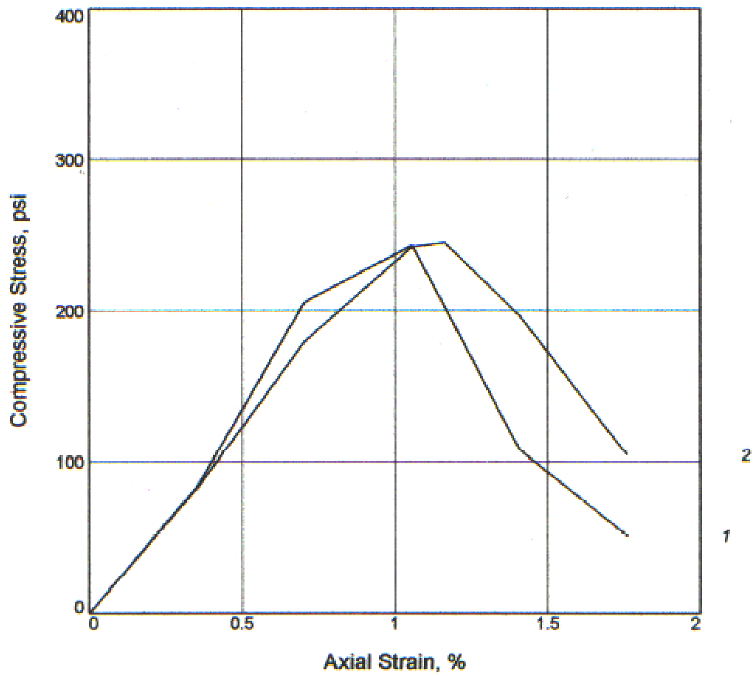
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.19 4% Lime + 14% CKD, 7 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2		
Unconfined strength, psi	243.70	245.55		
Undrained shear strength, psi	121.85	122.77		
Failure strain,	1.1	1.2		
Strain rate, in./min.	0.03	0.03		
Water content, %	22.0	22.4		
Wet density, pcf	119.0	118.9		
Dry density, pcf	97.6	97.2		
Saturation, %	79.7	80.3		
Void ratio	0.7599	0.7665		
Specimen diameter, in.	1.31	1.31		
Specimen height, in.	2.84	2.84		
Height/diameter ratio	2.16	2.16		

Description: 4% Lime + 14% CKD, 7 Day Cure

LL = **PL =** **PI =** **Assumed GS=** 2.75 **Type:** Lime Pretreated / CKD Treated

Project No.:
Date: 08/25/10
Remarks:
Figure C.19 4% Lime + 14% CKD,
7 Day Cure
Unconfined Compression Test

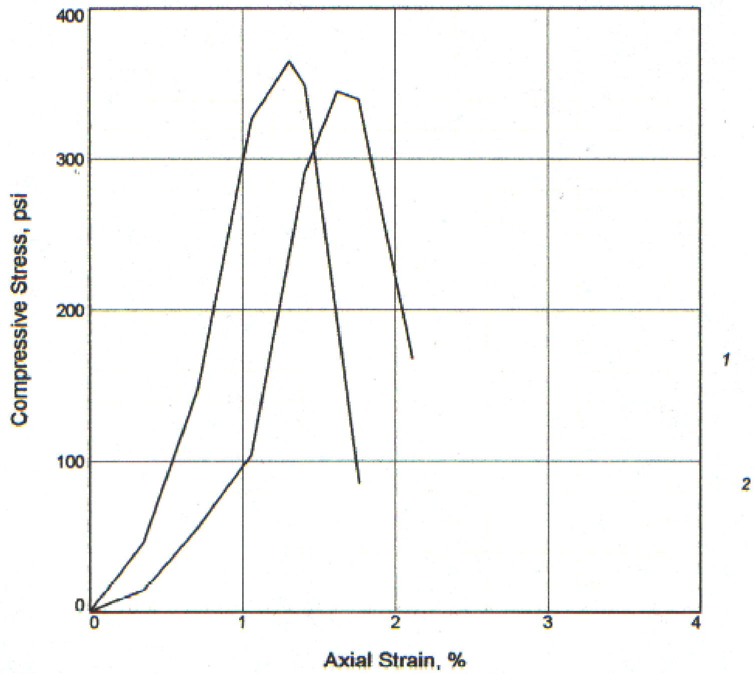
Client:
Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil
Location: US 77
Sample Number: 19

UNCONFINED COMPRESSION TEST
Oklahoma State University

Tested By: JU

Figure C.20 4% Lime + 14% CKD, 28 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2		
Unconfined strength, psi	344.82	365.17		
Undrained shear strength, psi	172.41	182.58		
Failure strain,	1.6	1.3		
Strain rate, in./min.	0.03	0.03		
Water content, %	22.3	22.3		
Wet density, pcf	118.7	119.3		
Dry density, pcf	97.0	97.5		
Saturation, %	79.7	80.8		
Void ratio	0.7691	0.7610		
Specimen diameter, in.	1.32	1.32		
Specimen height, in.	2.84	2.83		
Height/diameter ratio	2.15	2.15		

Description: 4% Lime + 14% CKD, 28 Day Cure

LL =	PL =	PI =	Assumed GS= 2.75	Type: Lime Pretreated / CKD Treated

Project No.:

Date: 09/15/10

Remarks:
Figure C.20 4% Lime + 14% CKD,
28 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 20

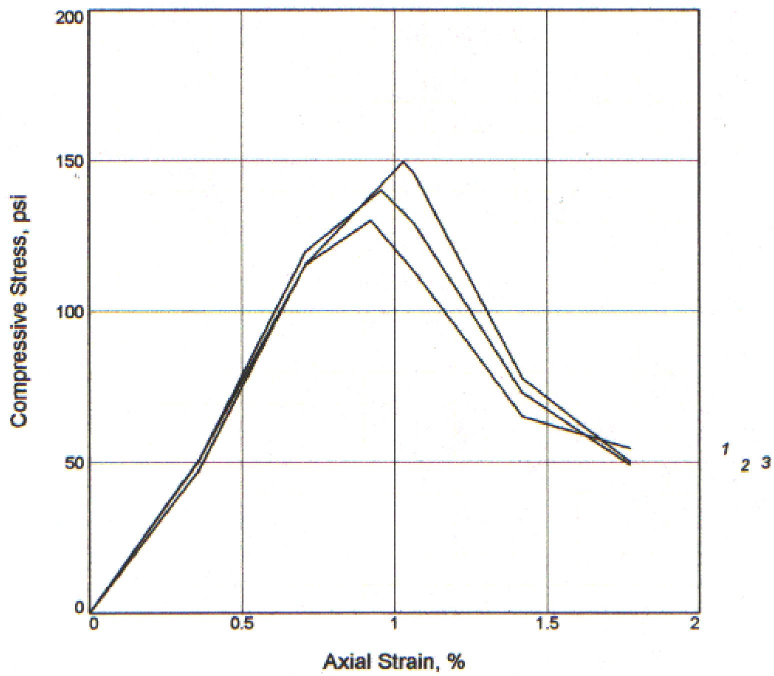
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.21 4% Lime + 12% Fly Ash, 7 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3
Unconfined strength, psi	130.19	140.13	149.43
Undrained shear strength, psi	65.09	70.07	74.72
Failure strain,	0.9	1.0	1.0
Strain rate, in./min.	0.03	0.03	0.03
Water content, %	19.0	18.8	18.9
Wet density, pcf	120.5	120.6	121.5
Dry density, pcf	101.3	101.6	102.2
Saturation, %	75.2	74.8	76.5
Void ratio	0.6953	0.6900	0.6796
Specimen diameter, in.	1.31	1.31	1.31
Specimen height, in.	2.82	2.82	2.82
Height/diameter ratio	2.15	2.15	2.15

Description: 4% Lime + 12% Fly Ash, 7 Day Cure

LL = 36.0 | **PL =** 28.3 | **PI =** 7.7 | **Assumed GS=** 2.75 | **Type:** Lime Pretreated / Fly Ash Trea

Project No.:

Date: 06/12/10

Remarks:
Figure C.21 4% Lime + 12% Fly Ash,
7 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 21

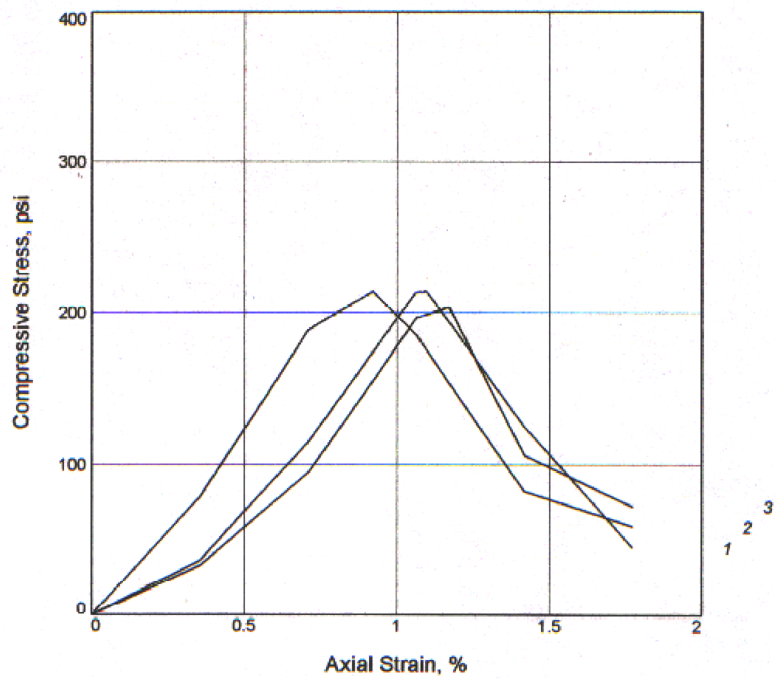
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.22 4% Lime + 12% Fly Ash, 28 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2	3
Unconfined strength, psi	213.91	213.82	203.83
Undrained shear strength, psi	106.95	106.91	101.91
Failure strain,	1.1	0.9	1.2
Strain rate, in./min.	0.03	0.03	0.03
Water content, %	19.0	18.8	18.9
Wet density, pcf	121.7	121.6	121.9
Dry density, pcf	102.3	102.3	102.5
Saturation, %	76.9	76.4	76.9
Void ratio	0.6789	0.6780	0.6741
Specimen diameter, in.	1.31	1.31	1.31
Specimen height, in.	2.83	2.82	2.82
Height/diameter ratio	2.15	2.15	2.15

Description: 4% Lime + 12% Fly Ash, 28 Day Cure

LL = 36.0	**PL =** 28.3	**PI =** 7.7	**Assumed GS=** 2.75	**Type:** Lime Pretreated / Fly Ash Trea

Project No.:
Date: 07/21/10
Remarks:
Figure C.22 4% Lime + 12% Fly Ash,
28 Day Cure
Unconfined Compression Test

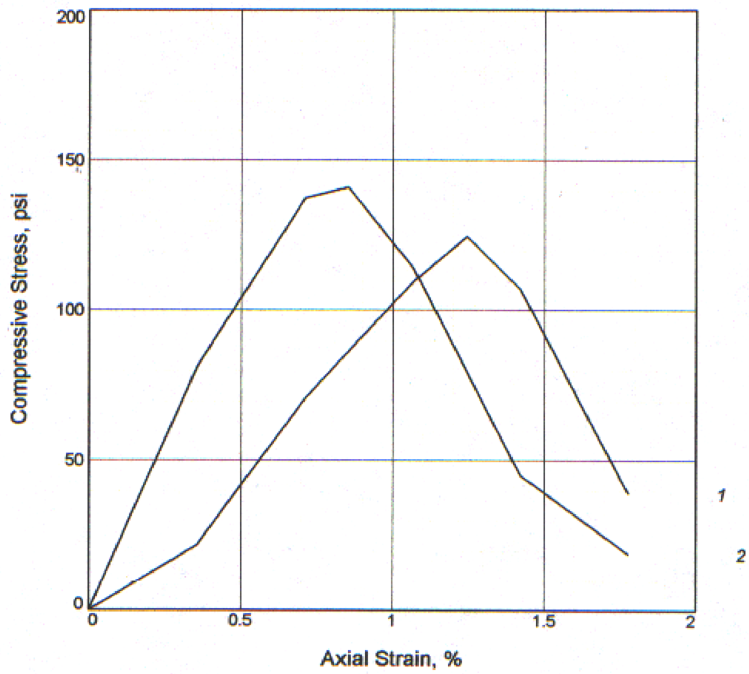
Client:
Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil
Location: US 77
Sample Number: 22

UNCONFINED COMPRESSION TEST
Oklahoma State University

Tested By: JU

Figure C.23 4% Lime + 15% Fly Ash

UNCONFINED COMPRESSION TEST



Sample No.	1	2		
Unconfined strength, psi	124.79	140.88		
Undrained shear strength, psi	62.40	70.44		
Failure strain,	1.2	0.9		
Strain rate, in./min.	0.03	0.03		
Water content, %	18.4	18.6		
Wet density, pcf	119.6	120.0		
Dry density, pcf	101.0	101.2		
Saturation, %	72.4	73.5		
Void ratio	0.6992	0.6969		
Specimen diameter, in.	1.31	1.31		
Specimen height, in.	2.81	2.81		
Height/diameter ratio	2.14	2.15		

Description: 4% Lime + 15% Fly Ash, 7 Day Cure

LL =	PL =	PI =	Assumed GS= 2.75	Type: Lime Pretreated / Fly Ash Trea

Project No.:

Date: 08/27/10

Remarks:
Figure C.23 4% Lime + 15% Fly Ash,
7 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 23

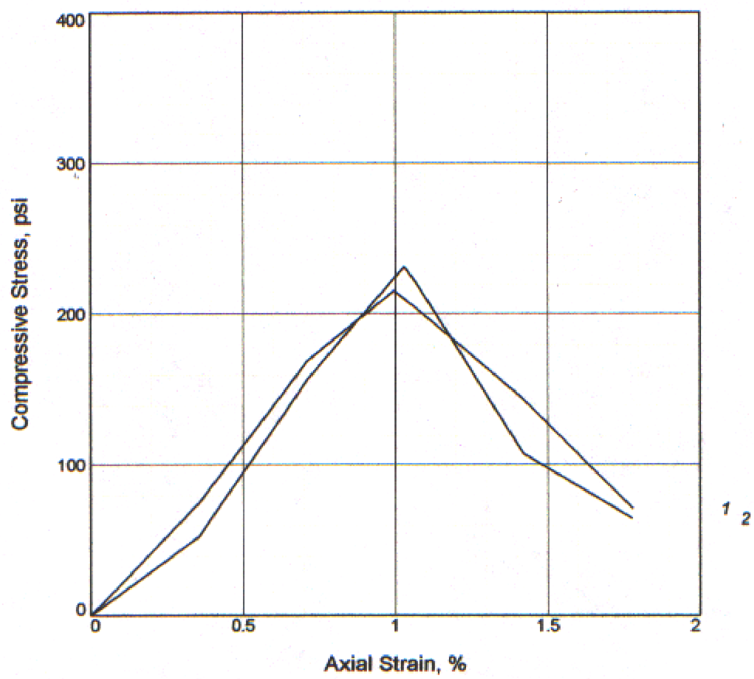
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.24 4% Lime + 15% Fly Ash, 28 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2		
Unconfined strength, psi	214.97	231.45		
Undrained shear strength, psi	107.49	115.73		
Failure strain,	1.0	1.0		
Strain rate, in./min.	0.03	0.03		
Water content, %	19.0	19.0		
Wet density, pcf	120.6	120.6		
Dry density, pcf	101.3	101.3		
Saturation, %	75.2	75.4		
Void ratio	0.6943	0.6946		
Specimen diameter, in.	1.31	1.31		
Specimen height, in.	2.81	2.82		
Height/diameter ratio	2.14	2.15		

Description: 4% Lime + 15% Fly Ash, 28 Day Cure

LL =	PL =	PI =	Assumed GS= 2.75	Type: Lime Pretreated / Fly Ash Trea

Project No.:

Date: 09/17/10

Remarks:
Figure C.24 4% Lime + 15% Fly Ash,
28 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US77

Sample Number: 24

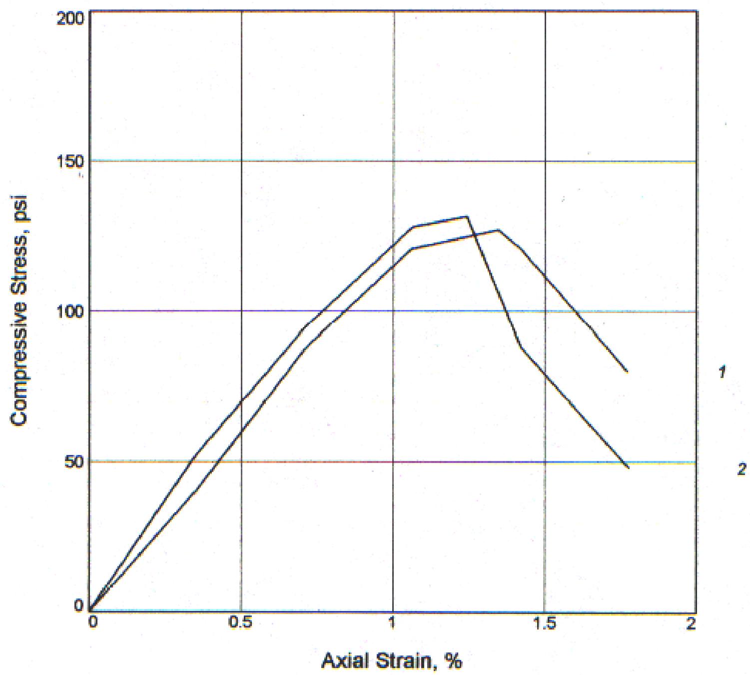
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.25 4% Lime + 18% Fly Ash, 7 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2		
Unconfined strength, psi	127.26	131.74		
Undrained shear strength, psi	63.63	65.87		
Failure strain,	1.3	1.2		
Strain rate, in./min.	0.03	0.03		
Water content, %	20.2	19.6		
Wet density, pcf	122.9	123.6		
Dry density, pcf	102.2	103.3		
Saturation, %	81.9	81.6		
Void ratio	0.6797	0.6614		
Specimen diameter, in.	1.31	1.31		
Specimen height, in.	2.83	2.82		
Height/diameter ratio	2.15	2.15		

Description: 4% Lime + 18% Fly Ash, 7 Day Cure

LL =	PL =	PI =	Assumed GS= 2.75	Type: Lime Pretreated / Fly Ash Trea

Project No.:

Date: 08/27/10

Remarks:
Figure C.25 4% Lime + 18% Fly Ash,
7 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 25

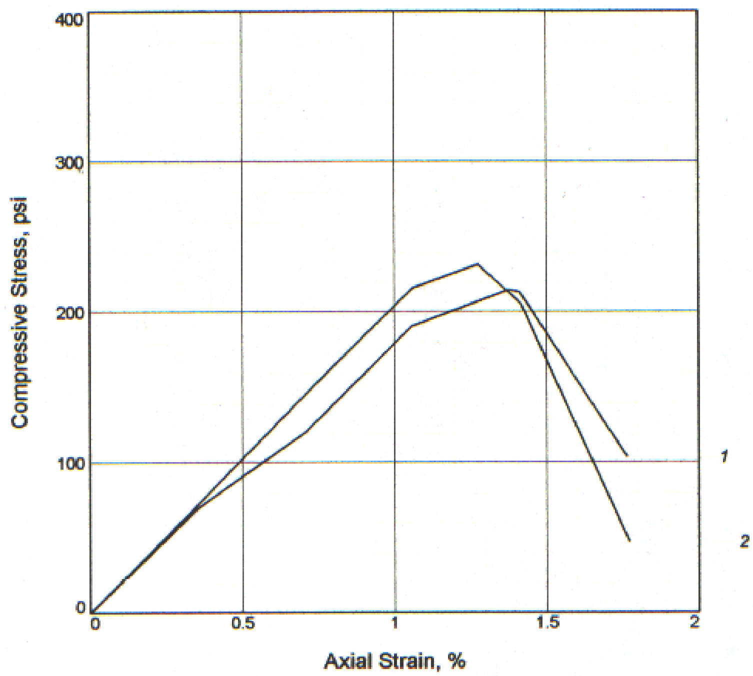
UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

Figure C.26 4% Lime + 18% Fly Ash, 28 Day Cure

UNCONFINED COMPRESSION TEST



Sample No.	1	2		
Unconfined strength, psi	214.47	231.44		
Undrained shear strength, psi	107.24	115.72		
Failure strain,	1.4	1.3		
Strain rate, in./min.	0.03	0.03		
Water content, %	20.0	20.0		
Wet density, pcf	123.2	122.5		
Dry density, pcf	102.7	102.1		
Saturation, %	82.0	80.7		
Void ratio	0.6722	0.6813		
Specimen diameter, in.	1.31	1.31		
Specimen height, in.	2.83	2.83		
Height/diameter ratio	2.16	2.15		

Description: 4% Lime + 18% Fly Ash, 28 Day Cure

LL =	PL =	PI =	Assumed GS= 2.75	Type: Lime Pretreated / Fly Ash Trea

Project No.:

Date: 09/17/10

Remarks:
Figure C.26 4% Lime + 18% Fly Ash, 28 Day Cure
Unconfined Compression Test

Client:

Project: Evaluation of Lime Pretreatment for Cementitious Stabilization of High Plasticity Soil

Location: US 77

Sample Number: 26

UNCONFINED COMPRESSION TEST

Oklahoma State University

Tested By: JU

VITA

Jason T. Unruh

Candidate for the Degree of

Master of Science

Thesis: EVALUATION OF LIME PRETREATMENT FOR CEMENTITIOUS STABILIZATION OF HIGH PLASTICITY SOIL

Major Field: Civil Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in December, 2010.

Completed the requirements for the Bachelor of Science in Biosystems Engineering at Oklahoma State University, Stillwater, Oklahoma in July, 2008.

Experience:

Undergraduate/Graduate Research Assistant, Department of Civil Engineering, Oklahoma State University, January 2007 to August 2009.

Name: Jason T. Unruh Date of Degree: December, 2010

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: EVALUATION OF LIME PRETREATMENT FOR CEMENTITIOUS STABILIZATION OF HIGH PLASTICITY SOIL

Pages in Study: 89 Candidate for the Degree of Master of Science

Major Field: Civil Engineering

Scope and Method of Study:

This research covers the effects of CKD, fly ash, lime and CKD, and lime and fly ash on a high plasticity soil. Three percentages of CKD and fly ash along with a single percentage of lime with a percentage of CKD and fly ash was evaluated. The evaluation of each treatment included laboratory testing to determine the plasticity, shrink-swell potential, and strength characteristics of the soil and chemical combinations. The untreated soil was evaluated to create a base line for the properties. The results of the laboratory testing for each treatment (type and percentage) were compared against the untreated soil and that of similar chemical additive type.

Findings and Conclusions:

Stabilization of high plastic soils with lime as a pretreatment and CKD or fly ash as a secondary treatment is more effective for improving the engineering properties of a soil than using a single treatment like CKD or fly ash alone. Pretreatment of an A-6 soil improves the soil by: decreasing the plasticity; decreasing the BLS; and increasing the UCS.

ADVISER'S APPROVAL: Dr. Donald R. Snethen