EFFICACY OF ROAD BOND EN1 AND CONDOR SS AS SOIL STABILIZERS

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16. ABSTRACT

The Oklahoma Department of Transportation (ODOT) uses lime-based stabilizers including quick lime, hydrated lime, Class C fly ash (CFA) and cement kiln dust (CKD) to increase bearing capacity of fine-grained subgrade soils within the state of Oklahoma. Lime, CFA, and CKD have been successfully used as soil stabilizers; however, lime-based stabilizers may react negatively when mixed with sulfate bearing soils which are prevalent in Oklahoma. In an effort to remedy the issues with sulfate bearing and non-sulfate bearing soils, multiple companies have developed alternative additives to the commonly used lime-based additives. Two companies, Earth Science Products and C.S.S Technology, Inc. have produced the acid based chemical additives Condor SS and Roadbond EN 1, respectively. The goal of this research was to determine how Condor SS and Roadbond EN 1 perform relative to lime and fly ash additives in sulfate and non-sulfate bearing clayey soils found within the state of Oklahoma. The approach for this project was to test the two aforementioned chemical additives against lime and fly ash additives according to the test methods outlined in ASTM D 4609 with three different soils from Oklahoma, one of which contained significant levels of soluble sulfate. The main test used to evaluate the two chemical stabilizers was the unconfined compression test (UCT) to evaluate strength gains from the stabilizer and free swell oedometer test to gauge whether chemical addition decreased swelling potential or swelling pressure. Roadbond EN1 and Condor SS did not substantially increase the unconfined compressive strength (UCS) of any of the soils tested nor meet the requirements of ASTM D 4609 per OHD L-50. Roadbond EN1 and Condor SS did not appear to have a significant effect on the liquid limit, plastic limit, or plasticity index of any of the soils tested. The swelling potential of the soils tested were not reduced by the addition of Roadbond EN1 or Condor SS. While increases in UCS were not substantial, there was some noted improvement in the 28-day UCS in the sulfate bearing soil with Roadbond EN1 and Condor SS. In addition, these additives did not produce adverse swelling reactions as noted for fly ash and lime in this soil.

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APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
in	Inches	25.4	millimeters	mm
ft	Feet	0.305	meters	m
yd	Yards	0.914	meters	m
mi	Miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	Acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	Gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	Ounces	28.35	grams	g
lb	Pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	pound force	4.45	newtons	N
lbf/in^2	pound force per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
mm	millimeters	0.039	inches	in
m	Meters	3.28	feet	ft
m	Meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	Liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	Grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF
ILLUMINATION				
lx	Lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	pound force	lbf
kPa	kilopascals	0.145	pound force per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Disclaimer

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Summary

The Oklahoma Department of Transportation (ODOT) uses lime-based stabilizers including quick lime, hydrated lime, Class C fly ash (CFA) and cement kiln dust (CKD) to increase bearing capacity of fine-grained subgrade soils within the state of Oklahoma. Lime, CFA, and CKD have been successfully used as soil stabilizers; however, lime-based stabilizers may react negatively when mixed with sulfate bearing soils which are prevalent in Oklahoma. In an effort to remedy the issues with sulfate bearing and non-sulfate bearing soils, multiple companies have developed alternative additives to the commonly used lime-based additives. Two companies, Earth Science Products and C.S.S Technology, Inc. have produced the acid based chemical additives Condor SS and Roadbond EN 1, respectively. The goal of this research was to determine how Condor SS and Roadbond EN 1 perform relative to lime and fly ash additives in sulfate and non-sulfate bearing clayey soils found within the state of Oklahoma. The approach for this project was to test the two aforementioned chemical additives against lime and fly ash additives according to the test methods outlined in ASTM D 4609 with three different soils from Oklahoma, one of which contained significant levels of soluble sulfate. The main test used to evaluate the two chemical stabilizers was the unconfined compression test (UCT) to evaluate strength gains from the stabilizer and free swell oedometer test to gauge whether chemical addition decreased swelling potential or swelling pressure. Roadbond EN1 and Condor SS did not significantly increase the unconfined compressive strength (UCS) of any of the soils tested nor meet the recommended performance measures of ASTM D 4609 per OHD L-50. Roadbond EN1 and Condor SS did not appear to have a significant effect on the liquid limit, plastic limit, or plasticity index of any of the soils tested. The swelling potential of the soils tested was not reduced by the addition of Roadbond EN1 or Condor SS. While increases in UCS were not substantial, there was some noted improvement in the 28-day UCS in the sulfate bearing soil with Roadbond EN1 and Condor SS. In addition, these additives did not produce adverse swelling reactions as noted for fly ash and lime in this soil.

INTRODUCTION

The Oklahoma Department of Transportation (ODOT) uses lime-based stabilizers including quick lime, hydrated lime, Class C fly ash (CFA) and cement kiln dust (CKD) to increase bearing capacity of fine-grained subgrade soils within the state of Oklahoma. Lime, CFA, and CKD have been successfully used as soil stabilizers; however, lime based stabilizers may react negatively when mixed with sulfate bearing soils which are prevalent in Oklahoma. In an effort to remedy the issues with sulfate bearing and non-sulfate bearing soils, multiple companies have developed alternative additives to the commonly used lime based additives. Two companies, Earth Science Products and C.S.S Technology, Inc. have produced the chemical additives Condor SS and Roadbond EN 1, respectively. The approach for this project was to test the performance of the two aforementioned chemicals and compare those with lime and fly ash additives according to the standard test method for evaluating admixtures (ASTM D 4609). The goal of this research was to determine if Condor SS and or Roadbond EN 1 can be used as an alternative to lime or fly ash additives in selected sulfate and non-sulfate bearing clayey soils found within the state of Oklahoma.

1.1 Overview of Study

To determine the efficacy of Condor SS and Roadbond EN1 as chemical stabilizers for some soils found within Oklahoma, a series of unconfined compression tests (UCTs) have been conducted utilizing the Harvard Miniature

Apparatus. Overall, 324 specimens were made using the Harvard Miniature Apparatus with different soil-chemical combinations to provide a range of results over two curing times. Of the 324 specimens made only about half were tested to determine the strength gains, if any, from the mixtures as described in depth in Chapter 3 of this report. The other half was used to examine the resistance of samples to soaking in water per ASTM D 4609. The swelling potential was investigated by oedometer testing by conducting 13 free swell tests on the various soil-chemical combinations.

1.2 Objectives of Study

The objective of this study was to determine if the chemical stabilizers, Condor SS and Roadbond EN1, can effectively stabilize three typical clayey soils found within Oklahoma; one of which contained significant sulfate. A suitable soil stabilizer will generally have the ability to increase the unconfined compression strength (UCS), decrease the plasticity, and decrease the swell and shrinkage potential of the soil.

There were five main tasks of this study:

1) Determine the UCS, index properties, and swell potential of two plastic soils ($25<PI<35$) as well as a sulfate bearing soil.
2) Determine the UCS of the three aforementioned soils mixed with both Condor SS and Roadbond EN 1 at three different application concentrations. Also, determine the UCS of the three soils when mixed with fly ash or lime, whichever was applicable for stabilization according to OHD-L50 (ODOT 2009).

3) Determine the effect of the chemical additives on Atterberg limits of the soil (plastic and liquid limit, plasticity index).
4) Determine the effect of the chemical additives on the swelling potential, swelling pressure, and compressibility properties of the three aforementioned soils.
5) Investigate the soil stabilization effectiveness (by UCTs) when Condor SS and Roadbond EN1 additives are combined with fly ash at reduced percentage when compared to fly ash alone.

1.4 Report Layout

This report is divided into 5 chapters. Chapter 2 presents a discussion of different stabilization methods currently used in Oklahoma, a discussion of the stabilization of sulfate bearing soils and the potential heave that can result from stabilization, and a look into previous work completed on Roadbond EN1, Condor SS, and other acid based stabilizers. Chapter 3 presents the soils used in the study, the chemicals used, and the methods used to complete the research. Chapter 4 presents the results from the research and provides a discussion of the results. Chapter 5 presents the conclusions of this study and recommendations for further research related to this project.

2.0 LITERATURE REVIEW

2.1 Introduction

This literature review gives a brief overview of the stabilization of fine-grained soils, some of the results of studies involving chemical stabilization, and the nature of sulfate bearing soil which allows an insight into the difficulties faced when stabilizing sulfate bearing soils. There is also an overview of previous published work involving Roadbond EN1, Condor SS, and other acid based stabilizers. This report will build on the research that is available regarding stabilization with Roadbond EN1 and Condor SS as well as evaluate the two chemicals relative to other commonly used lime based chemicals.

2.2 Stabilization of Fine-Grained Soil using Chemicals Containing Lime

The State of Oklahoma contains a variety of fine-grained soils. In order to increase mechanical stability, improve durability and alter the volume change associated with moisture adsorption, soil stabilization is often used for fine-grained soils (Little 1987). There are three types of stabilization: mechanical, physical, and chemical; the focus of this report is chemical stabilization. Common stabilization chemicals include hydrated lime and quicklime, CFA, and CKD.

2.2.1 Lime Stabilization

Hydrated lime and quicklime have been used extensively in Oklahoma as a chemical stabilizer for road subgrades and is readily available for use as a soil stabilizer. Stabilization with lime has been found to be effective in stabilizing clayey soils; however, lime has little effect on highly organic soils and soils with low clay content (Ingles and Metcalf 1973). Epps et al. (1971) defines soils that can be stabilized with lime to be classified as A-5, A-6, and A-7 with some soils classified as A-2-6 and A-2-7 according to AASHTO classification. The benefits of the lime stabilizer on the soil are caused primarily by decreasing the water sensitivity of the soil and increasing flocculation of the soil particle structure. The cementation factors of the lime are thought to be a minor contributor to improvements of the soil (Mitchell and Hooper 1961). However, Aly et. al. (1978) found that the cementing of minerals formed in the soil-lime reaction to be important and dependent on the availability of water for the cementing reaction to occur. Aly et. al.'s conclusion, based on water availability, leads to the understanding that while the cementation may be a minor factor the results of no to little cementation in a soil-lime mixture are noticeable during laboratory testing.

Little (1987) found that due to a pozzolanic reaction from the soil-lime mixture, strength increases greater than 100 psi could be achieved with a 28 day cure time and a curing temperature of 70°F both in the field and in the laboratory. The pozzolanic reaction has been illustrated by Little (1987) in the following equations:

$$Ca^{++} + OH^{-} + \text{Soluble Clay Silica} \rightarrow \text{Calcium Silicate Hydrate (CSH)}$$

$$Ca^{++} + OH^{-} + \text{Soluble Clay Alumina} \rightarrow \text{Calcium Aluminate Hydrate (CAH)}$$

The reaction will go as long as enough calcium remains in the system and the pH of the system remains high enough to maintain solubility (Little 1987). Based on the pozzolanic reaction, Little (1987) reports that the ability of a soil to react with lime to form cementing materials is an inherent property and characteristic of the soil. This means if a soil does not possess the chemical structure to react with lime then regardless of the amount of lime or curing conditions little to no cementation will occur within the soil-lime mixture.

Khattab et al. (2007) completed a study with a natural bentonite from France mixed with 4% lime to find that the soil-lime mixture had an increase in shear strength and a reduction in swell potential and pressure. Khattab et al. (2007) also concluded that the soil-lime mixture should not be allowed to dry too quickly if the cementation reaction is to take place, which agrees with the work completed by Little (1987) regarding the pozzolanic reactions dependency on water availability. One conclusion drawn from Khattab et al. (2007) and Little (1987) is due to the necessity of available water, soil stabilization with lime should not be completed if water is not readily available for the reaction to take place especially during the hotter and dryer months of the year.

2.2.2 Fly Ash Stabilization

Fly ash has been found in multiple studies to be a suitable stabilizer for soils. Fly ash is a byproduct of coal burning power plants and its usage in stabilization reduces disposal of material in landfills. Fly ash is regarded as non-plastic fines which are often hollow spheres of aluminum, silicon, and iron oxides (Kumar et al. 2007). The standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete (ASTM C618-12a) classifies fly ash within two categories, Class C and Class F fly ash. Class F fly ash is typically produced from the combustion of anthracite or bituminous coal, while Class C fly ash is produced from the combustion of lignite or subbituminous coal and typically has a higher calcium content (ASTM C618-12a). Within Oklahoma there are multiple sources of fly ash making it readily available pending the project location for soil stabilization. OHD L-50 (2009) recommends stabilizing soils that are AASHTO classified as A-2-6, A-2-7, A-3, A-4, A-5, and A-6 with fly ash ranging from 12% for the A-2-6 soil up to 14% for the A-6 soil. The larger range of soils that can be stabilized with fly ash, as opposed to lime, suggest a cementation process occurs with fly ash stabilization. In order to obtain a pozzolanic reaction and create a flocculated soil structure, as can be found with lime, the soil in some cases must be mixed with both lime and fly ash (Kumar et al. 2007). However, Class C fly ash contains some lime and is used effectively to stabilize moderately plastic soils.

Kumar et at. (2007) found that when testing expansive clay and a fly ash and lime-soil mixture that the addition of fly ash to the lime-soil mixture increased the strength as fly ash content increased. The strength gains that Kumar et al. (2007) found were as much as 50 psi after 14 days of curing and up to 100 psi with 28 days of curing at a lime concentration of 6% by dry mass. However, at a lime concentration of 8% the strength gain was about the same for both curing times in the range of about 30 psi (Kumar et al (2007). The decrease in strength with a decrease in lime concentration suggests that there is an upper limit in the capacity of stabilizing soil with lime and fly ash.

A comprehensive study has been completed at the University of Oklahoma where 8 different soils with multiple AASHTO classifications were stabilized with fly ash, lime, and CKD. The study was based on the ODOT publication OHD L-50 “Soil Stabilization Mix Design Procedure,” which requires a 50 psi increase in unconfined compressive strength (UCS) to be the determining factor for mix design approval (ODOT 2009). The study reported the 50 psi increase in UCS was met at 9-12% fly ash for soil classified as A-7-6, and at 6% fly ash for soil classified as A-6 (Cerato et al. 2011).

Fly ash has been studied with the expectation that it reduces the swelling potential of expansive plastic clays. One study on volume change behavior of fly ash stabilized clays concluded that the swelling potential of expansive clays was reduced by as much as 50% when the soil was mixed to a 20% fly ash concentration (Phanikumar et al. 2007). The decrease in plasticity can probably be attributed partly to the fact that fly ash is, according to the USCS classification system, non-plastic fines. This implies that little to no expansive behavior should be induced. The large amount of fly ash Phanikumar et al. (2007) used in order to reduce the swell potential by 50% may be impractical in terms of economic feasibility.

Brooks et al. (2011) completed a study regarding the effect of fly ash on UCS, California bearing ratio (CBR), and Atterberg limits for two lean clay soils found in southeastern Pennsylvania. The study concluded that the addition of fly ash increased the UCS by as much as 144% in all but one soil that was tested, reduced the plasticity index by as much as 16%, and increased the CBR results by as much as 140% (Brooks et al. 2011). The aforementioned study also found that maximum dry density decreased as the amount of fly ash increased and that the optimum moisture content increased as the fly ash concentration increased (Brooks et al. 2011).

Research discussed in this section suggests that fly ash alone can be used with lean clays and silts. The stabilization mechanism is attributed to the cementation of the fly ash particles upon hydration. That in combination with, lime can be used on highly plastic clays, in order to initiate pozzolanic reactions and flocculate the soil particles. OHD L-50 (2009) doesn't recommend stabilizing highly plastic clays, AASHTO classification A-7-5 and A-7-6, with fly ash alone which is generally consistent with literature provided in this section.

2.2.3 Cement Kiln Dust Stabilization

Another byproduct available in Oklahoma as well as many other places in the world is cement kiln dust (CKD). CKD is collected in the kiln exhaust gases during the manufacturing of cement. Similarly to fly ash, many efforts have been made to find a use for this kiln dust to avoid disposal in landfills. CKD has cementitious properties which make it a possible stabilizer for some soils (Miller and Azad 2000). OHD L-50 (2009) recommends that CKD can be used in stabilization of the following AASHTO classified soils: A-1, A-2, A-3, A-4, and A-5. The amount of CKD that is recommended in OHD L-50 (2009) ranges from 5% to 6%, by dry weight of soil, and recommends a mix design be made to stabilize A-4 and A-5 soils. Miller and Azad (2000) would go on to discuss that due to the process in which CKD is produced the composition will vary from plant to plant and can even vary within the same plant based on the beginning materials fed into the kiln during cement production.

Miller and Zaman (2000) reported from a study that three different sources of CKD improved the strength of the tested soils more than the quicklime control. The study showed that the CKD had resulted in similar plasticity index modification as lime and that CKD is both a modifier and stabilizer of soil where quicklime is primarily a modifier of cohesive soil (Miller and Zaman 2000). Another study was completed on CKD at some field test sites, namely Oakdale Drive in Enid, Oklahoma. The results from UCTs of field samples showed an increase of 400% after 7 days of curing and 448% after 28 days of curing for the northern portion of the project, classified as an A-6 soil with a P.I. of 11, when mixed with 12% CKD (Snethen et al. 2008). For the southern portion of Oakdale Drive, classified as a non-plastic A-2-4 soil, it was reported that an increase in the UCS of 941% occurred after 7 days of curing and 1405% after 28 days of curing occurred with 12% CKD (Snethen et al. 2008).

The comprehensive study from the University of Oklahoma involving 8 soils with different AASHTO classifications referred to previously in the fly ash stabilization section reported when CKD was used to stabilize an A-6 soil and an A-4 soil the required increase in UCS was met using 9% and 8% CKD additive respectively (Cerato et al. 2011).

The research discussed in this section suggests that CKD can be used as an effective stabilizer of silty soils and lean clays due to the materials ability to form cementitious bonds when hydrated. CKD is readily available in many locations and has no predetermined use since it is a byproduct, making it a good fit for soil stabilization where economically feasible. Despite the benefits associated with CKD the quality of the material can vary significantly depending on the plant it was made at, making it difficult to adopt in standard use (Miller and Zaman 2000). However, despite the variation in CKD composition ODOT has adopted a standard for using CKD in OHD L-50 (2009) and has a list of approved Portland Cement Plant locations in which the CKD can be used for stabilization of state funded road projects.

2.3 Chemical Stabilization of Sulfate Bearing Soil

Lime stabilization of plastic soils has become common in the past few decades, which led to another issue with stabilization, lime-induced heave in sulfate soils. In order to change the properties of the sulfate rich soil to achieve the desired engineering properties, soil stabilization is often sought. However, lime (CaO) reacts with sulfate ($CaSO_4$*$2H_2O$) in the soil forming expansive ettringite crystals leading to stabilization induced heave (Mitchell and Dermatas 1992). The ettringite crystals in some cases can expand up to 250% (Berger et al. 2000) causing extensive heave of the soil.

Mitchell and Dermatas (1992) found that when soil or groundwater contained soluble sulfates, or sulfate in solution, that it would combine with alumina in clay to form a series of calcium-aluminum-sulfate hydrate compounds to form ettringite crystals ($[Ca_3Al(OH)_6]_2(SO_4)_3 * 26H_2O$). Once the ettringite crystal formation begins the process can continue as long as enough material, including water, is available for the reaction to take place and the pH and temperature remains favorable (above 15°C) (Mitchell and Dermatas 1992). A comparison of untreated Hickory Clay with 10,000 ppm sulfate content and treated Hickory Clay with 10,000 ppm sulfate with 5% lime was tested by Campbell (2010). The results provide a good example of the amount of heave that lime stabilization can induce in sulfate bearing soil as shown in Figure 1, which displays the swelling potential associated with lime-induced heave.

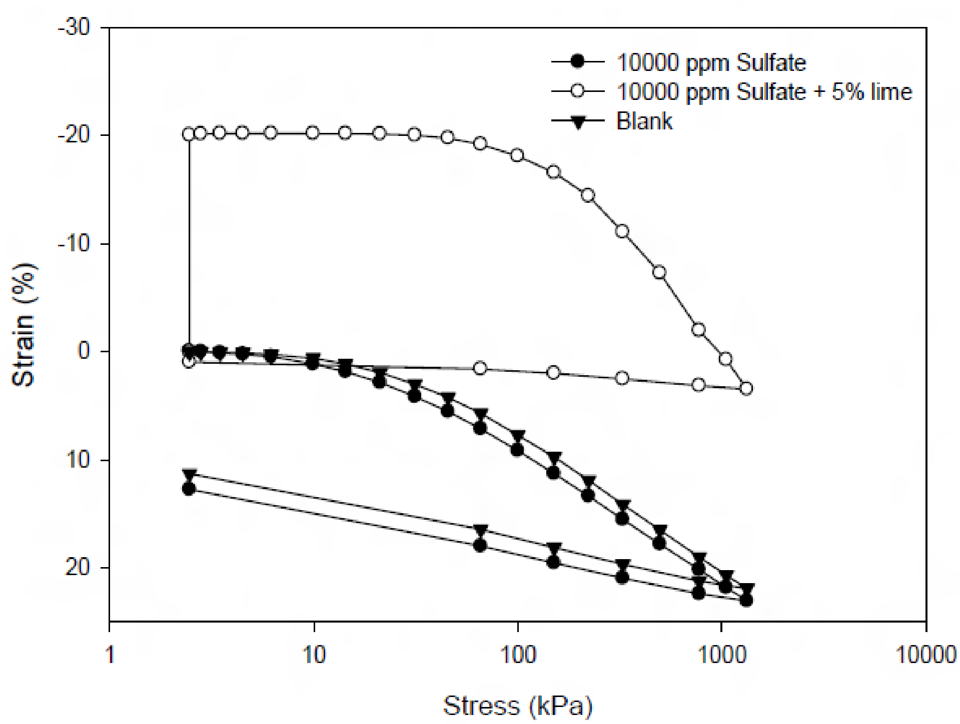

Figure 1: Average Free Swell Oedometer Results of Hickory Clay With 10,000 ppm Sulfate and with 10,000 ppm Sulfate and 5% Lime: Blank=Raw Soil (From Campbell 2010)

The comparison from Campbell (2010) was completed by starting with a blank non-sulfate soil and then adding sulfate to the soil in the desired concentrations. From the oedometer results on Hickory Clay with lime and sulfate at 10,000 ppm a negative strain (swelling) of 20% was reported showing the extent to which sulfate bearing soil can heave when treated with lime. The results emphasize the need to consider stabilizing soil by some other method not involving lime to avoid heaving of the soil.

Soil containing soluble sulfate in excess of 30,000 ppm can be found throughout the western part of the state of Oklahoma (Nevels and Laguros 2004).The ettringite crystal formation from stabilization induced heave has been noted in Oklahoma; a clay shale belonging to the Blaine geological formation was stabilized with lime for use as a roadway subgrade, and four months after stabilization 8 in. (200 mm) of heave was observed at the site (Nevels and Laguros 2004). Cerato et al. (2011) conducted a study to determine the threshold amount of sulfate to induce heave when stabilized with lime and reported that since the nature of swelling in these soils is a product of both lime and soil mineralogy that even small amounts of sulfate could cause swell problems when mixed with lime.

Research has been conducted to find a solution to the necessary stabilization of sulfate bearing soils that doesn't cause heave. Puppala et al. (2004) reported that sulfate-resistant cement, cement Types I/II and V, improved sulfate bearing soil by reducing plasticity, enhancing UCS, and decreasing free vertical swell and linear shrinkage. To complete the study on sulfate-resistant cement, Puppala et al. (2004) collected 4 clayey soils (27<PI<47) with sulfate contents ranging from 287 to 32,100 ppm and reported that the UCS was independent of the sulfate content of the soil when stabilized with the sulfate-resistant cement. Puppala et al. (2004) also reported that the free swell of the 4 clayey soils tested was reduced from a free swell of 20 to 50% down to 0% free swell, making sulfate-resistant cement a feasible stabilizer for sulfate bearing soils.

The research outlined above sheds light on the difficulties associated with stabilizing sulfate bearing soils with lime based stabilizers. Once detection of sulfate is noted in soils, stabilization with lime must be approached with caution or not at all. Despite the difficulties associated with sulfate bearing soils, recent research, such as with sulfate-resistant cement stabilization, suggest there are alternative methods which can have similar results to lime based stabilizers.

2.4 Previous Soil Stabilization Studies of Non-Lime Based Chemicals

In an effort to lower soil stabilization cost and to avoid the lime-induced heave with sulfate soils mentioned in the last section, some non-lime based stabilizers have been introduced into the market. While the exact chemical makeup of some of these non-lime based stabilizers is proprietary, the two stabilizers tested and discussed in this research are acid based chemical stabilizers. More specifically, Roadbond EN1 is Sulfonated D-Limonene and Condor SS is Sulfonated Naphthalene (Rajendran and Lytton 1997). They are essentially sulfonated oils mixed with strong sulfuric acid. Since the compositions of these types of soil stabilizers and/or mode of action are sometimes unknown they should always be tested by laboratory means or careful field trials by independent authorities (Ingles and Metcalf 1973). Acid based soil stabilizers typically work due to the stabilizer attacking the soil particles, usually the clay minerals, which forms new insoluble minerals which can bind the soil together (Ingles and Metcalf 1973). Sulphonated oils act as weak organic bases and when mixed with strong sulfuric acid produce a weaker acid with high chemical stability and ionizing capability, which contributes to increased density and strength in soil (Scholen 1992).

According to the manufacturer of Roadbond: *Roadbond EN1 stabilizer causes clay to release weakly ionized water molecules from the clay matrix and replaces the water with strongly ionized sulfate radicals. The exchange is permanent and takes place at normal pH levels. As in lime stabilization, metal hydrates are formed which help increase the strength of the clay and by leaving the clay matrix intact, the permeability is significantly reduced. When mixed with base material and compatible in-place material, ROADBOND EN 1 stabilizer dissolves the mineral salts and natural cementitious properties of the soil. Mixing the soil disperses the dissolved material into the void spaces between the soil grains where it cures and crystallizes.*

According to the makers of Condor SS: *Condor SS is a sulphonated oil product derived from a petroleum industry's waste product. Sulphonated oil is particularly effective as a soil electrolyte because of its high chemical stability with powerful ionizing capabilities. Simply stated sulphonated oil ionizes the* *excess water found in expansive clay soils, which vigorously exchanges its electrical charges with the soil's particles, causing the water to adhere to the particles to break its electrochemical bond and separate, thus becoming free water, which drains through gravity, evaporation, and compaction.*

Previous studies have been conducted with non-lime based stabilizers on both sulfate bearing and non-sulfate bearing soils. In a study to reduce sulfate swell in the Dallas, Texas area, namely SH 161 and IH 635, it was reported that Roadbond EN 1 showed “superior qualities regarding strength, stiffness, permeability and other properties when compared to lime” (and Rajendran and Lytton 1997). Specifically, Rajendran and Lytton reported an increase in stiffness of 400%, an increase in strength of 188%, and a decrease in permeability of 55%, when treating the soil with Roadbond EN1 compared with untreated soil in the IH 635 project, which contained up to 2600 ppm of sulfate (Rajendran and Lytton 1997). For the test completed on SH 161, containing up to 5300 ppm of sulfate, an increase in stiffness of 850%, an increase in strength of 275%, and a decrease in permeability of 75% was reported when the soil was treated with Roadbond EN1 compared with untreated soil (Rajendran and Lytton 1997). It should be noted however, that the samples tested for strength and stiffness in the study were allowed to cure exposed to atmosphere for 36 hours before testing. This type of exposure would produce drying with a significant increase in suction and strength in high PI sols such as those tested. Thus, it is unclear how much of the increase in strength and stiffness may be due to treatment versus increased matric suction.

Studies regarding the injection of Condor SS have also been conducted by the Texas Department of Transportation (TxDOT). In the study, Condor SS was injected into two test sites following the manufacturer recommendations for application by a distributer of Condor SS. The two test sites were chosen based on a history of swelling and shrinking behavior of the soil; the report does not provide information regarding the parameters of the soil (Bobrowski 1992). To gauge the effectiveness of Condor SS on the soil, the Falling Weight Deflectometer (FWD) test was conducted and pocket penetrometer readings were taken. The results of injecting Condor SS into the subgrade and soil showed little or no improvement with the FWD; however, the pocket penetrometer showed an increase of up to 1.5 tsf in UCS for some areas tested (Bobrowski 1992). It should be noted that the pocket penetrometer is difficult to accurately read, has problems with crusting of the soil surface making it difficult to accurately determine when the tip has penetrated the required depth, and it has a small 0.3 cm diameter tip which leads to discrete sampling (Gifford et al. 1977).

The research presented in this section, while brief, shows that some improvement has been observed with Roadbond EN1 when mixed with a sulfate bearing soil; however, available published literature for both Roadbond EN1 and Condor SS is limited. This report will serve to fill in some of the knowledge gap by reporting results of testing the effects of both aforementioned chemicals on three different soils found within Oklahoma, one of which contains soluble sulfate.

CHAPTER 3: MATERIALS, METHODS, AND SCOPE OF WORK

3.1 Introduction

This chapter presents the soils used in testing, the sample preparation methods, and test procedures used to complete this research.

3.2 Soils and Stabilizers

Three different soils were gathered from within the state of Oklahoma to conduct this research. The three soils collected for this study include: Lela Clay, Renfrow Clay, and Vernon Soil. Lela Clay and Renfrow Clay have moderately high plasticity while the Vernon Soil contained high concentration of soluble sulfate (>20,000 ppm) with a lower plasticity. Lela Clay classified as an A-7-6(32) soil according to the AASHTO system and comes from Kay County along US 177. Renfrow Clay classified as an A-7-6(38) and comes from Logan County near Pennsylvania Avenue. Vernon Soil classified as an A-7-6(18) and comes from the south side of Route 412 on the border of Woodward and Major Counties. The soil sampling locations can be seen on a map in Figure 2.

The test soils used in this project were also used in previous projects completed at the University of Oklahoma. Some of the soil properties from the previous testing are presented in Table 1. The properties for Vernon Soil came from Cerato et al. (2008) and the properties for Lela Clay and Renfrow Clay came from Miller et al. (2011).

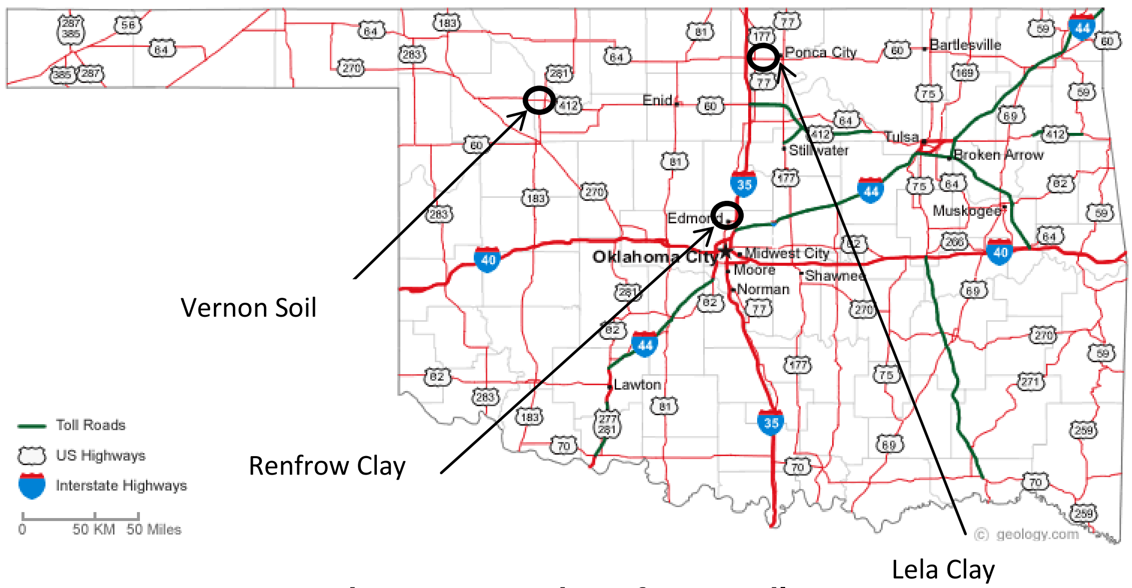

Figure 2: Location of Test Soils

Table 1: Soil Properties (From *Miller et al. 2011 and +Cerato et al. 2008)

Soil Name	Total SSA (m^2/g)	Sulfate Content (ppm)	Cation Exchange Capacity (meq/100g)	Calcite Content (%)	Dolomite Content (%)	Carbonate Content (%)	pH	Conductivity (mS/cm)
Lela Clay *	161	2086	26.9	3.2	1.0	4.2	7.29	1199
Renfrow Clay *	116	262	18.2	3.0	3.9	6.9	7.88	476
Vernon Soil +	127	8533	36.6	2.2	0.76	2.9	8.1	2035

The stabilizers used in this research were Condor SS, Roadbond EN1, lime, and fly ash. Condor SS is manufactured by Earth Science Products located in Aurora, OR and is classified as an ion exchanging soil stabilizer containing 23% buffered sulfuric acid, 72% water, and 5% natural ion exchange polymers. Roadbond EN1 is manufactured by C.S.S Technology, Inc. located in Tolar, TX and is classified as a soil stabilizer with the chemical formula of the product being proprietary; it is mentioned that it contains sulfuric acid, but the percentage is proprietary. The lime used in this research was Hi-Yield® Horticultural Hydrated Lime produced by Voluntary Purchasing Groups, Inc.

located in Bonham, TX and having the chemical name of Calcium Hydroxide ($Ca(OH)_2$). The fly ash used in this research is from Oklahoma Gas and Electric's (OG&E) coal power plant located in Red Rock, OK.

The manufacturer of Condor SS suggests using a working solution when applying the chemical in the field while the manufacturer of Roadbond EN1 recommends using an application rate based off of volume of soil to be treated, which comes out to about 810 ft^3 of soil treated per gallon of undiluted chemical. The "working solution" refers to mixing the raw chemical with water and then adding the prescribed amount of working solution to the soil. Traditionally soil stabilizers are presented on a basis of dry mass of soil. To stay consistent with current trends in data presentation this report will present the results of the additive concentration in terms of dry soil mass and not working solution. Since the concentration will be presented in terms of dry mass of soil, the concentration of dry mass will vary for each soil since the air dry water content was different for each soil tested.

3.3 Unconfined Compression Test

The samples to be tested for UCS were prepared using the Harvard Miniature Apparatus. The Harvard Miniature Apparatus was calibrated for each soil to be used according to the Standard Guide for Evaluating Effectiveness of Admixtures for Soil Stabilization (ASTM D4609). To complete the calibration a standard compaction test was first conducted according to the Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (ASTM D 698-12), to establish the maximum dry density (γ_{dmax}) and optimum moisture content (OMC) of each untreated soil. Once the OMC and γ_{dmax} for each soil were determined the soil was prepared at the OMC and compacted in the Harvard Miniature Apparatus in 5 layers varying the blows per layer. The range of blows per layer versus γ_d was then plotted against the standard compaction test curve produced previously. The number of blows per layer selected for testing is that which produces the γ_d within 1 lb. /ft^3 of γ_{dmax} from the standard compaction test curve as required in ASTM D4609.

To prepare air-dried soil for compaction it was processed over a US #10 sieve, then brought up about 1% past the OMC with water (including water in the chemical additive) and then mixed thoroughly to ensure uniform moisture before being covered with a damp towel while the specimens were being molded. To minimize water loss during sample preparation only enough soil to prepare 6 samples was mixed at a time. To prepare each specimen, about 130 grams of soil was removed from the mixing bowl and then the soil was placed into the Harvard Miniature Apparatus in 5 layers and compacted using a drop hammer with the calibrated number of blows for each soil. This method of compaction is different than that described in ASTM D4609, which uses a spring-loaded kneading tamper. However, the drop hammer provides advantages over the tamper and more consistent application of the compaction energy as described in Miller et al. (2011). Once the soil was compacted in the apparatus the sample was trimmed along the top of the mold and extruded. The extruded specimen was then weighed and quickly wrapped in cellophane to avoid water loss, labeled, and placed in the humidity room.

Once the soil specimens had cured in the humidity room for 14 days, 6 specimens of each soil-chemical combination were removed from the humidity room to be tested. While OHD L-50 recommends a 7-day curing period, for research purposes 14 days of curing was used in the current work. This is consistent with previous research (e.g. Miller and Zaman 2001, Miller et al. 2011), which indicates that for conventional lime based additives, significant strength gains generally occur during the first 7 to 14 days, after which gains are more modest. The soil was tested using a GEOTEST load frame. The load frame used during this research is shown in Figure 3 with a soil specimen loaded in the frame.

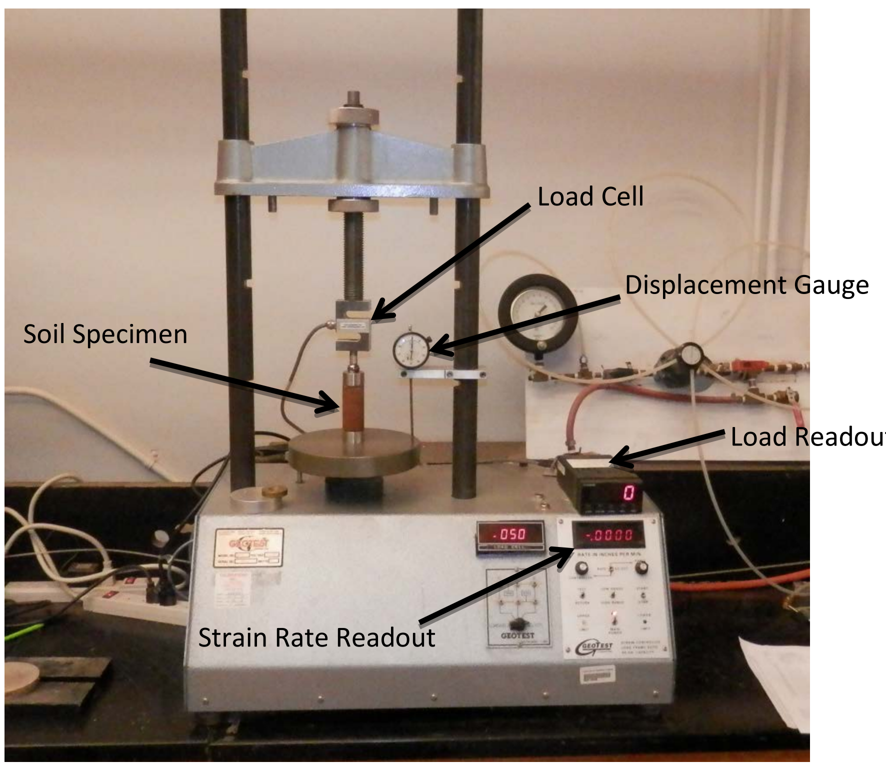

Figure 3: UCT Load Frame

Before testing the soil specimens they were unwrapped and weighed again to monitor any moisture gain or loss during curing. The specimens were then placed into the UCT load frame and tested at a constant strain of 1% per minute. The load carried by the specimen was then recorded based on increments of displacement of 0.01 inches for up to 0.2 inches and then at increments of displacement of 0.02 inches thereafter until 15% strain or a few increments after peak strength was reached. After testing, a portion of the specimen was removed and the weight was recorded for moisture content determination. Due to the small size of each specimen, generally about half of the sample was removed to provide representative water content. For each soil, 3 specimens were tested as outlined previously to obtain a more statistically representative strength for each soil-additive combination. The 3 remaining specimens of each soil were unwrapped and the weight of each specimen recorded before being submerged in water for 48 hours. After 48 hours of submergence the samples were removed and patted dry with a paper towel before being weighed again to monitor moisture gain and tested for UCS. For the specimens that were soaked for 48 hours, only samples that remained intact could be tested; the samples that broke apart during submergence were disposed of.

To establish the OMC and γ_{dmax} for each soil-additive combination a standard compaction curve was produced using the same calibrated Harvard Miniature Apparatus as for the untreated soil. For this project different chemical working solutions were produced; however, the standard compaction curve was only produced for the highest concentration of working solution for each chemical stabilizer, and assumed to be the same for the other concentrations tested.

The range of concentrations chosen for Condor SS was based on the strongest manufacturer recommended concentration of 1 gallon of chemical to 100 gallons of water, the weakest recommended concentration of 1 gallon of chemical to 500 gallons of water, and one concentration of 1 gallon of chemical to 350 gallons of water in the middle. The manufacturer of Roadbond EN1 recommends stabilizing soil based on a rate of 1 gallon of undiluted chemical to 810 ft^3 of soil. The concentration of Roadbond EN1 for this study was chosen from a range of concentrations in an effort to stay consistent with the concentrations mixed for Condor SS, since the manufactures of Roadbond EN1 recommends stabilization based on the volume of soil. Each acid based chemical stabilizer was also tested at 6% concentration (of undiluted chemical) based on dry soil mass to test the efficacy of the chemicals at higher concentrations where the pH of the soil is altered significantly.

For soil types used in this study, recommendations in ODOT OHD L-50 specify using either lime or fly ash. To allow for a way to gauge the effectiveness of Roadbond EN1 and Condor SS against the typically used stabilizers, specimens of each soil used in this research were prepared and tested for UCS with either lime or fly ash as directed by OHD L-50.

The manufacturer of Roadbond EN1 recommends stabilizing soil, based on plasticity index, with a combination of Roadbond EN1 and fly ash. For

Vernon soil the recommended combination is 3% Roadbond EN1 working solution, which is equal to 0.015% (undiluted chemical) by dry soil mass, plus 5% fly ash. The 3% of working solution refers to mixing the soil to minus 3% of OMC and then adding the last 3% of moisture to the soil using the working solution, which is Roadbond EN1 in pure form diluted to 1:200 (pure solution: water). The concentration of Roadbond EN1 on the basis of dry mass for the soils tested will be 0.015%. In order to stay consistent with both chemicals being tested, Condor SS was tested using the same mixing recommendations as the Roadbond EN1. Lela Clay and Renfrow Clay were tested using the same methods and concentrations as Vernon Soil.

To provide an overview of the different stabilizers, concentrations of stabilizers, and curing times, a testing matrix for UCT was produced as shown in Table 2. From the test matrix presented a total of 360 specimens were produced, 6 for each soil-additive combination.

3.4 Atterberg Limits Test

For each soil the liquid limit and plastic limit were determined for the untreated soil, soil treated with Roadbond EN1, and soil treated with Condor SS. The Atterberg Limit tests were conducted according to the Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils (ASTM D4318). All the Atterberg Limit tests were conducted starting with the soil at the wettest point and allowing the soil to dry in air in order to complete the test.

Table 2: UCT Test Matrix

Soil	Stabilizer and Concentration by Dry Mass	Curing Time (days)
Lela Clay	Untreated	14 & 28
	Roadbond EN1 0.2%	14 & 28
	Roadbond EN1 0.1%	14
	Roadbond EN1 0.06%	14
	Roadbond EN1 6%	14
	Roadbond EN1 0.015% + 5% Fly Ash	14 & 28
	Condor SS 0.2%	14 & 28
	Condor SS 0.06%	14
	Condor SS 0.004%	14
	Condor SS 6%	14
	Condor SS 0.015% + 5% Fly Ash	14 & 28
	Fly Ash 5%	14 & 28
	Hydrated Lime 6%	14 & 28
Renfrow Clay	Untreated	14 & 28
	Roadbond EN1 0.13%	14 & 28
	Roadbond EN1 0.07%	14
	Roadbond EN1 0.04%	14
	Roadbond EN1 6%	14
	Roadbond EN1 0.015% + 5% Fly Ash	14 & 28
	Condor SS 0.13%	14 & 28
	Condor SS 0.04%	14
	Condor SS 0.003%	14
	Condor SS 6%	14
	Condor SS 0.015% + 5% Fly Ash	14 & 28
	Fly Ash 5%	14 & 28
	Hydrated Lime 6%	14 & 28
Vernon Soil	Untreated	14 & 28
	Roadbond EN1 0.2%	14 & 28
	Roadbond EN1 0.1%	14
	Roadbond EN1 0.06%	14
	Roadbond EN1 6%	14
	Roadbond EN1 0.015% + 5% Fly Ash	14 & 28
	Condor SS 0.2%	14 & 28
	Condor SS 0.06%	14
	Condor SS 0.004%	14
	Condor SS 6%	14
	Condor SS 0.015% + 5% Fly Ash	14 & 28
	Fly Ash 14%	14 & 28
	Fly Ash 5%	14 & 28

For the Atterberg Limit tests conducted for a given soil mixed with either Roadbond EN1 or Condor SS, the soil was brought up to the wettest point of the test using a 1% by volume solution of Roadbond EN1 or Condor SS and water as the source of moisture. Atterberg Limit tests were conducted two times, the first time involved mixing the soil with the chemical solution or water and beginning the test immediately while the second set of tests involved mixing the soil with water or the chemical solution past the wettest expected point of the test and then the soil mixture was sealed and allowed to cure for 14 days in a humidity room before being tested in the same manner as the uncured samples. In order to get statistically representative averages of the results, each soil-chemical combination was tested by two people.

3.5 Oedometer Test

To test the effect of the addition of Roadbond EN1 and Condor SS on swell potential and swelling pressure, oedometer tests were conducted according to the Standard Test Methods for One-Dimensional Swell or Collapse of Cohesive Soils (ASTM D4546-08) method C. For both Roadbond EN1 and Condor SS the largest concentration of chemical mixed with water was used to bring the soils up to OMC. Each of the 3 soils was also tested untreated and with the recommended amount of lime or fly ash as prescribed by OHD L-50. To examine the effect of lime mixed with a sulfate soil, the Vernon soil was mixed with 4% lime and tested.

For the soil-stabilizer specimens the dimensions of the oedometer ring were measured and the volume calculated. The soil used for the oedometers was processed over a US No. 10 sieve before mixing with either water or the chemical and water solution. The soil was then mixed at or slightly over OMC and then enough soil was removed to be compacted in the oedometer ring so that the dry density of the soil would be similar to that used for UCT specimens. The soil was compacted in two lifts using moist tamping with a small rod in the oedometer ring to achieve the target density before being placed in the oedometer cell. The oedometer cell was then placed into an oedometer frame that is connected to a data acquisition system that records the vertical displacement at predetermined time increments. The oedometer frame was a Wykeham Farrance load frame connected to a data logger. The oedometer frame loaded with a free swell sample can be seen in Figure 4.

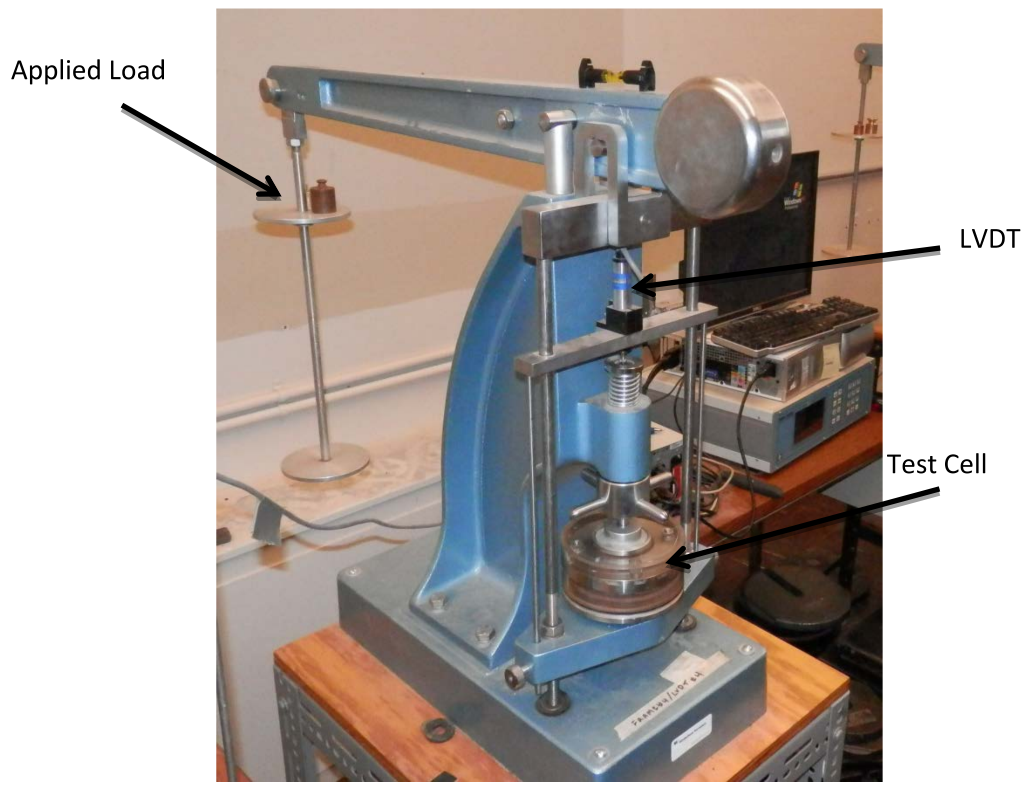

Figure 4: Oedometer Frame

Immediately after placing the sample in the oedometer frame, a seating load of 130 psf was applied and the sample was inundated with water and allowed to swell for 24 hours or until the vertical displacement was less than 0.003 mm per hour. After swelling displacement was at or near zero, the sample was loaded incrementally until the vertical displacement was less than 0.003 mm per hour before the next load was applied.

3.6 pH Test

To determine the change in pH with an increase in concentration of the acid based stabilizer by soil dry mass, a series of pH tests were conducted. The pH test for the acid based stabilizers was completed by mixing 25 grams of dry soil that had been processed over the No. 40 sieve with varying amounts of either stabilizer. The concentrations of stabilizer that were tested for this research were; 0.2, 2, 4, and 6% by dry mass. Once the soil and chemical were mixed together, 100 grams of deionized water was added to the container with the soil chemical mixture and the mixture was shaken for 30 seconds every 10 minutes for one hour. After the one hour had passed the soil chemical mixtures were ready to be tested. The pH was determined using a Thermo Scientific Orion 2-Star Benchtop pH meter. The benchtop meter had to first be calibrated with solutions of a known pH, once the calibration was completed the pH of each soil chemical mixture was determined.

4.0 RESULTS AND DISCUSSION

4.1 Lela Clay

4.1.1 Soil Properties

The liquid limit, plastic limit, plasticity index, specific gravity, and particle size distribution were determined for untreated Lela Clay. Atterberg limits (liquid and plastic limits) were determined for uncured samples and samples cured for 14 days as described in Chapter 3. For each curing time (0 and 14 days), Atterberg limits were determined for untreated soil and soil treated with Roadbond EN1 1% and Condor SS 1% by volume chemical solution by two people. The results of the Atterberg Limits can be found in the Table 3, the results are representative of the average and range (in parentheses) of the two separate tests performed.

Table 3: Lela Clay Atterberg Limits Results

	No Curing Time			14-Day Curing Time		
Stabilizer	Liquid Limit	Plastic Limit	Plasticity Index	Liquid Limit	Plastic Limit	Plasticity Index
Untreated	52.8 (± 0.8)	22.5 (± 2.5)	30.3 (± 1.7)	53.1 (± 0.8)	25.0 (± 0.5)	28.1 (± 0.2)
Roadbond EN1 1%	54.2 (± 1.0)	24.1 (±0.6)	30.1 (± 1.6)	53.7 (± 1.1)	24.1 (± 0.9)	29.6 (± 1.9)
Condor SS 1%	53.9 (± 0.7)	23.4 (± 1.4)	30.5 (± 2)	53.3 (± 0.8)	24.7 (± 0.9)	28.6 (± 1.7)

Results in Table 3 show there is little difference between cured and uncured Atterberg limits and little difference between treated and untreated soil. The results lead to the conclusion that Roadbond EN1 and Condor SS have little effect on the plasticity index of Lela Clay for the concentrations and curing times tested.

The γ_d for the untreated soil was found to be 92.7 pcf at a moisture content of 23%; the compaction curves for the untreated and chemically treated Lela Clay can be found in Appendix C. The specific gravity of the soil was found to be 2.70 following the Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer (ASTM D854-10). The results from the sieve analysis and hydrometer analysis can be found in Figure 5. From the results of the hydrometer analysis it can be seen that Lela Clay contains a significant percentage (43%) of soil particles smaller than 0.002 mm, which corresponds to the clay-size fraction.

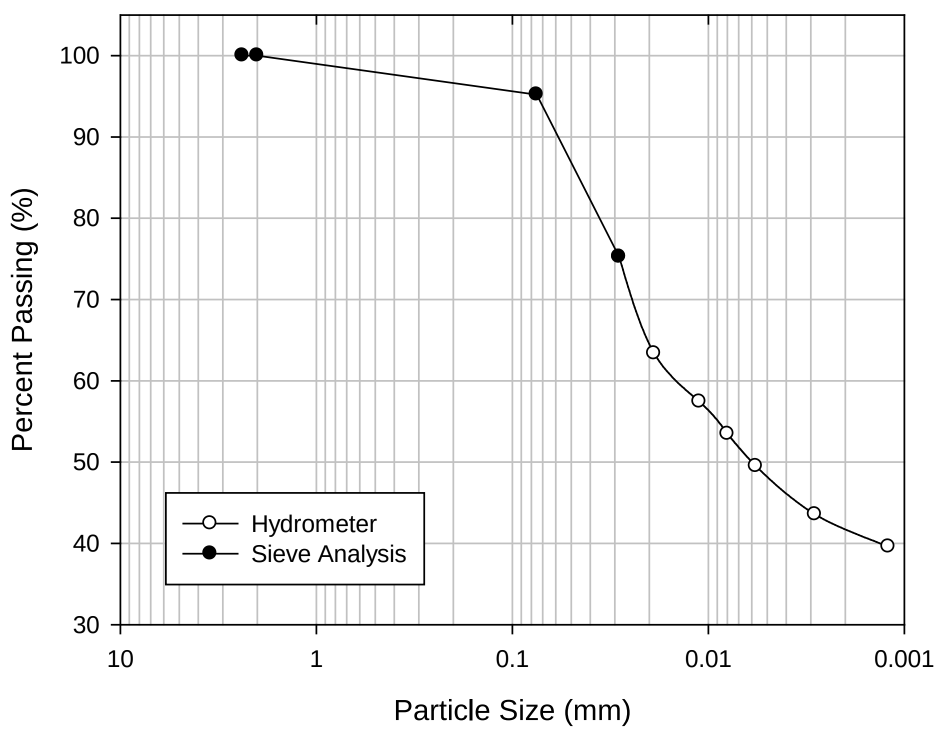

Figure 5: Lela Clay Grain Size Distribution

4.1.2 UCT Results - Lela Clay with Roadbond EN1

To test the stabilizing performance of Roadbond EN1, a series of UCTs were conducted. The UCTs were performed for three concentrations of Roadbond EN1: 0.2%, 0.1%, and 0.06% by dry soil weight for 14-day curing and the strongest concentration of 0.2% for 28-day curing. The results of each individual test can be found in Appendix A. The comparison of the 14-day UCS for three concentrations of Roadbond EN1 and untreated soil can be found in Figure 6. Symbols represent the average UCS of three specimens with range bars depicting the lower and upper values. From this figure it appears that the addition of Roadbond EN1 had an insignificant effect on the Lela Clay when tested after 14 days of curing. The soaked samples of Lela Clay with Roadbond EN1 did not remain intact and could not be tested. The water contents and densities for the samples tested were reasonably consistent during the testing and don’t explain variations in the results. The water contents and densities of each sample tested can be found in Appendix B.

In order to determine the influence of longer curing times on samples treated with Roadbond EN1, Lela Clay specimens were prepared to a 0.2% dry mass concentration and allowed to cure for 28 days. The UCT results for the soil-chemical combination and cure time showed no significant improvement in strength when compared to the untreated specimen. The results of the UCTs can be found in Appendix A. Samples that were soaked in water after 28 days of curing did not remain intact during the 48 hour submergence and were not testable.

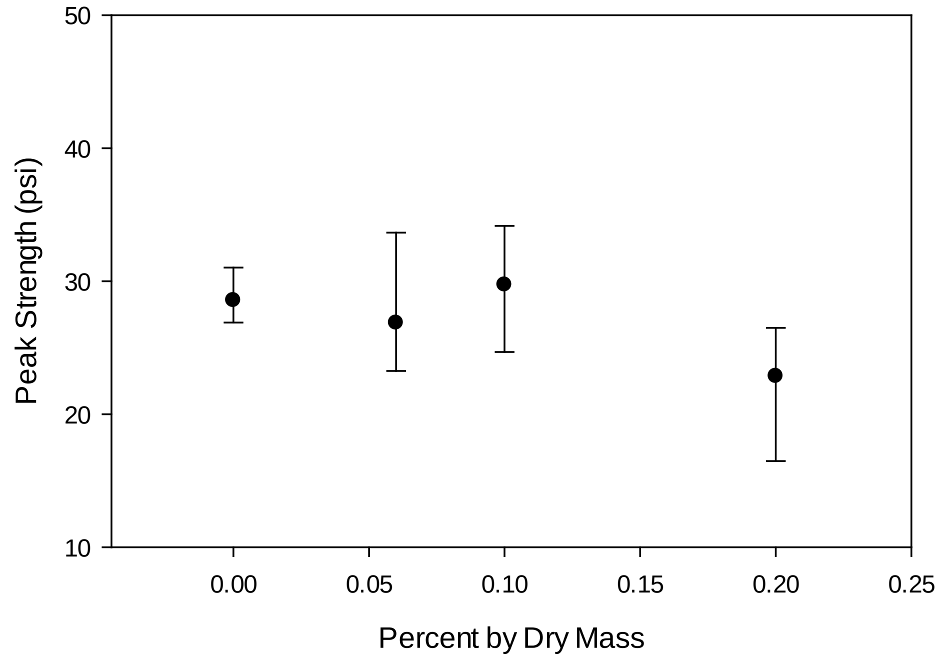

Figure 6: Lela Clay with Roadbond EN1, UCT 14-Day Curing

The water contents and dry densities for the samples tested were reasonably consistent and do not explain the behavior found in the results. The water contents and densities of each sample tested can be found in Appendix B.

4.1.3 UCT Results - Lela Clay with Condor SS

To test the performance of Condor SS in stabilizing Lela Clay, a series of UCTs were completed. The concentrations of Condor SS tested were 0.2%, 0.06%, and 0.004% based on dry mass, for the 14-day curing UCT and a 0.2% concentration for the 28-day curing time UCT. The results of each UCT conducted can be found in Appendix A. The comparison of the concentrations of Condor SS mixed with Lela Clay can be found in Figure 7. From the figure it can be seen that no significant strength gains were found when Condor SS was mixed with Lela Clay and allowed to cure for 14 days. The results of UCS are representative of three tests as explained previously for Roadbond. Submerged specimens did not remain intact and were not testable. The dry densities and water contents were relatively uniform for these tests and do not explain the performance of Condor SS. The water contents and densities of each sample tested can be found in Appendix B.

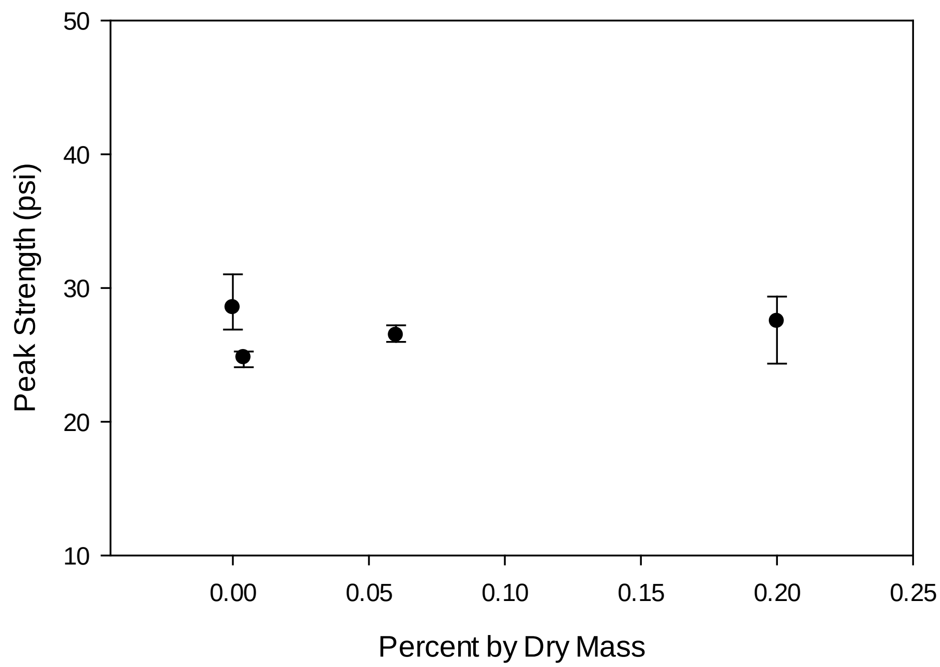

Figure 7: Lela Clay with Condor SS, UCT 14-Day Curing

The results for the 28-day curing time UCT showed no improvement in strength when Condor SS was mixed with Lela Clay. The results of the UCTs can be found in Appendix A. The submerged specimens did not remain intact and were not testable. The water contents and densities of each sample tested can be found in Appendix B.

4.1.4 UCT Results - Lela Clay with Lime

Lela Clay was prepared with 6% lime as directed by OHD L-50 for a soil with AASHTO classification of Lela Clay. Lela Clay was mixed with and tested after 14-day and 28-day curing. To provide a better comparison for Roadbond EN1, Condor SS, and lime, the results have been presented in Figure 8 and 9 for each curing time. From the 14-day curing comparison it can be seen that lime increased the UCS of Lela Clay substantially better than either Condor SS or Roadbond EN1. The 48-hour saturated specimens for Lela Clay and lime remained intact during submergence and, as can be seen in the lime comparison still performed better than the Roadbond EN1 or Condor SS that were not soaked. The strength gains from the addition of lime to Lela Clay conformed to the requirements set out by OHD L-50, which call for a 50 psi strength gain. The dry densities don't explain the strength differences found in the tests. The water contents and densities of each sample tested can be found in Appendix B.

The comparison for Lela Clay when mixed with Roadbond EN1, Condor SS, or lime after a 28-day curing time in Figure 9 shows that lime causes the largest improvement. As before, the lime specimens remained intact when submerged for 48 hours after curing for 28 days. The results of the submerged tests show the lime increased the strength of the Lela Clay about 30 psi. The dry densities and water contents (Appendix B) were relatively consistent and do not explain the lower strength values found for the two acid-based chemical additives.

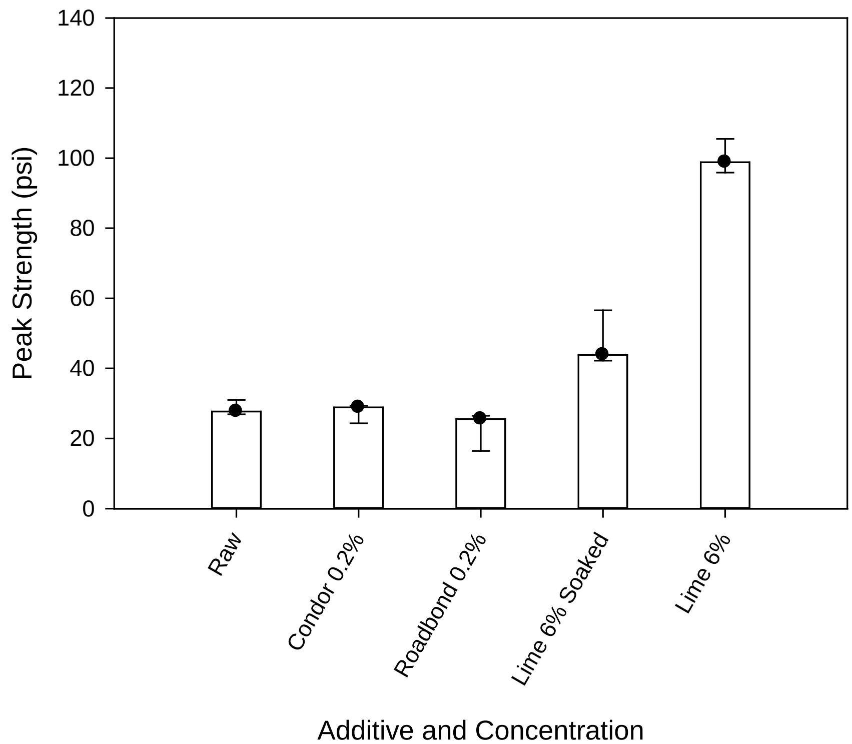

Figure 8: Lela Clay with Lime, UCT 14-Day Cure Time Comparison

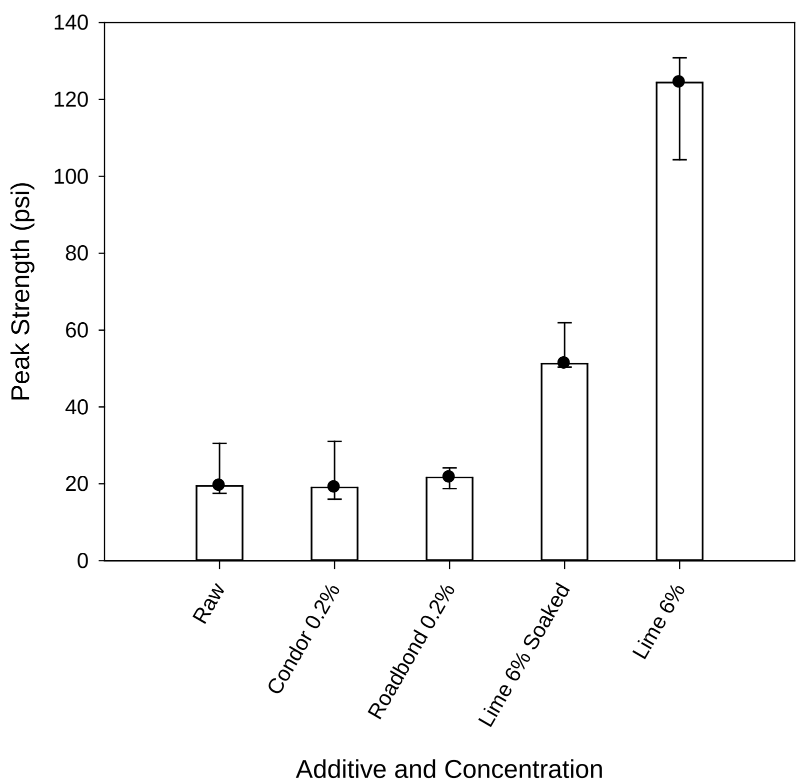

Figure 9: Lela Clay UCT Comparison, 28-Day Cure Time

4.1.5 UCT Results - Lela Clay with Fly Ash and Roadbond EN1/Condor SS

Lela Clay was prepared with a combination of 5% fly ash and 0.015% of either Roadbond EN1 or Condor SS. Lela Clay was also prepared with 5% fly ash alone to determine whether any gains in UCS were the result of the Roadbond EN1/Condor SS – fly ash combination or fly ash alone. The specimens were allowed to cure for 14 and 28 days. The individual results of each test conducted can be found in Appendix A. The UCT results for the 14-day curing are shown in Figure 10. From the results it can be seen that slight strength gains were achieved when 5% fly ash was added with the Condor SS in Lela Clay; however, the gains in strength were not large enough to warrant stabilization with this method. A few of the soaked samples containing only fly ash survived the 48 hour submergence and the results are presented with the non-soaked results. Other soaked samples did not survive submergence. The water contents and densities of each sample tested are relatively uniform and can be found in Appendix B.

The results of the Roadbond EN1/Condor SS plus 5% fly ash for the 28 day curing are shown in Figure 11. The results show that no notable strength gains were achieved as a result of the addition of either Roadbond EN 1 or Condor SS. Condor SS did increase the strength of the soil more than Roadbond EN1 when mixed with fly ash; however, the average strength increase is not enough to warrant use of the product. Some of the soaked specimens did remain intact and are included in the plot, but generally the soaked specimens performed poorly in terms of survival and strength.

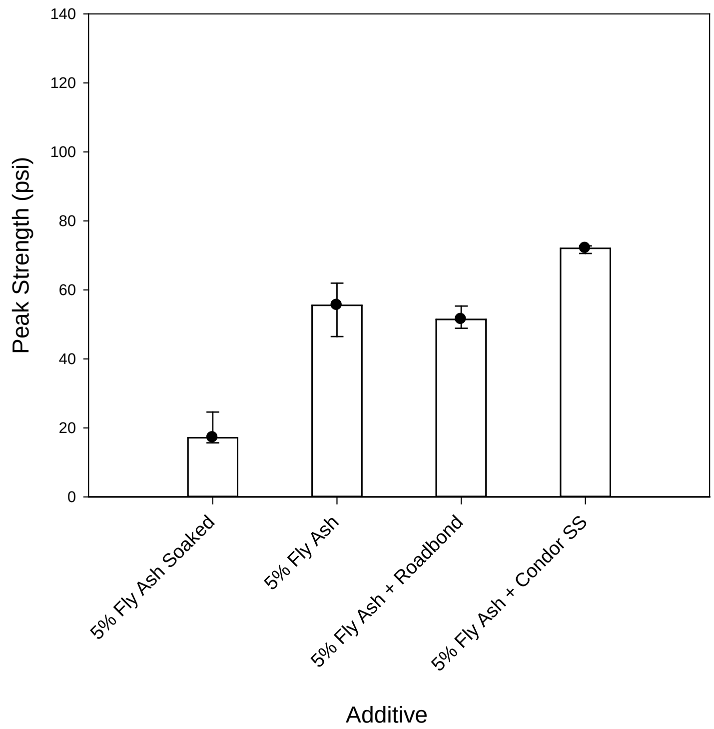

Figure 10: Lela Clay with Fly Ash and Roadbond EN1/Condor SS, UCT 14-Day Curing Comparison

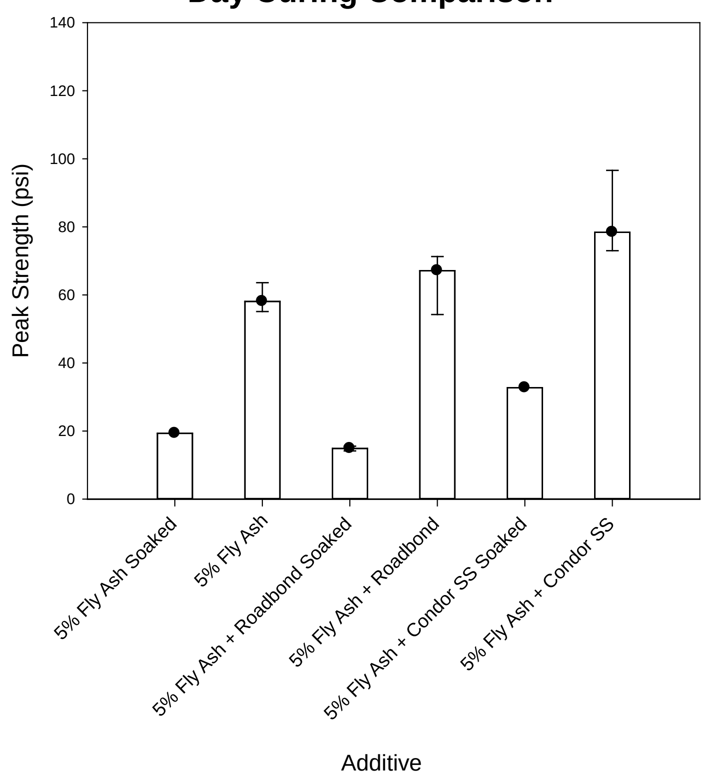

Figure 11: Lela Clay with Fly Ash and Roadbond EN1/Condor SS, UCT 28-Day Curing Comparison

4.1.6 Lela Clay Oedometer Test Result

Roadbond EN1 and Condor SS were mixed with Lela Clay using a concentration of 0.2% for the free swell oedometer tests. Lela Clay was also mixed with 6% lime for comparison. The results for the free swell test can be found in Figure 12. From the results of the oedometer tests it can be seen that Roadbond EN1 and Condor SS had virtually no effect on reducing swelling or altering the corresponding swelling pressure when mixed with Lela Clay. However, when Lela Clay was prepared with 6% lime, the soil swelled less and had much lower compressibility compared to the other chemicals. The water contents and densities of each sample tested can be found in Appendix B.

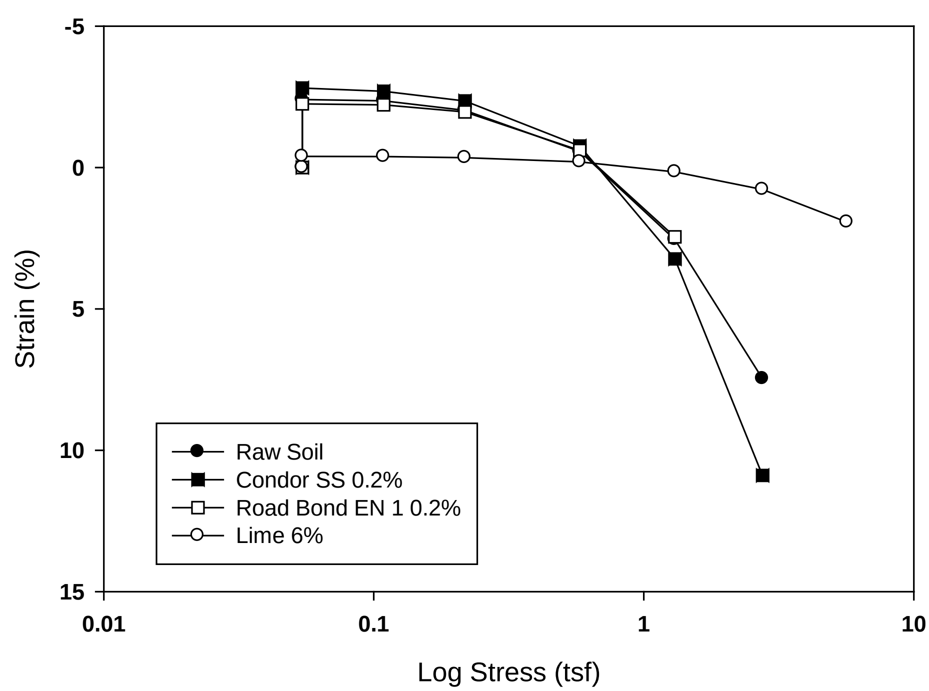

Figure 12: Lela Clay Free Swell Oedometer

4.1.7 PH Curve

A series of pH test on Lela Clay with either Roadbond EN1 or Condor SS was completed, the results can be found in Figure 13. The results show that for the concentrations which either chemical was tested in the UCT and free swell oedometer tests that the pH is only slightly influenced. The pH doesn't become considerably changed until about 1 to 2% concentration by dry mass of either chemical is added to the soil. The small change in pH for the concentrations tested in this study may provide some explanation of why the results that were found for Lela Clay did not show much improvement.

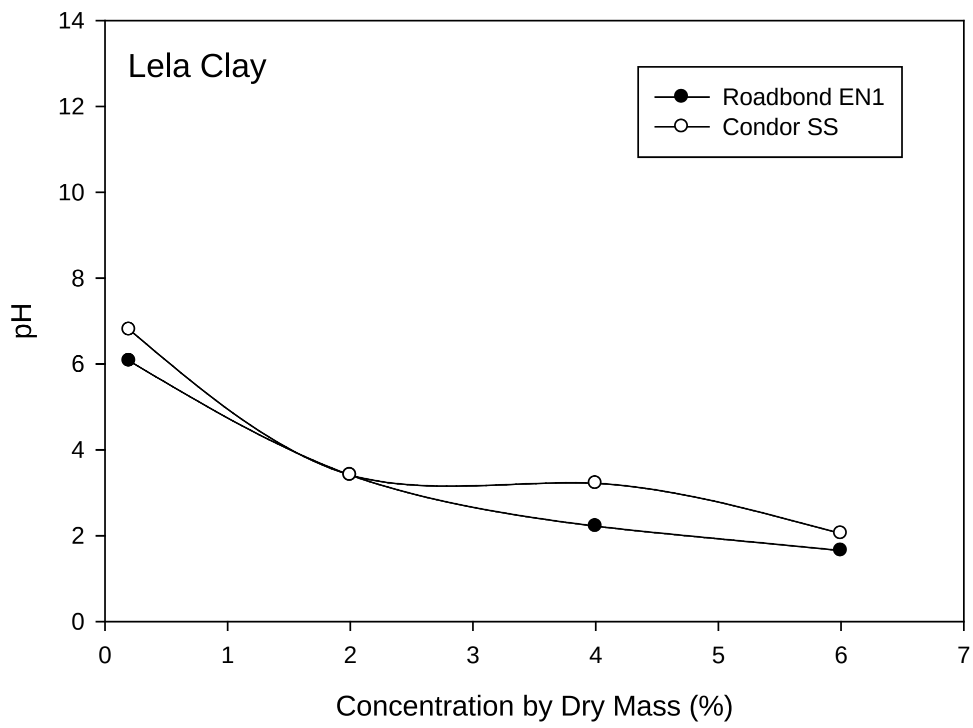

Figure 13: Lela Clay pH Test Results

4.2 Renfrow Clay

4.2.1 Soil Properties

The effects of both Roadbond EN1 and Condor SS on the liquid limit and plastic limit for Renfrow Clay were determined as described in Chapter 3. The specific gravity and particle size distribution were also determined for untreated Renfrow Clay. The results of the Atterberg Limits can be found in Table 4, the results are representative of the average and range of two duplicate test performed excluding the untreated soil with no curing time. Results from one of the tests for the untreated soil with no curing were recorded incorrectly and were excluded.

Table 4: Renfrow Clay Atterberg Limits Results

	No Curing Time			14-Day Curing Time		
Stabilizer	Liquid Limit	Plastic Limit	Plasticity Index	Liquid Limit	Plastic Limit	Plasticity Index
Untreated	59.4 (± 2.1)	26.2	33.2	54.8 (± 0.4)	27.6 (± 0.1)	27.2 (± 0.3)
Roadbond EN1 1%	55.2 (± 1.6)	25.6 (± 3.0)	29.6 (± 0.7)	53.7 (± 1.1)	26.3 (± 1.1)	27.4 (± 2.0)
Condor SS 1%	54.0 (± 1.0)	24.8 (± 0.2)	29.2 (± 1.2)	52.5 (± 0.7)	26.8 (± 2.6)	25.7 (± 3.4)

Results from Table 4 show that little difference was observed between cured and uncured Atterberg limits and between treated and untreated soil. The results lead to the conclusion that Roadbond EN1 or Condor SS have little effect on the plasticity index of Renfrow Clay for the curing times and concentrations of stabilizer tested.

The γ_d for the soil was found to be 97 pcf at a moisture content of 24%, the compaction curves for the untreated and chemically treated Renfrow Clay can be found in Appendix C. The specific gravity for Renfrow Clay was found to be 2.68. The results from the sieve and hydrometer analysis can be found in Figure 14. From the hydrometer analysis results it can be seen that Renfrow Clay contains a significant percentage (35%) of soil particles smaller than 0.002 mm, which corresponds to the clay-size fraction.

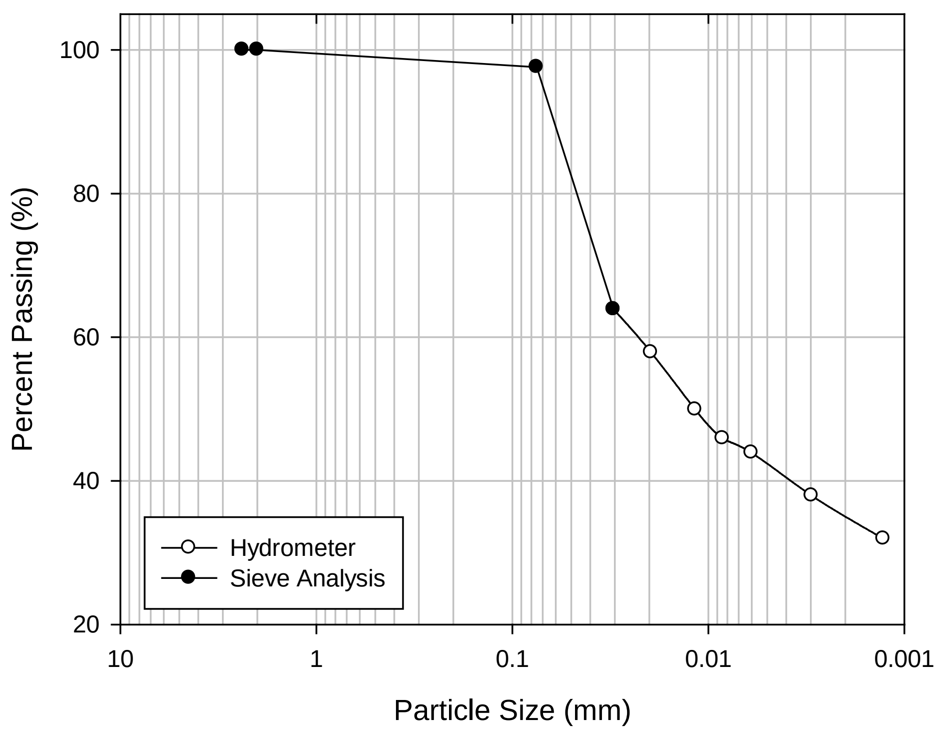

Figure 14: Renfrow Clay Grain Size Distribution

4.2.2 UCT Results - Renfrow Clay with Roadbond EN1

Roadbond EN1 was mixed with Renfrow Clay at several different concentrations to perform a series of UCTs after 14 days and 28 days of curing. The concentrations of the working solution of Roadbond EN1 used in the 14-

day curing specimens were: 0.13%, 0.07%, 0.04%, and the 28-day curing samples were made with 0.13% concentration. A comparison of the 14-day curing period UCTs for the three concentrations of Roadbond EN1 can be found in Figure 15. The results from each individual UCT can be found in Appendix A. From the test results it appears that Roadbond EN1 did not increase the strength of Renfrow Clay for the concentrations tested. The soaked samples of Renfrow Clay with Roadbond EN1 did not remain intact and could not be tested. The behavior found in the testing does not appear to be the result of varying dry density or water content. The water contents and densities of each sample tested can be found in Appendix B.

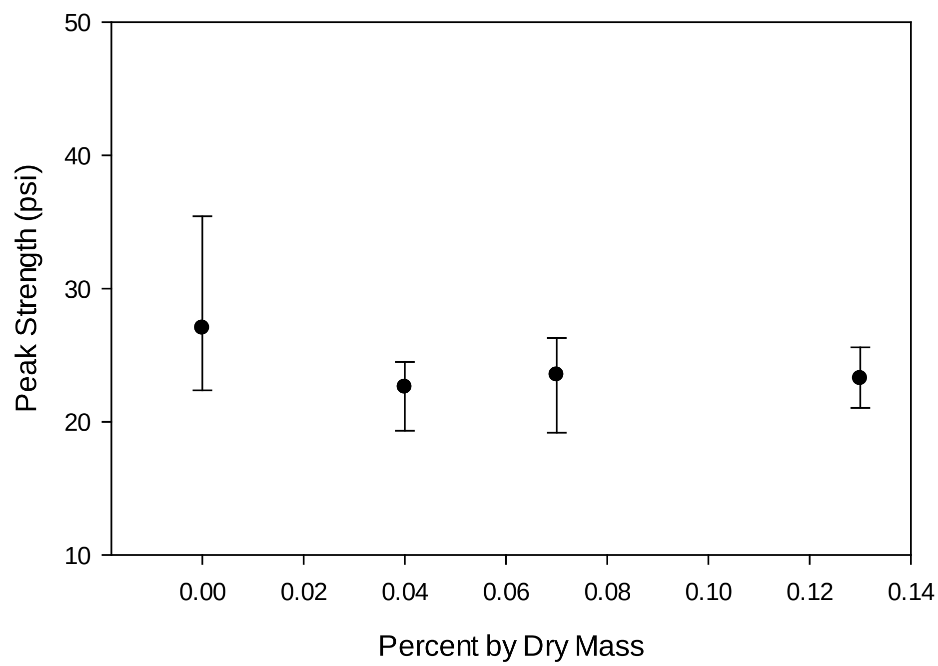

Figure 15: Renfrow Clay with Roadbond EN1, UCT 14-Day Curing

The results of the 28-day curing time UCT can be found in Appendix A. Roadbond EN1 showed no significant strength gains for Renfrow Clay and did not meet the requirements laid out by ODOT OHD L-50 regarding stabilizer strength gains. Samples that were soaked in water after 28 days of curing did not remain intact during submergence in water and were not testable. The water content and dry density do not appear to explain the behavior for the tests. The water contents and densities of each sample tested can be found in Appendix B.

4.2.3 UCT Results - Renfrow Clay with Condor SS

Condor SS was mixed with Renfrow Clay at several different concentrations to prepare UCT specimens as described in Chapter 3. The concentrations of Condor SS for the 14-day curing were: 0.13%, 0.07%, and 0.003%, and 0.13% concentration for the 28-day curing UCT. A comparison of the concentrations with a 14-day cure time UCT can be found in Figure 16. The individual UCT results can be found in Appendix A. From the results of the 14-day curing the addition of Condor SS to the soil doesn’t appear to significantly increase the strength of the soil. Submerged specimens did not remain intact and were not tested. The water content and dry density for the specimens tested is relatively uniform and doesn’t explain the behavior found in the test. The water contents and densities of each sample tested can be found in Appendix B.

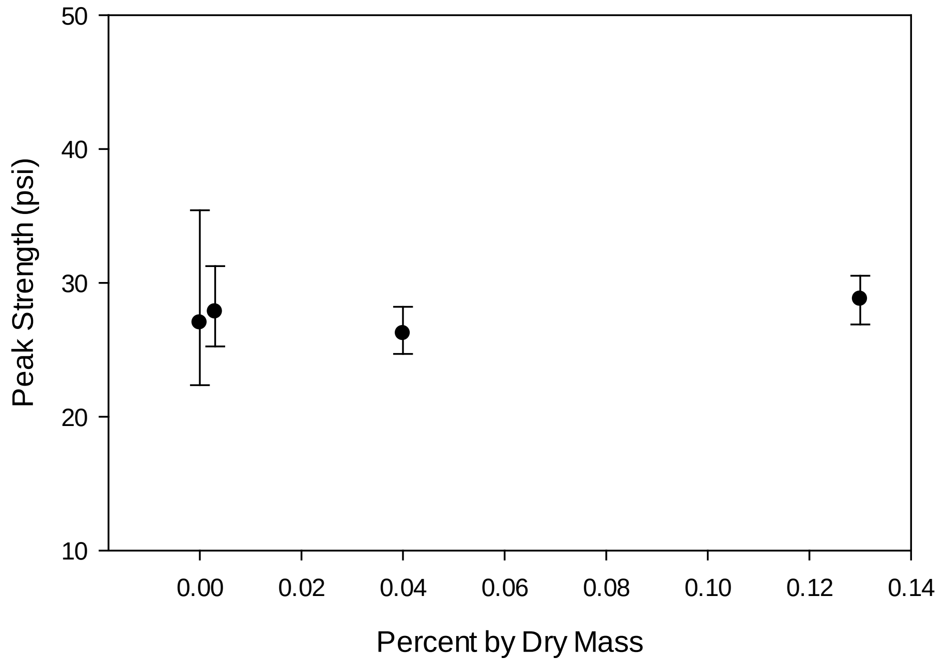

Figure 16: Renfrow Clay with Condor SS, UCT 14-Day Curing

The results of the 28-day curing for Condor SS and Renfrow Clay can be found in Appendix A. The results of the 28-day curing UCT show no strength gains when Renfrow Clay was mixed with Condor SS. The submerged specimens for this test did not remain intact and were not tested. The slight variation in the water content and dry densities doesn't appear to explain the behavior of the tests. The water contents and densities of each sample tested can be found in Appendix B.

4.2.4 UCT Results - Renfrow Clay with Lime

Renfrow Clay was prepared with 6% lime as directed by OHD L-50 for a soil with AASHTO classification of Renfrow Clay. To allow for comparisons to be made for Roadbond EN1 and Condor SS against the recommended stabilization agents used in Oklahoma, the results have been presented together in Figure 17 for the 14-day curing and in Figure 18 for the 28-day curing. For the 14-day curing specimens, the lime stabilized Renfrow Clay performed much better than either Roadbond EN1 or Condor SS. The strength gains that were found with the addition of lime conform to the specifications set out by OHD L-50. Unlike Roadbond EN1 and Condor SS treated specimens, all the specimens treated with lime remained intact during the 48 hour submergence following either curing time. The results of the submerged specimens have also been presented and proved to outperform the un-submerged Roadbond EN1 and Condor SS specimens in regards to UCS. The performance in strength of the samples doesn’t appear to be the result of variations in water content or dry density. The water contents and densities of each sample tested can be found in Appendix B.

The comparison for Renfrow Clay mixed with Roadbond EN1, Condor SS, or lime after a 28-day curing show the lime outperforms the other two chemical stabilizers. The soaked samples for the 28-day curing Renfrow Clay-lime 6% combination held together during submergence. The results for the soaked UCT are shown in Figure 18 as well. The results show that the soaked specimens when mixed with lime outperformed the two chemical stabilizers analyzed in this study when mixed with Renfrow Clay.

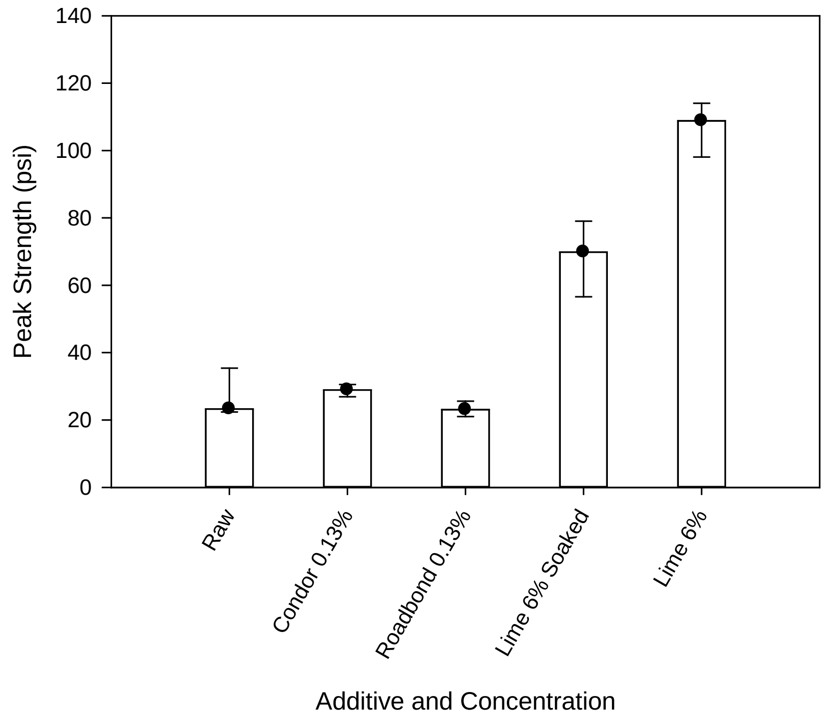

Figure 17: Renfrow Clay with Lime, UCT 14-Day Curing Comparison

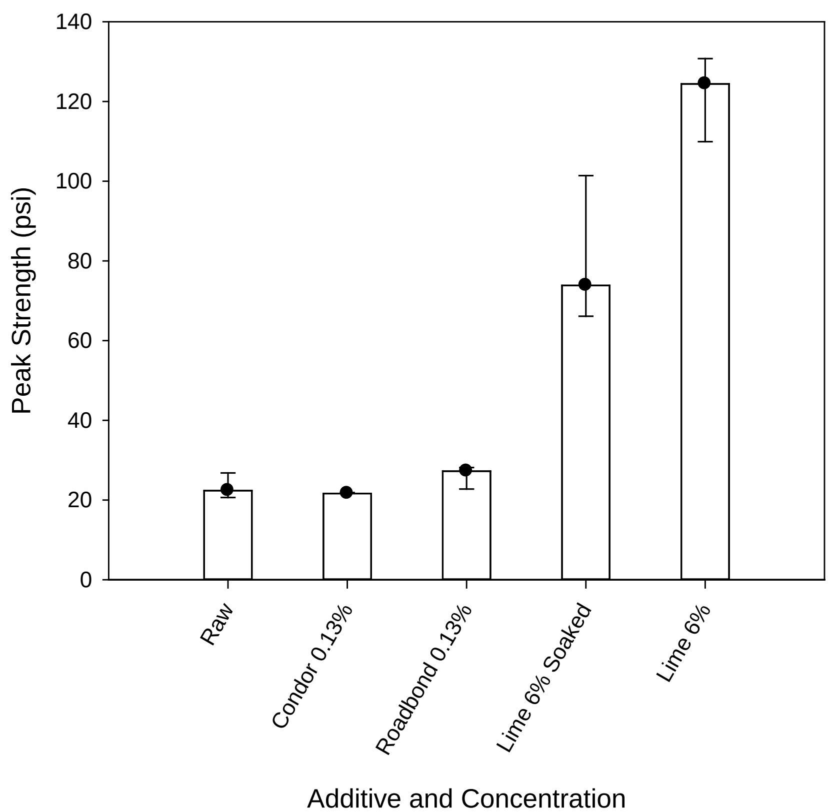

Figure 18: Renfrow Clay with Lime, UCT 28-Day Curing Comparison

4.2.5 UCT Results – Renfrow Clay with Fly Ash and Roadbond EN1/Condor SS

Renfrow Clay was prepared with a combination of 5% fly ash and 0.015% of either Roadbond EN1 or Condor SS. To determine if any strength gains found were the result of the fly ash and acid-based stabilizer combination or just the result of the addition of fly ash, Renfrow Clay was also mixed with 5% fly ash. The specimens were allowed to cure for 14 or 28 days. The results of the UCTs can be found in Figure 19 and Figure 20 for both curing times. No difference can be noted when either Roadbond EN1 or Condor SS is added to the soil-fly ash mixture and allowed to cure for 14 days. The results of these tests lead to the conclusion that the gains in strength are likely from the addition of fly ash to the soil. Some of the soaked specimens remained intact and were tested. From the soaked specimen comparison the strength was relatively unchanged with the addition of Condor SS to the soil and fly ash mixture. The samples tested have relatively uniform dry densities and water contents. The water contents and densities of each sample tested can be found in Appendix B.

The results of the 28-day curing specimens are shown in Figure 20. The results show that no notable improvement was achieved from the addition of Roadbond EN1 or Condor SS. For this curing time all of the submerged specimens remained intact and were able to be tested. For the submerged specimens, the soil treated with only fly ash performed as good as or better than the specimens with either Roadbond EN1 or Condor SS, but generally all submerged specimens performed poorly in terms of strength. The samples tested had relatively uniform dry densities and water content. The water contents and densities of each sample tested can be found in Appendix B.

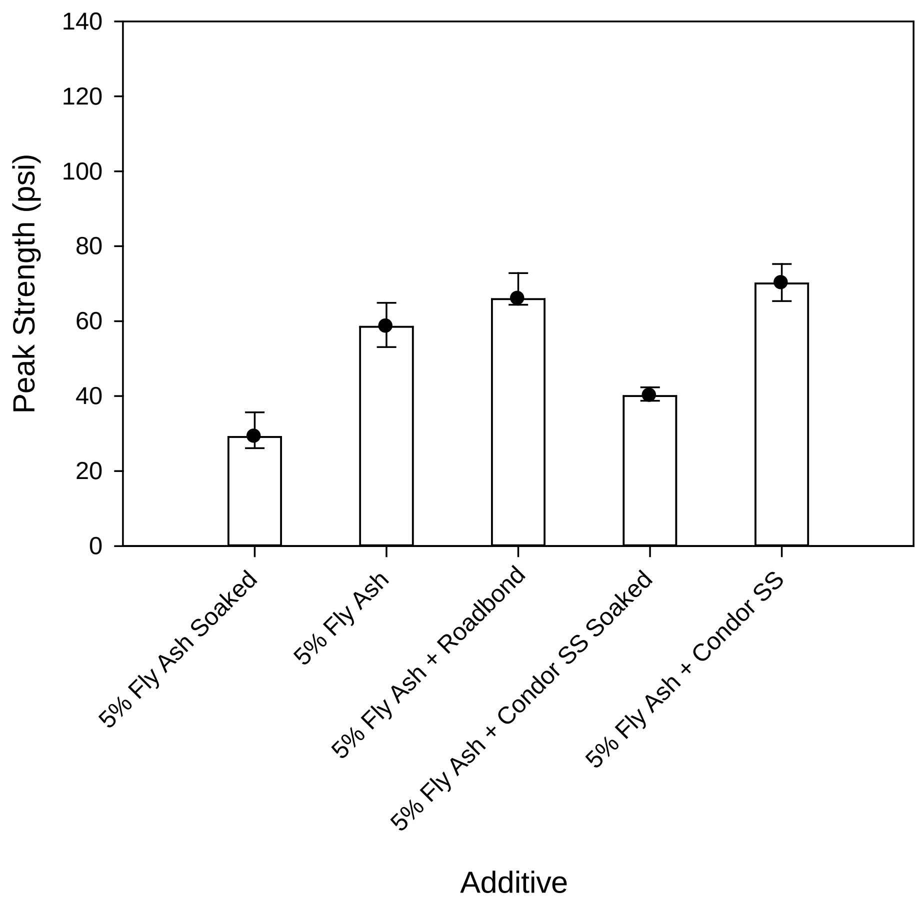

Figure 19: Renfrow Clay with Fly Ash and Roadbond EN1/Condor SS, UCT 14-Day curing

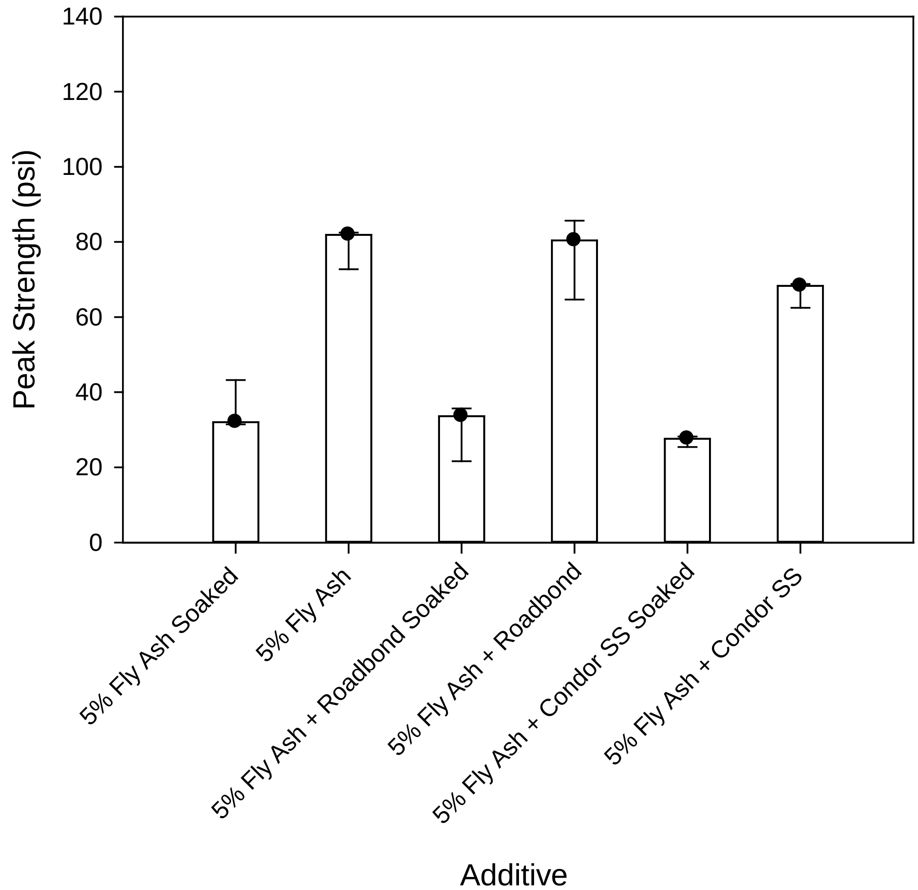

Figure 20: Renfrow Clay with Fly Ash and Roadbond EN1/Condor SS, UCT 28-Day Curing

4.2.6 Renfrow Clay Oedometer Test Results

Roadbond EN1 and Condor SS were mixed with Renfrow Clay using a 0.13% concentration for each stabilizer and subjected to a free swell oedometer test. Lime was also mixed with the Renfrow Clay at a concentration of 6% for a comparison. The results of the free swell test can be found in Figure 21. From the results of the oedometer tests it can be seen that Roadbond EN1 and Condor SS did not reduce the swelling potential or swelling pressure of the Renfrow Clay for the chemical concentrations tested. However, the addition of

6% lime to the soil proved to decrease the swelling of the soil and lower the compressibility of the soil more than the other chemicals tested. The water contents and densities of each sample tested can be found in Appendix B.

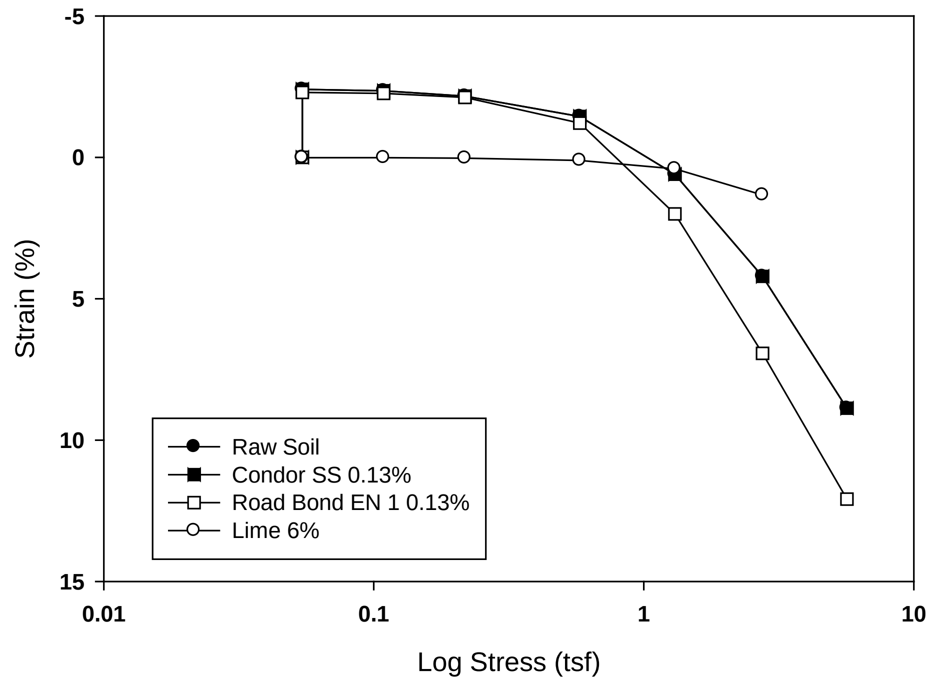

Figure 21: Renfrow Clay Free Swell Oedometer

4.2.7 PH Curve

From a series of pH test with different concentrations of either Roadbond EN1 or Condor SS a pH curve has been prepared and can be found in Figure 22. From the pH curve it can be seen that for the concentrations of either chemical tested for UCS and swelling potential, the soil pH did not change substantially. Condor SS did not have as great of an influence on Renfrow Clay as Roadbond EN1. The small change found in the pH for the chemicals tested may provide some explanation why neither Roadbond EN1 nor Condor SS affected the Atterberg limits, increased the strength of the soil or decreased swelling potential.

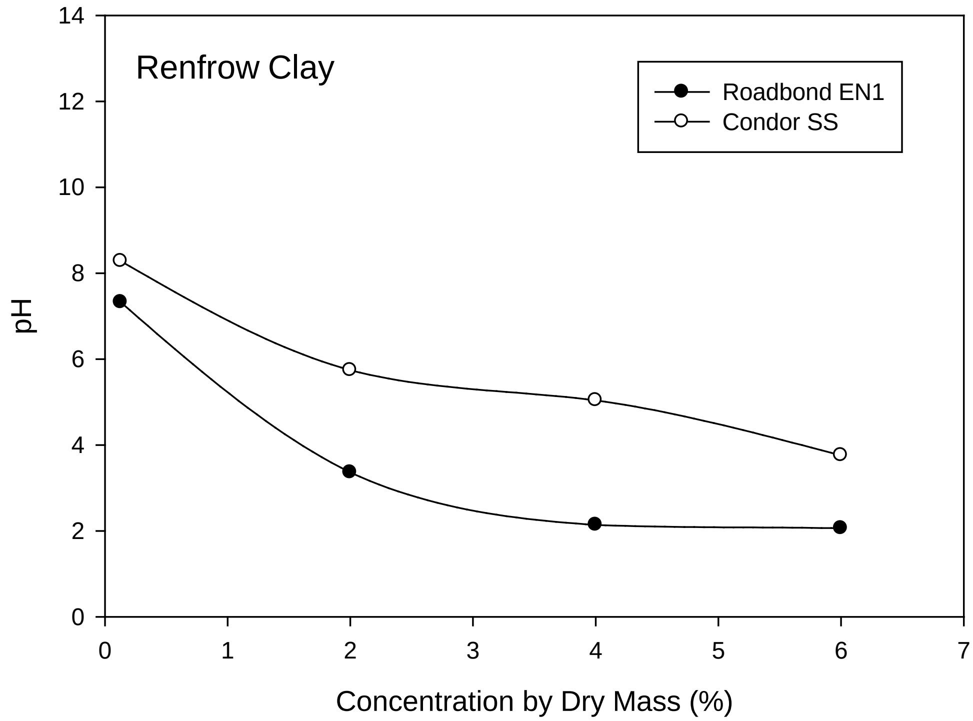

Figure 22: Renfrow Clay pH Test Results

4.3 Vernon Soil

4.3.1 Soil Properties

The Atterberg Limits (liquid limit and plastic limit) were determined for the untreated Vernon Soil. To determine the effect of Roadbond EN1 and Condor SS on the Atterberg Limit tests all of the soil-chemical combinations were tested for uncured samples and 14-day cured samples as described in Chapter 3. The results from the Atterberg Limits testing on Vernon Soil can be found in Table 5; these results are representative of the average and range of two sets of testing.

Table 5: Vernon Soil Atterberg Limits Results

	No Curing Time			14-Day Curing Time		
Stabilizer	Liquid Limit	Plastic Limit	Plasticity Index	Liquid Limit	Plastic Limit	Plasticity Index
Untreated	46.6 ($\pm$0.7)	28.6 ($\pm$1.8)	18.0 ($\pm$2.5)	45.1 ($\pm$0.2)	29.2 ($\pm$2.0)	15.9 ($\pm$1.8)
Roadbond EN1 1%	44.9 ($\pm$0.2)	29.6 ($\pm$0.8)	15.3 ($\pm$1.0)	44.6 ($\pm$0.3)	29.9 ($\pm$1.0)	14.7 ($\pm$0.7)
Condor SS 1%	42.9 ($\pm$0.8)	29.9 ($\pm$1.2)	14 ($\pm$2.0)	43.7 ($\pm$0.7)	28.8 ($\pm$0.7)	14.8 ($\pm$0.1)

Results in Table 5 show that when the soil was allowed no curing that both chemical stabilizers slightly reduced the plasticity of the soil with Condor SS having a larger effect on the Vernon Soil than did the Roadbond EN1.When the soil was mixed with either Roadbond EN1 or Condor SS and cured for 14 days little difference was observed in the liquid and plastic limits for the soil.

The γ_d of the soil was found to be 94 pcf at a moisture content of 28%, the compaction curves for both untreated and chemically treated Vernon Soil can be found in Appendix C. The specific gravity of Vernon Soil was found to be 2.72. The results from the sieve and hydrometer analysis can be found in Figure 23. From the hydrometer results it can be seen that the soil contains a significant percentage (30%) of particles smaller than 0.002 mm, which corresponds to the clay-size fraction.

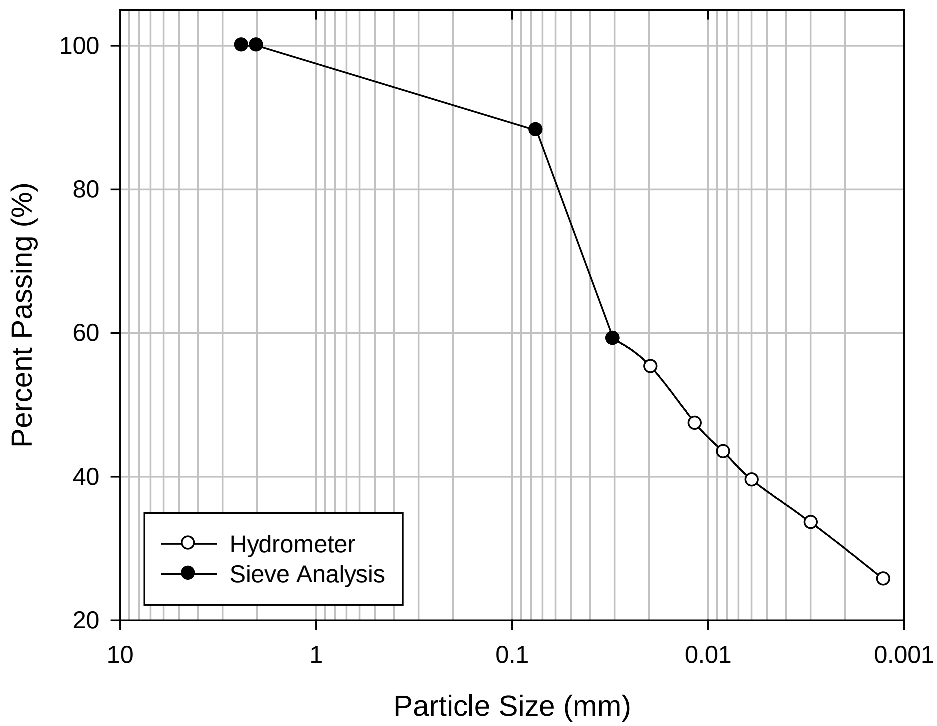

Figure 23: Vernon Soil Grain Size Distribution

4.3.2 UCT Results - Vernon Soil with Roadbond EN1

Several different concentrations of Roadbond EN1 were mixed with Vernon Soil to study the effects of increasing the concentration against the peak strength gains provided by the stabilization. For the UCTs two different curing times were studied, 14 days and 28 days. Three concentrations were studied for the 14-day curing time; 0.2%, 0.1%, and 0.06%. For the 28-day curing only the greatest concentration, 0.2% of Roadbond EN1 was tested. A comparison of the concentrations of Roadbond EN1 allowed to cure for 14 days can be found in Figure 24. The results of each test can be found in Appendix A. From this figure it appears that no strength gains were found for the concentrations tested. All of the samples that were soaked for 48 hours did not remain intact and were not tested. The performance of Roadbond EN1 doesn't appear to be effected greatly by variations in water content or dry density. The water contents and densities of each sample tested can be found in Appendix B.

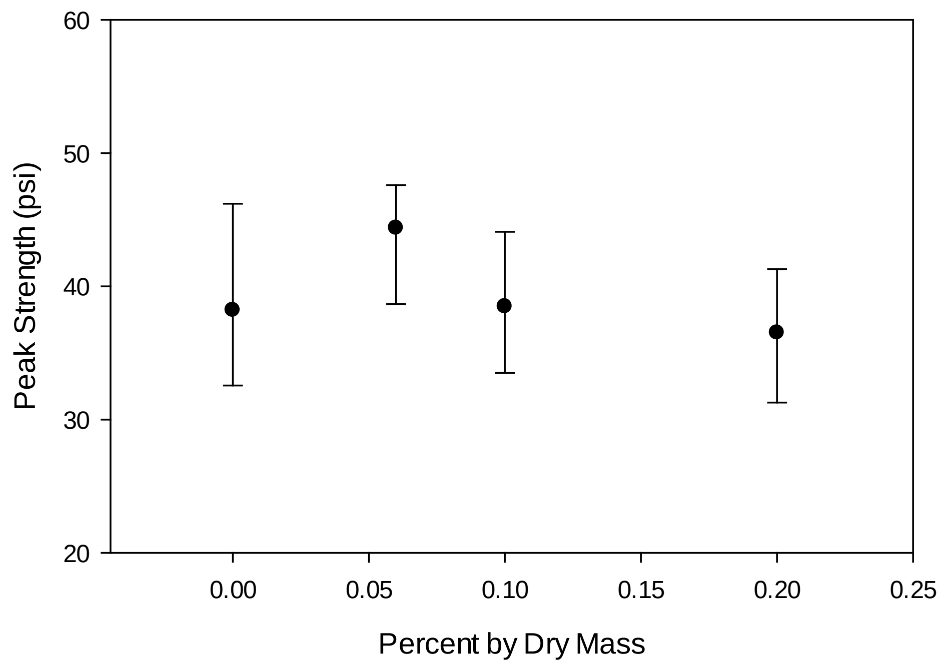

Figure 24: Vernon Soil with Roadbond EN1, UCT 14-Day Curing

The UCTs results for the 28-day curing when Roadbond EN1 was mixed with Vernon Soil at 0.2% concentration can be found in Appendix A. From the results of the 28-day curing UCTs some strength gains were found when the soil was mixed with Roadbond EN1. If the averages of the untreated peak strengths and the strengths of Roadbond EN1 treated samples are considered, there is a gain of greater than 20 psi. However, the strength increase from the addition of Roadbond EN1 does not meet the standard 50 psi requirement in OHD L-50. The 48 hour submerged specimens for all the soils tested did not remain intact and were not tested. The water contents and densities of each sample tested were relatively uniform and can be found in Appendix B.

4.3.3 UCT Results - Vernon Soil with Condor SS

Condor SS was mixed with Vernon Soil and specimens were prepared for two different curing times, 14 days and 28 days as described in Chapter 3. Three concentrations of Condor SS were prepared and tested for the 14-day curing; 0.2%, 0.06%, and 0.004%. For the UCS testing with 28 days of curing only the greatest concentration (0.2%) of Condor SS was tested. A comparison of the UCTs for Vernon Soil when mixed with the manufacturer recommended concentrations of Condor SS and allowed to cure for 14 days can be found in Figure 25. From the comparison it can be seen that the addition of Condor SS to Vernon Soil tended to decrease the peak compressive strength of the soil. The results of each UCT can be found in Appendix A. The submerged specimens did not remain intact and were not testable. The water content for one of the 0.004% concentration stabilized samples was relatively high; however there doesn’t appear to be a trend with the variation in water content or dry density and performance of Condor SS. The water contents and densities of each sample tested can be found in Appendix B.

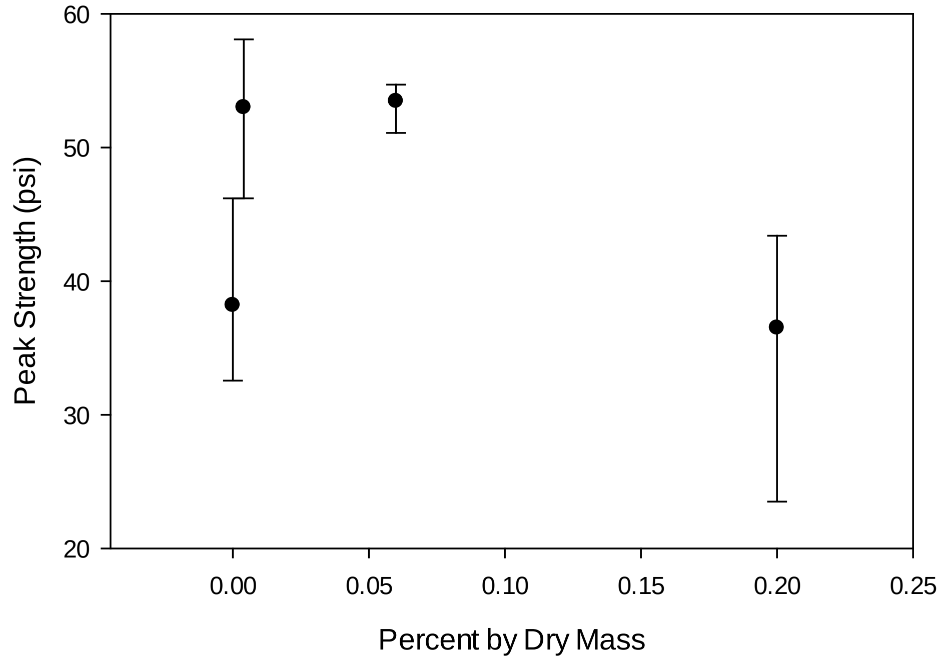

Figure 25: Vernon Soil with Condor SS, UCT 14-Day Curing

The results of the UCTs for the 28-day curing are located in Appendix A. From the results, it was found that for two of the tests the strength almost doubled when Condor SS was mixed with the soil for the concentration tested. This is the greatest strength gain noted of all the soils with either Roadbond EN1 or Condor SS. However, the strength gains do not meet the 50 psi increase requirement. The submerged specimen did not remain intact and were not testable. The water contents and densities of each sample tested are relatively uniform and can be found in Appendix B.

4.3.4 UCT Results - Vernon Soil with Fly Ash

Vernon soil was prepared with 14% class C fly as a basis for comparing either acid based chemical against a currently used stabilizer. It should be noted that when a sulfate soil is mixed with fly ash or any other form of stabilizer containing sulfate, swelling due to ettringite formation may occur when adequate water is present as described in Chapter 2. With this in mind Vernon Soil would not be stabilized with fly ash in practice and the basis for stabilization here is solely based off of the classification of the soil and not the sulfate content. The soil specimens were tested for two curing times, 14 and 28 days. The results of the 14-day curing UCT's can be found in Figure 26 along with the highest concentration of either Roadbond EN1 or Condor SS tested. From the results it can be seen that the addition of 14% fly ash greatly increases the strength of the soil more than either Roadbond EN1 or Condor SS. The submerged samples did not remain intact due to the swelling from the addition of water to the soil-chemical combinations and were not tested. Variations in the water content or dry density of the samples don't appear to explain the performance of the chemical additives. The water contents and densities of each sample tested can be found in Appendix B.

The UCTs results for the 28-day curing Vernon Soil mixed with 14 % fly ash can be found in Figure 27 compared with the 28 day curing Roadbond EN1 or Condor SS stabilized soil. The results show that the fly ash stabilized specimens have a much higher UCS; however fly ash should not be used to stabilize this soil due to the high expansive nature of the combination shown in the oedometer results for this soil. Roadbond EN1 and Condor SS did produce some notable increase in the 28-day strength compared to untreated soil, but not to the recommended performance measure of 50 psi increase.

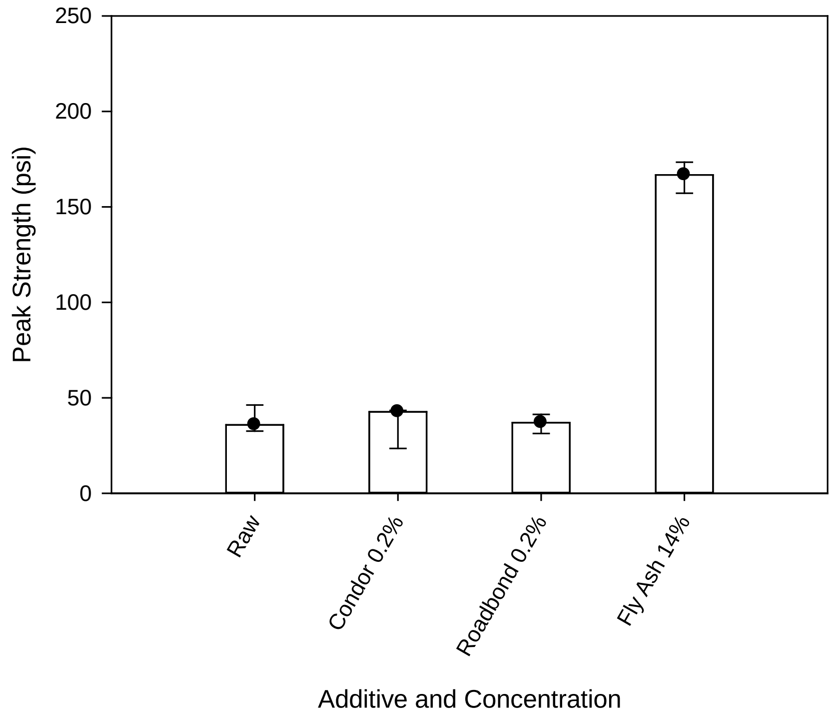

Figure 26: Vernon Soil with Fly Ash Comparison, UCT 14-Day Curing

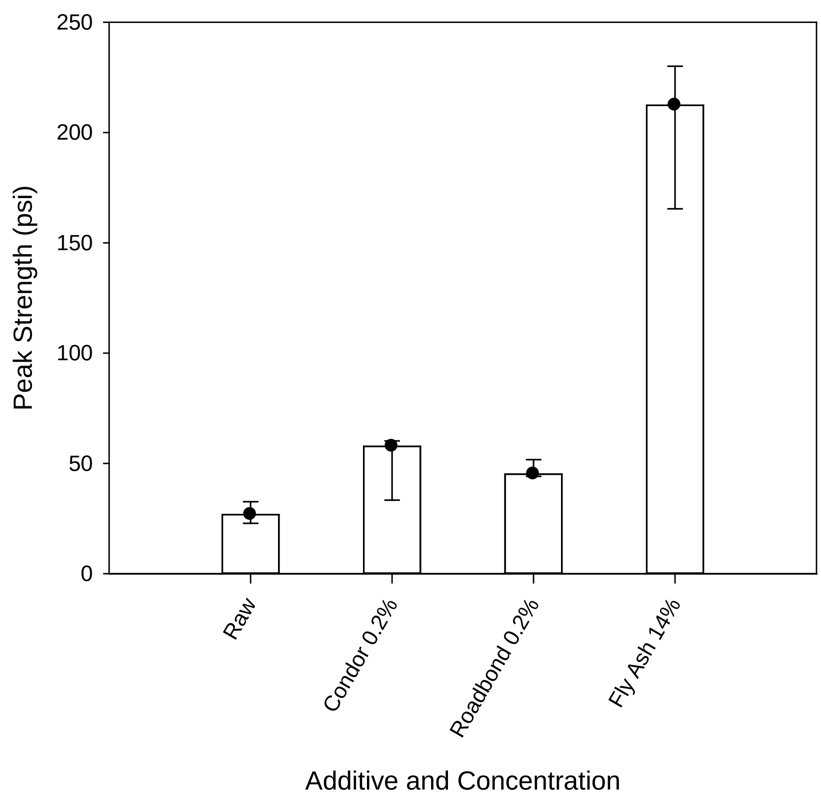

Figure 27: Vernon Soil with Fly Ash Comparison, UCT 28-Day Curing

4.3.5 UCT Results – Vernon Soil with Fly Ash and Roadbond EN1/Condor SS

Vernon Soil was prepared with 5% fly ash and 0.015% of either Roadbond EN1 or Condor SS. The specimens were allowed to cure for two different curing times, 14 and 28 days as described in Chapter 3. The results of the 14-day curing UCTs can be found in Figure 28. The results show that the stabilization benefits achieved can be attributed to the addition of fly ash, with little improvement from the fly ash and Roadbond EN1 or Condor SS combinations. The submerged samples did not remain intact and were not tested. The water contents and dry densities of each sample tested are relatively uniform and can be found in Appendix B.

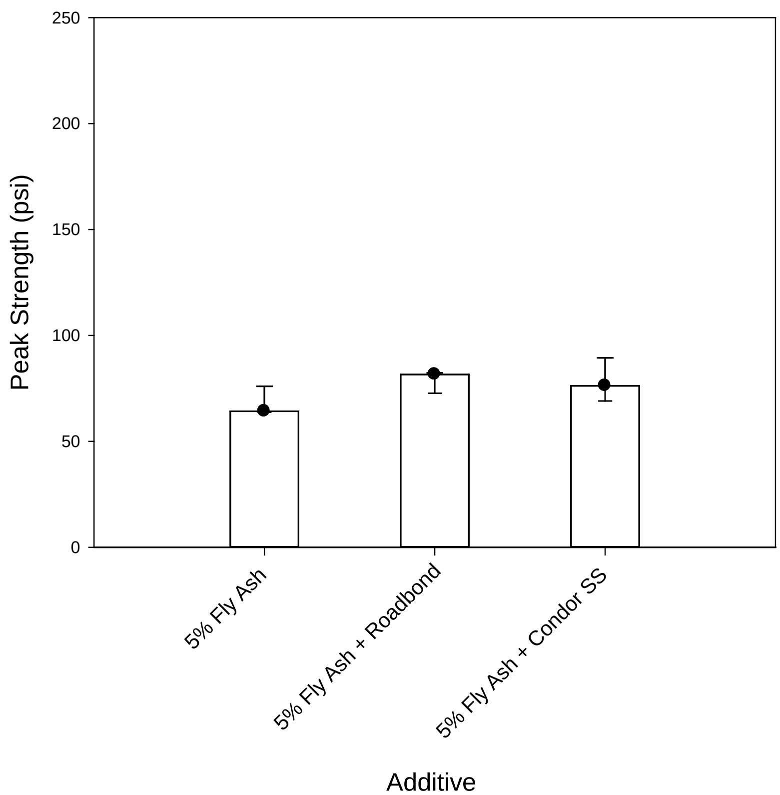

Figure 28: Vernon Soil with Fly Ash and Roadbond EN1/Condor SS, 14-Day Curing UCT Comparison

The results from the 28-day curing time fly ash and Roadbond EN1 or Condor SS combinations UCTs can be found in Figure 29. From the figure it can be seen that Vernon Soil with the addition of fly ash at 5% performed the same as fly ash plus either stabilizer, Roadbond EN1 or Condor SS. The soaked specimens did not remain intact and were not tested. The dry density and water content don't appear to explain the performance of the acid-based chemical additives. The water contents and densities of each sample tested can be found in Appendix B.

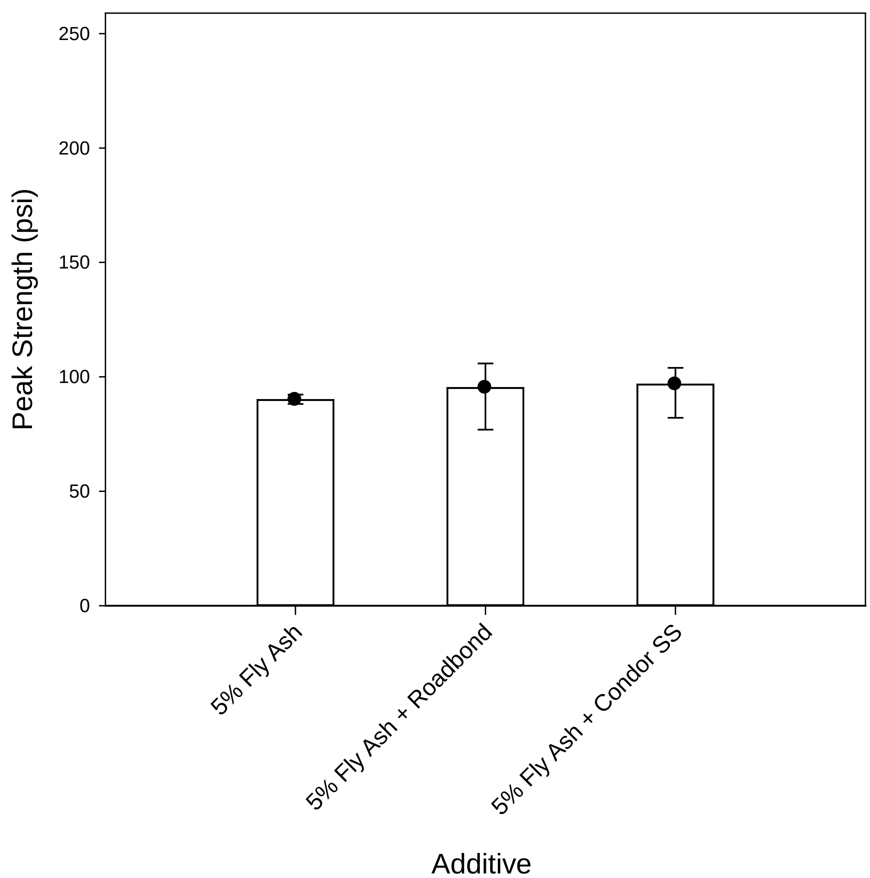

Figure 29: Vernon Soil with Fly Ash and Roadbond EN1/Condor SS, 28-Day Curing UCT Comparison

4.3.6 Vernon Soil Oedometer Test Results

Free swell oedometer test were completed with Vernon Soil mixed with Roadbond EN1 and Condor SS at a 0.2% concentration. The soil was also prepared with 4% lime and 14% fly ash to allow for a comparison of the potential swelling that can be experienced when Vernon Soil is mixed with calcium based stabilizers. The results of the free swell oedometer test can be found in Figure 30. From the results of the oedometers it can be seen that no swelling was observed in the soil for untreated soil and for soil treated with Roadbond EN1 or Condor SS. Since no swell was observed in the untreated soil, Roadbond EN1 and Condor SS can't be said to reduce the swell based on the test completed. However, as can be seen from the graph the soil will swell greatly, up to 10%, when mixed with lime or fly ash due to the ettringite crystal expansion discussed in Chapter 2. The water contents and densities of each sample tested can be found in Appendix B.

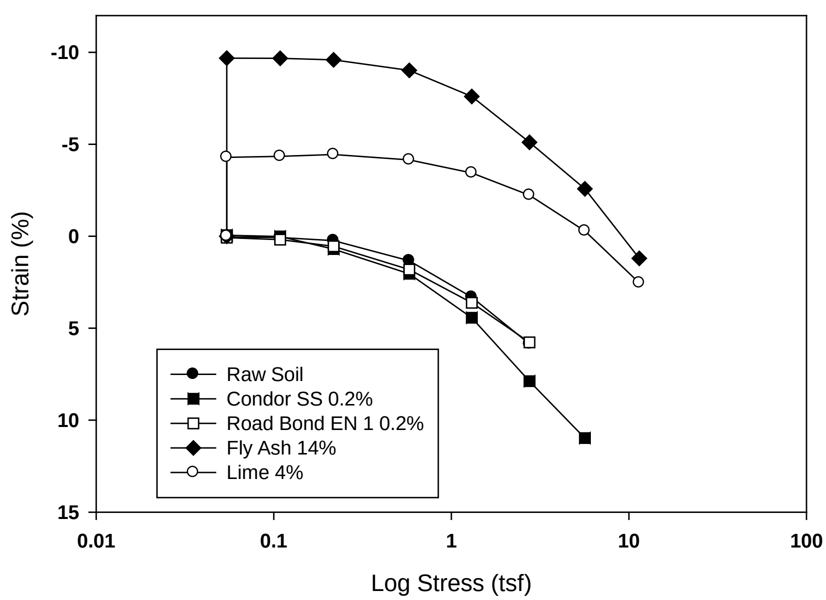

Figure 30: Vernon Soil Free Swell Oedometer

4.3.7 pH Curve

A series of pH test has been conducted to determine the effect of either Roadbond EN1 or Condor SS on Vernon Soil. The results of the pH tests can be found in Figure 31. From the results it can be seen that for the concentrations of either chemical tested for UCS and swelling potential, the soil pH did not change much. Significant pH change was not seen with Condor SS until a dry soil mass concentration of 4 to 6% and 2 to 4% with Roadbond EN1. The low change in pH for the concentrations of either chemical tested may help to explain why the acid based chemical stabilizers did not appear to increase the strength of the soil.

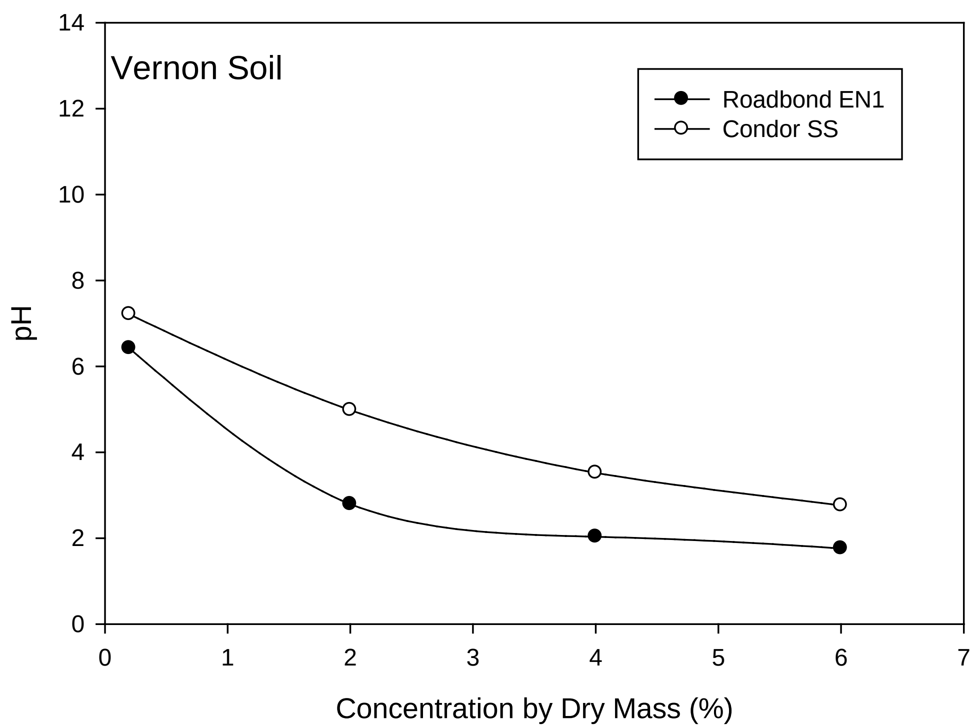

Figure 31: Vernon Soil pH Test Results

4.4 Influence of High Concentrations of Acid-Based Chemicals on Soil Strength

A series of UCTs were conducted for each soil mixed with either Roadbond EN1 or Condor SS at a dry mass concentration of 6% cured for 14 days. The purpose of testing was to investigate the effectiveness of the chemicals at high additive concentration when the soil pH is decreased greatly. From the pH curves shown in the previous sections the pH of the soil tends to change less above a dry mass concentration around 6%. This concentration was selected to test the influence of chemical additives at high dose. The results of each UCT conducted can be found in Appendix A. For all the soil-chemical combinations tested an increase in UCS was only found when Roadbond EN1 at 6% concentration was mixed with Lela Clay or Vernon soil as can be seen in Figure 33 and 86 (in the appendix), respectively. Despite the increase found in the two aforementioned soil-chemical combinations the strength gains do not meet the 50 psi increase requirement for effective chemical stabilizers. The other soil-chemical combinations did not perform better than the untreated soil. The soaked samples did not remain intact during submergence and were not tested.

5.0 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDIES

5.1 Conclusions

Roadbond EN1 and Condor SS soil stabilizers were mixed with three soils from the state of Oklahoma in an effort to study the performance of these non-lime based chemical stabilizers. The effect of Roadbond EN1 and Condor SS on the plasticity index of the soil was tested after no curing and 14 days of curing. To gauge the effects of Roadbond EN1 and Condor SS on strength, unconfined compression specimens were prepared with a range of concentrations for each stabilizer, and tested after curing 14 and 28 days. For comparison, soils were also mixed with lime or fly ash according to ODOT OHD L-50, and subjected to similar tests. For the study, two high plasticity soils were tested as well as one with moderate plasticity that also contained appreciable amounts of soluble sulfate. The soil containing sulfate, Vernon Soil, was of particular interest in this study since it cannot be effectively stabilized with lime or fly ash due to the adverse heave that occurs due to ettringite crystal formation. A series of free swell oedometer test were also conducted to determine the effect, if any, Roadbond EN1 or Condor SS had on the swelling potential. To gauge the benefits of the non-lime based stabilizers, the soils were also prepared with lime or fly ash and subjected to free swell oedometer tests.

Lela Clay (30<PI<35) when mixed with Roadbond EN1 or Condor SS for the concentrations tested in this study showed no improvement when subjected to UCTs for both curing times. The plasticity index of the soil remained relatively unchanged for both no curing and 14-day curing when Roadbond EN1 or Condor SS was added to the soil. In regards to free swell oedometer tests, both stabilizers had little effect on reducing swell potential or compressibility when mixed with Lela Clay. When Lela Clay was stabilized with 6% lime, as recommended by ODOT OHD L-50, the soil showed noticeable strength increases during the UCTs, and substantial reductions in swelling and compressibility.

Renfrow Clay (30<PI<35) when mixed with Roadbond EN1 and tested for UCS showed no improvement for the concentrations of stabilizer tested under the curing times studied when compared with the untreated samples subjected to the same testing method. Similar results were found when Renfrow Clay was mixed with Condor SS for the concentrations and curing times tested. The addition of Roadbond EN1 or Condor SS were found to not change the plasticity index of the soil for either curing time; no curing and 14 days of curing. Renfrow Clay subjected to free swell oedometer testing prepared with either Roadbond EN1 or Condor SS showed little to no change in swelling potential or compressibility for the concentrations used. When stabilizing Renfrow Clay with 6% lime as directed by ODOT OHD L-50, the soil showed noticeable strength gains and reductions in swell potential and compressibility.

Vernon Soil (15<PI<19) when mixed with Roadbond EN1 showed little improvement for the concentrations tested under the 14-day curing subjected to UCTs. The Vernon Soil-Roadbond EN1 combination subjected to 28 days of curing showed some improvement in strength; however, not enough improvement to be deemed an effective stabilizer based on a 50 psi increase in strength over the untreated soil. When the soil was mixed with Condor SS and allowed to cure 14 days little benefits were noted. However, similar to Roadbond EN1, when Condor SS and Vernon Soil were allowed to cure for 28 days before UCTs, the mixture showed the most promising results of all the soil-chemical combinations. Despite the promising strength gains from Condor SS, the soil-chemical combination still did not meet the required strength increase to be deemed an effective stabilizer. The addition of Roadbond EN1 and Condor SS had little effect on the plasticity index of the soil for no curing and 14 days of curing. During the free swell oedometer testing, little change was noted when either Roadbond EN1 or Condor SS was mixed with Vernon Soil. The lack of change during the free swell test is important since the lime-based stabilizers tested during this study showed large amounts of heave making both lime and fly ash undesirable for stabilizing Vernon Soil. In the literature Rajendran and Lytton (1997) reported large increases in the strength of a two sulfate bearing soils in the Dallas, TX area; however, the increases they reported were not found during this study. The large range of increases in performance of either Roadbond EN1 or Condor SS when tested with a sulfate bearing soil could be dependent on the amount of soluble sulfate present in the soil being tested, or many other variables associated with the different soils tested.

It is recommended that if non-lime based chemical additives are used in practice for soil stabilization, they should be subjected to a mix design process similar to that described in ASTM D 4609 as referenced in ODOT OHD L-50. This will help to ensure that the desired changes in soil properties are being obtained by using the selected chemical additive.

5.2 Recommendations for Further Studies

Based on this research and the research cited in the literature from Rajendran and Lytton (1997) there may be some potential for stabilizing sulfate bearing soils with either Roadbond EN1 or Condor SS. While the concentrations tested during this study did not yield the results required by OHD L-50, more work should be completed to determine the following:

1. Determine if the amount of soluble sulfate affects the performance of either Roadbond EN1 or Condor SS when prepared with a sulfate bearing soil.
2. Determine whether the longer curing times would yield better results for Roadbond EN 1 or Condor SS when prepared with a sulfate bearing soil.
3. Study the effects of the concentration of either Roadbond EN1 or Condor SS when prepared with a sulfate bearing soil.
4. Take a closer look at the micro-scale structure of a sulfate bearing soil stabilized with either Roadbond EN1 or Condor SS to determine if any visible changes are noted in the soil-chemical structure.

REFERENCES

Aly Sabry, M., & Parcher, J. (1978). *Engineering Properties Of Compacted Soil-Lime Mixes.* Stillwater, Oklahoma: Oklahoma State University.

ASTM. (2012). *Standard Specification For Coal Fly Ash And Raw Or Calcined Natural Pozzolan For Use In Concrete ASTM C618-12a.* West Conshohocken, PA: American Society for Testing and Materials.

Berger, E., Litte, D., & Graves, R. (2001). *Technical Memorandum: Guidelines For Stabilization Of Soils Containing Sulfates.* Retrieved December 17, 2012, from lime.org: http://www.lime.org/publications.html

Bobrowski, L. (1992). *Injection Of A Liquid Stabilizer Into Subgrade Soil Research Report (TxDOT).* Texas: Texas Department of Transportation, Division of Materials and Testing.

Brooks, R., Udoeyo, F. F., & Takkalapelli, K. V. (2011). Geotechnical Properties Of Problem Soils Stabilized With Fly Ash And Limestone Dust In Philadelphia. *Journal of Materials in Civil Engineering 23.5*, 711-716.

Campbell, M. (2010). *Improved Test Methods For Determining Sulfate Content In Soils.* Norman, Oklahoma: University of Oklahoma.

Cerato, A., Miller, G., & Elwood-Madden, M. (2008). *Calcium-Based Stabilizer Induced Heave In Oklahoma Sulfate-Bearing Soils.* Oklahoma City: Oklahoma Department of Transportation.

Cerato, A., Miller, G., & Snethen, D. (2008). *Validation And Refinement Of Chemical Stabilization Procedures For Pavement Subgrade Soils In Oklahoma - Volume I.* Oklahoma City: Oklahoma Department of Transportation.

Epps, J., Dunlap, W., Gallaway, B., & Currin, D. (1971). *Highway Research Record Number 351: Soil Stabilization: Asphalt, Lime, Cement-Soil Stabilization: A Mission Oriented Approach.* Washington D.C.: Highway Research Board.

Gifford, G. F., Faust, R. H., & Coltharp, G. B. (1977). Measuring Soil Compaction On Rangeland. *Journal of Range Management*, 457-460.

Harris, P. J., Sebesta, S., & Sullion, T. (2004). Hydrated Lime Stabilization Of Sulfate-Bearing Vertisols In Texas. *Journal of the Transportation Research Board*.

Ingles, O., & Metcalf, J. (1973). *Soil Stabilization Principles And Practice.* New York: John Wiley and Sons.

Khattab, S., Al-Mukhtar, M., & Fleureau, J. (2007). Long-Term Stability Charactersitics Of A Lime-Treated Plastic Soil. *Journal of Materials in Civil Engineering 19.4*, 358-366.

Kumar, A., Walia, B., & Bajaj, A. (2007). Influence Of Fly Ash, Lime, And Polyester Fibers On Compaction And Strength Properties Of Expansive Soil. *Journal of Materials in Civil Engineering*.

Little, D. (1987). *Fundamentals Of the Stabilization Of Soil With Lime.* Arlington, Virginia: National Lime Association.

Miller, G., & Shahriar, A. (2000). Influence Of Soil Type On Stabilization With Cement Kiln Dust. *Construction and Building Materials*.

Miller, G., & Zaman, M. (2000). Field And Laboratory Evalution Of Cement Kiln Dust As A Soil Stabilizer. Transportation Research Record, Journal of the Transportation Research Board, National Research Council, No. 1714, pp. 25-32.

Miller, G., Cerato, A., Snethen, D., Holderby, E., & Boodagh, P. (2011). *Validation And Refinement Of Chemical Stabilization Procedures For Pavement Subgrade Soils In Oklahoma-Volume II.* Research Report for the Oklahoma Department of Transportation, Report No.: FHWA-OK-11-02(2), University of Oklahoma.

Mitchell, J., & Dermatas, D. (1992). Clay Soil Heave Caused By Lime-Sulfate Reactions. In D. Walker, T. Hardy, D. Hoffman, & D. Stanley, *Innovations and Uses for Lime* (pp. 41-64). Philadelphia: Smerican Society for Testing and Materials.

Mitchell, J., & Hooper, D. (1961). Influence Of Time Between Mixing And Compaction On Properties Of Lime-Stabilized Expansive Clay. *Highway Research Board*, Bulletin 304.

Nevels, J. B., & Laguros, J. G. (2005). Discussion Of "Studies Of Sulfate-Resistand Cement Stabilization Methods To Address Sulfate-Induced Soil Heave" By Anand J. Puppala, Julie Ann Griffin, Laureano R. Hoyos, And Suppakit Chomtid". *Journal of Geotechnical and Geoenvironmental Engineering 131.11*, 1439.

ODOT. (2009). *OHD L-50 Soil Stabilization Mix Design Procedure.* Oklahoma City: Oklahoma Department of Transportation.

Phanikumar, B., & Sharma, R. S. (2007). Volume Change Behavior Of Fly Ash -Stabilized Clays. *Journal of Materials in Civil Engineering*, 61-74.

Puppala, A., Griffin, J., Hoyos, L., & Chomtid, S. (2004). Studies On Sulfate-Resistant Cement Stabilization Methods To Address Sulfate-Induced Soil Heave. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 4.

Rajendran, D., & Lytton, R. (1997). *Reduction Of Sulfate Swell In Expansive Clay Subgrades In The Dallas District.* College Station, Texas: Texas Transportation Institute.

Scholen, D.E. (1992). *Non Standard Stabilizers*. FHWA-FLP-92011, Federal Highway Administration, United States Department of Transportation, Washington, D.C.

Snethen, D., Miller, G., & Cerato, A. (2008). *Evaluation And Field Verification Of Strength And Structural Improvement Of Chemically Stabilized Subgrade Soil.* Research Report: ODOT Reference Number 2195, OSU EN 06-RS-200, Oklahoma State University, Oklahoma.

APPENDIX A: UNCONFINED COMPRESSION TEST RESULTS

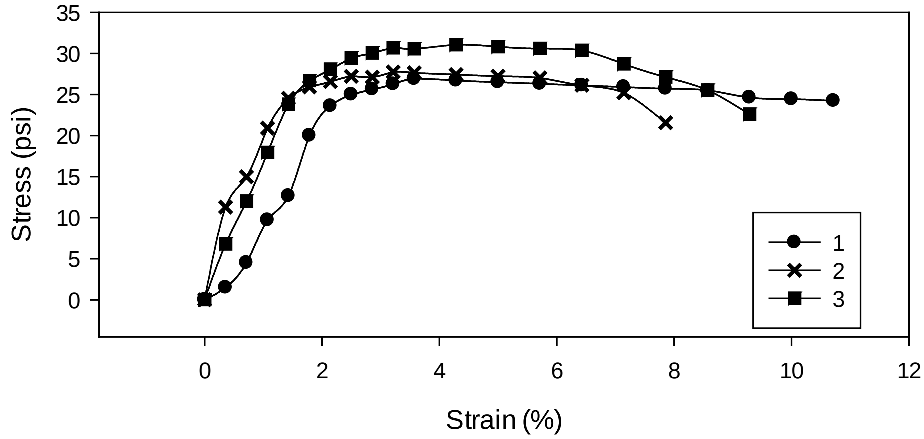

Figure 32: Lela Clay Untreated Soil 14-Day Curing

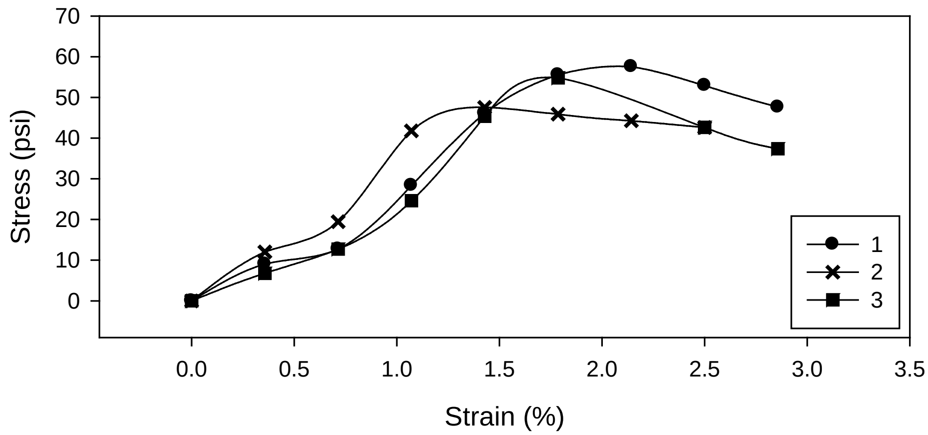

Figure 33: Lela Clay with Roadbond EN1 6% 14-Day Curing

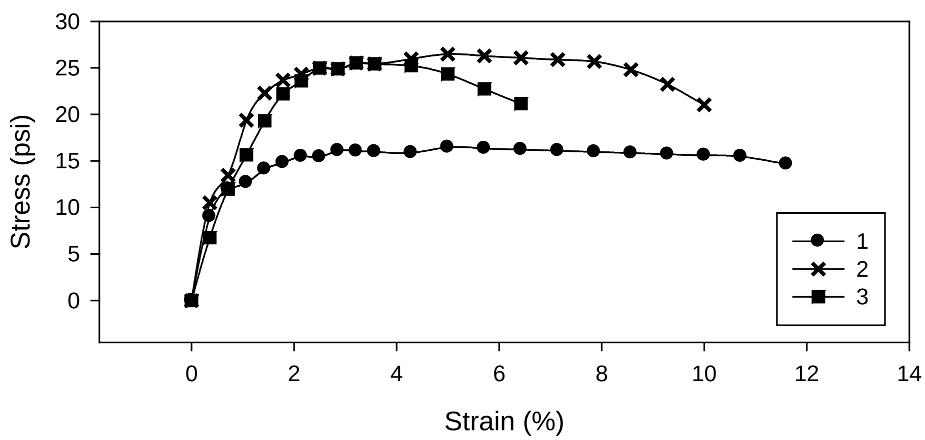

Figure 34: Lela Clay with Roadbond EN1 0.2% 14-Day Curing

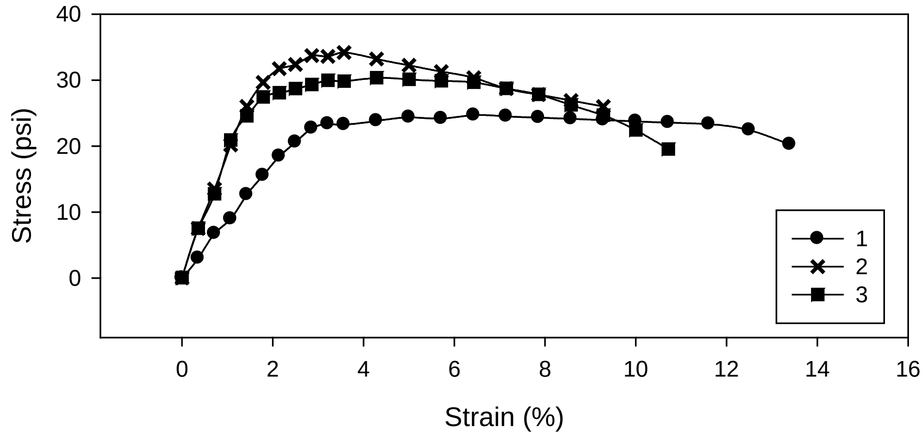

Figure 35: Lela Clay with Roadbond EN1 0.1% 14-Day Curing

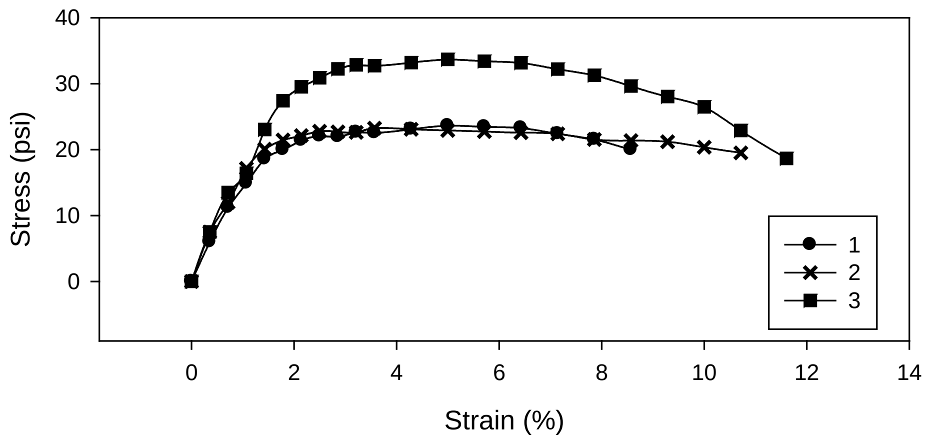

Figure 36: Lela Clay with Roadbond EN1 0.06% 14-Day Curing

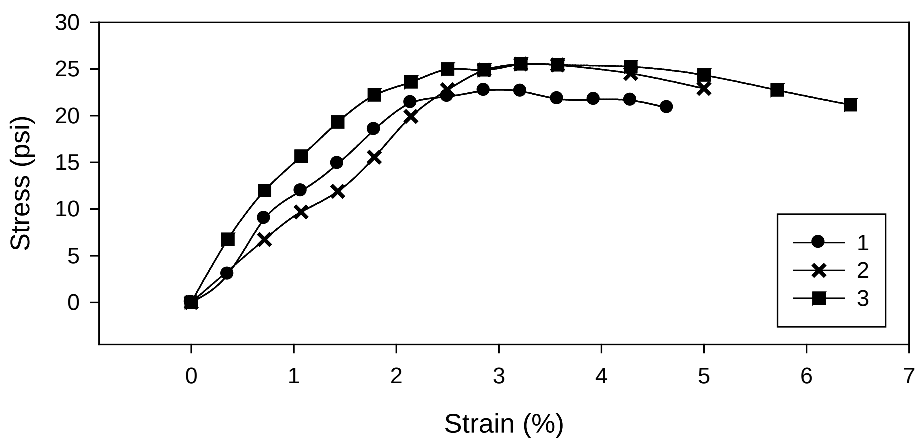

Figure 37: Lela Clay with Condor SS 6% 14-Day Curing

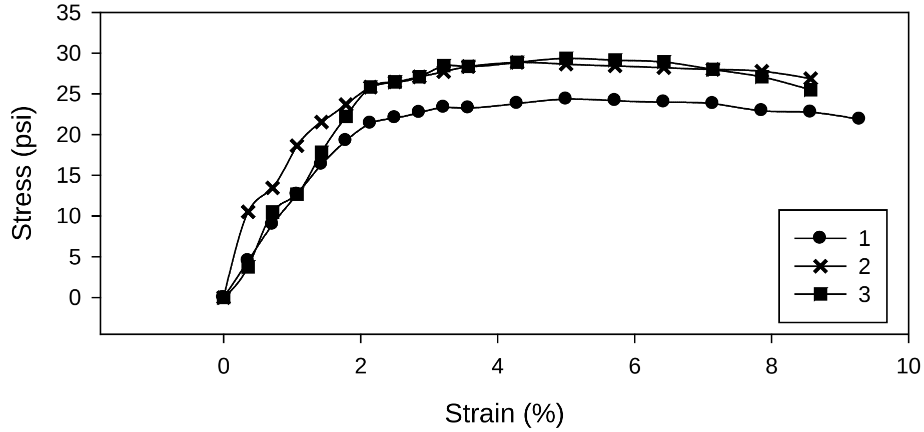

Figure 38: Lela Clay with Condor SS 0.2% 14-Day Curing

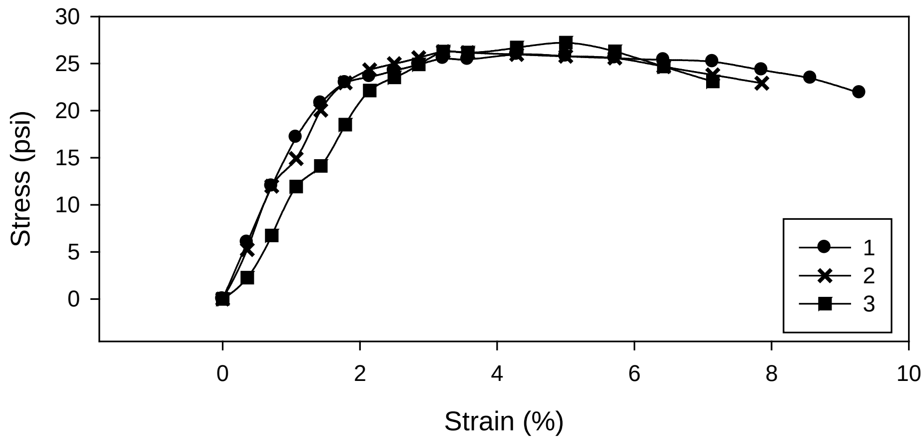

Figure 39: Lela Clay with Condor SS 0.06% 14-Day Curing

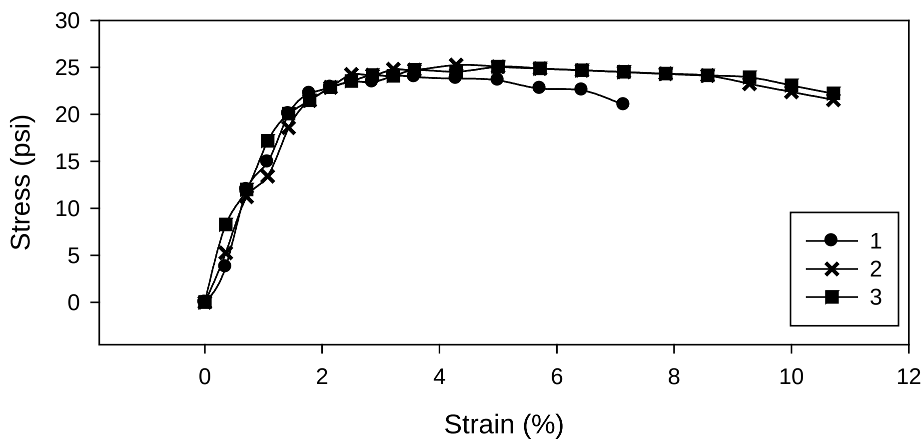

Figure 40: Lela Clay with Condor SS 0.004% 14-Day Curing

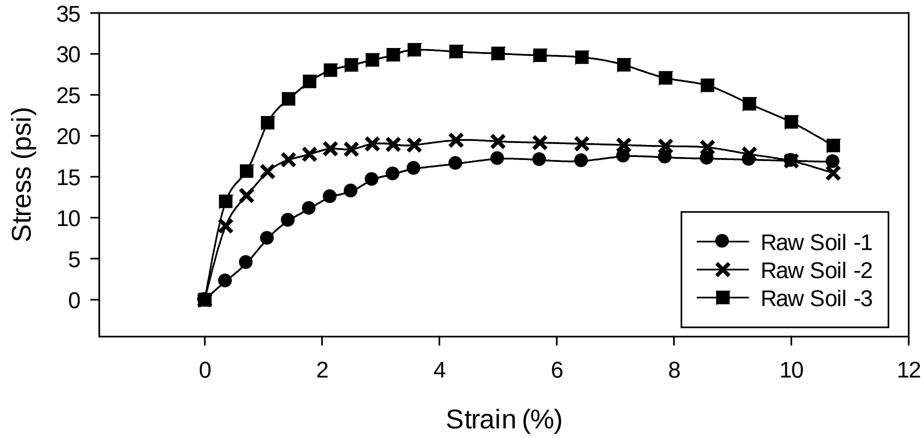

Figure 41: Lela Clay Untreated 28-Day Curing

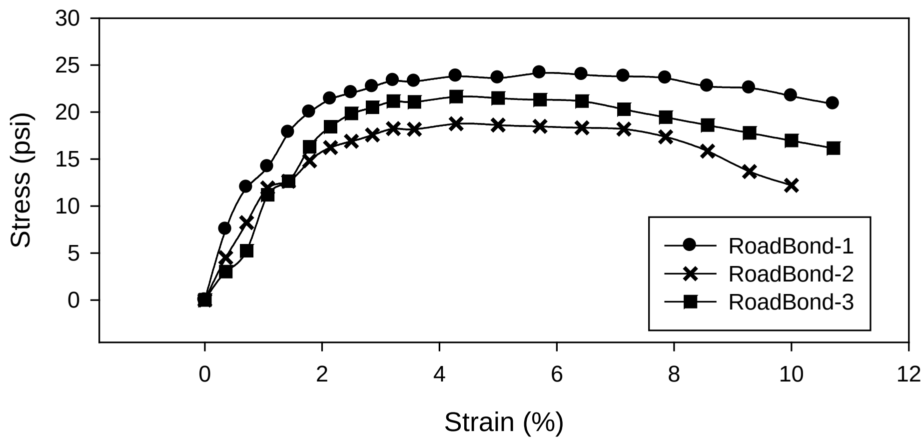

Figure 42: Lela Clay with Roadbond EN1 28-Day Curing

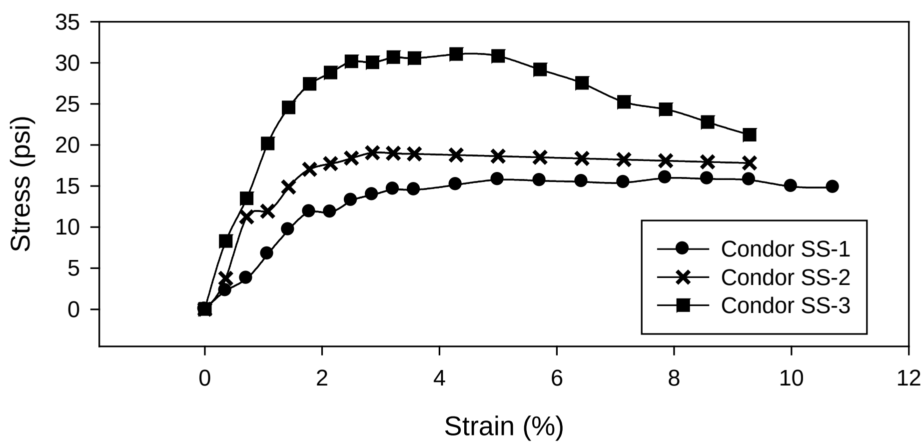

Figure 43: Lela Clay with Condor SS 28-Day Curing

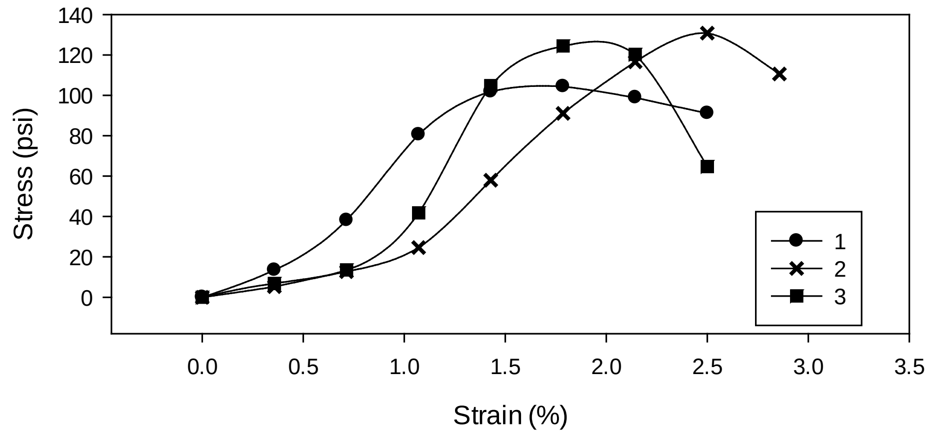

Figure 44: Lela Clay with Lime 6% 14-Day Curing

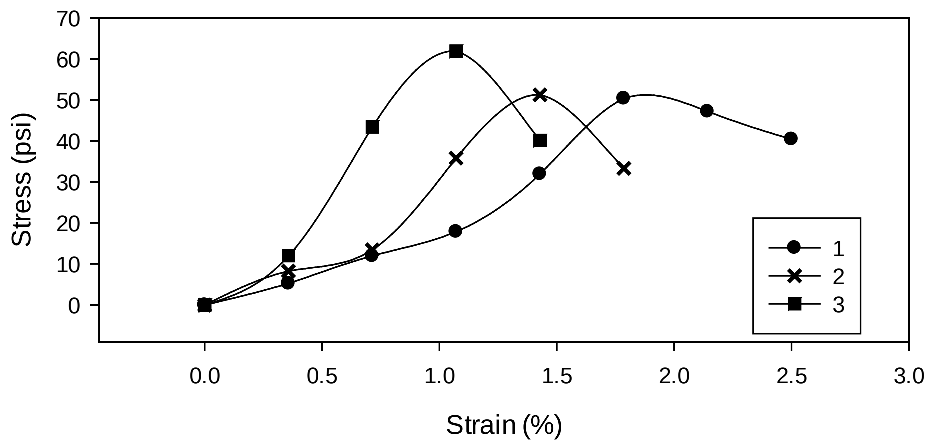

Figure 45: Lela Clay with Lime 6% 14-Day Curing Soaked 48 Hours

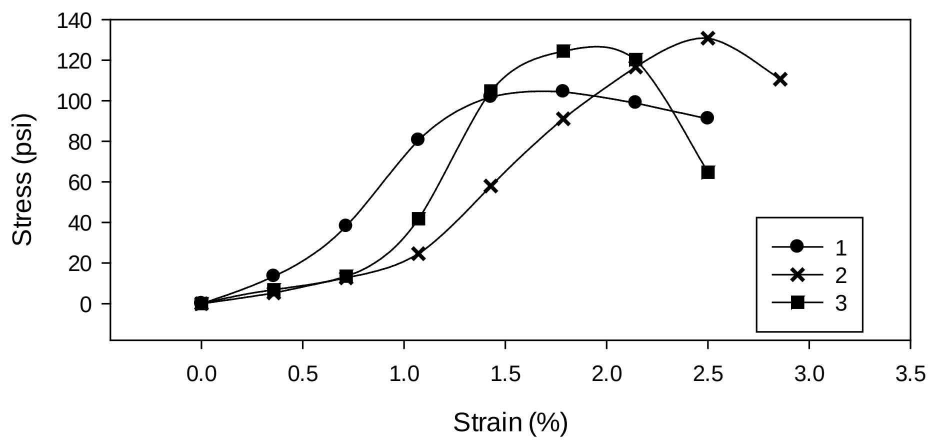

Figure 46: Lela Clay with Lime 6% 28-Day Curing

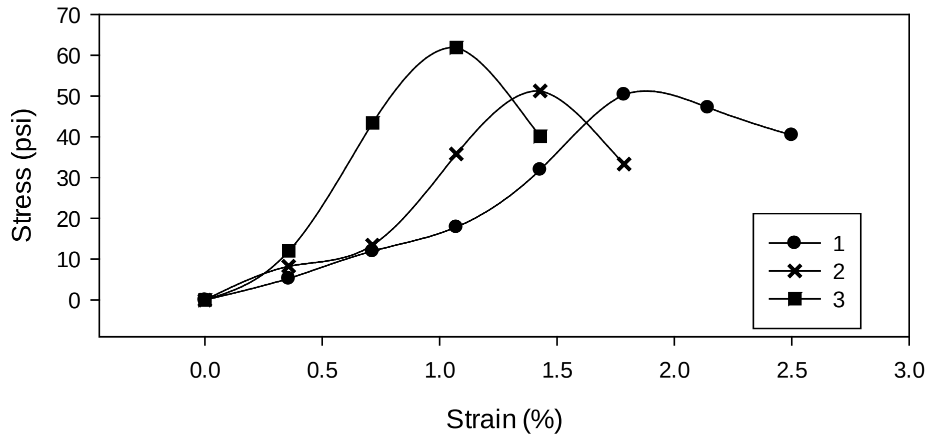

Figure 47: Lela Clay with Lime 6% 28-Day Curing Soaked 48 Hours

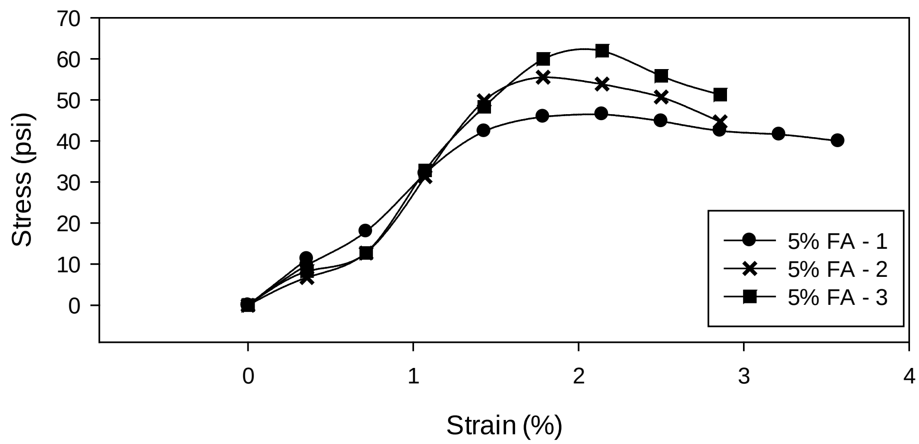

Figure 48: Lela Clay with Fly Ash 5% 14-Day Curing

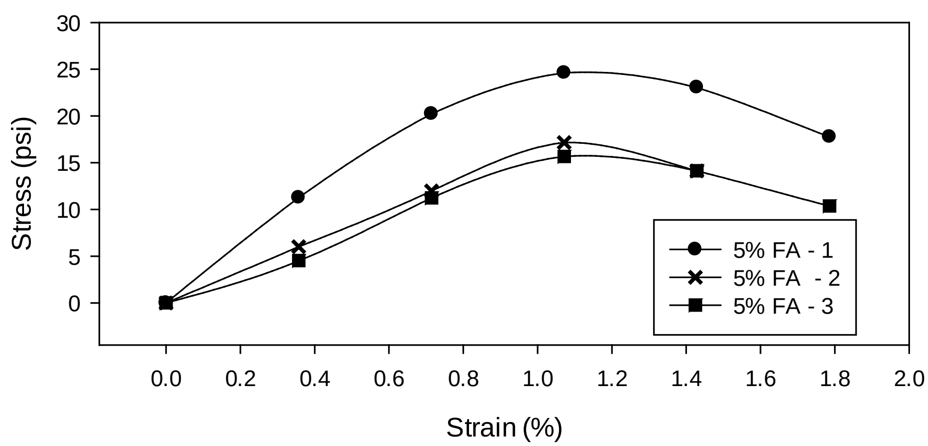

Figure 49: Lela Clay with Fly Ash 5% 14-Day Curing Soaked 48 Hours

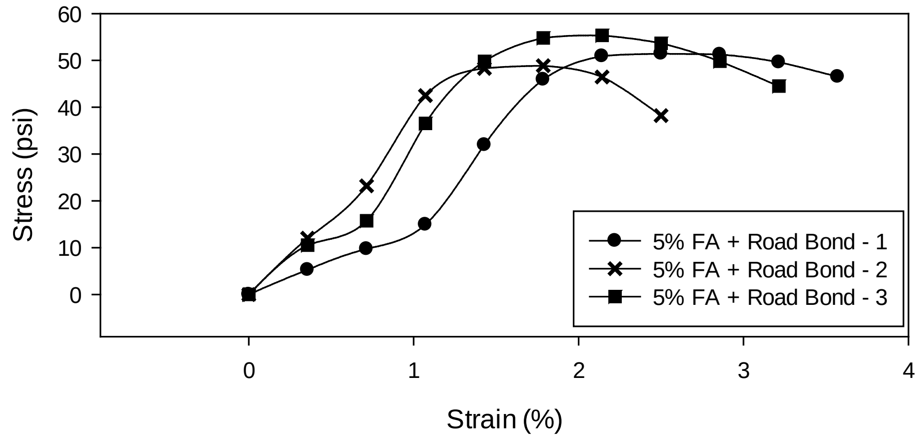

Figure 50: Lela Clay with Fly Ash 5% and Roadbond EN1 0.015% 14-Day Curing

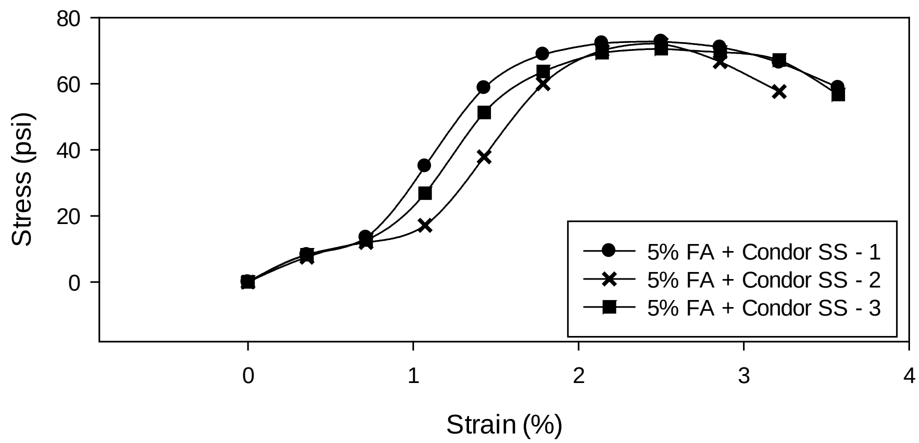

Figure 51: Lela Clay with Fly Ash 5% and Condor SS 0.015% 14-Day Curing

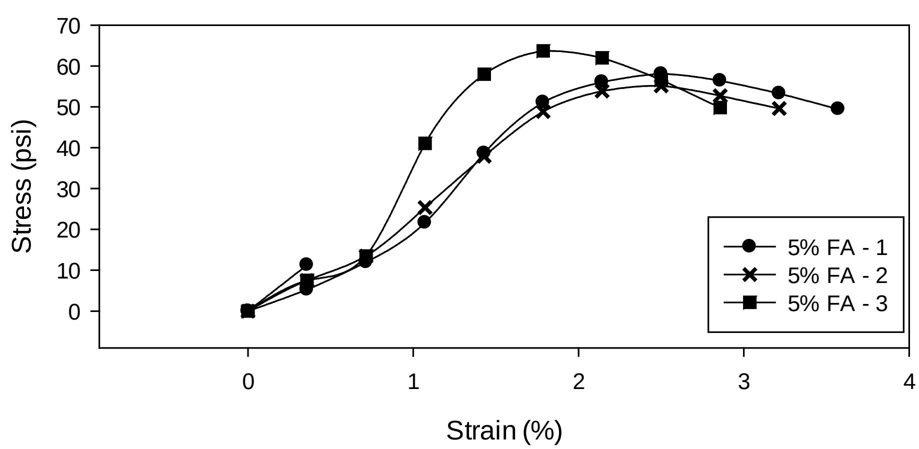

Figure 52: Lela Clay with Fly Ash 5% 28-Day Curing

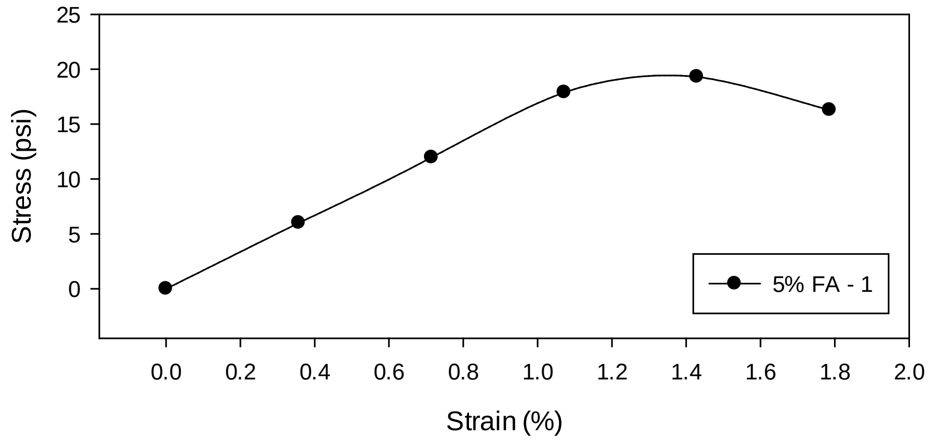

Figure 53: Lela Clay with Fly Ash 5% 28-Day Curing Soaked

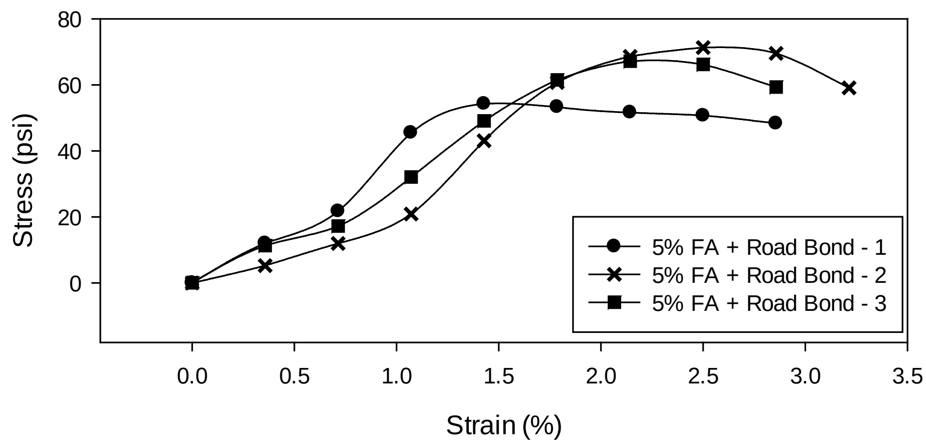

Figure 54: Lela Clay with Fly Ash 5% and Roadbond EN1 0.015% 28-Day Curing

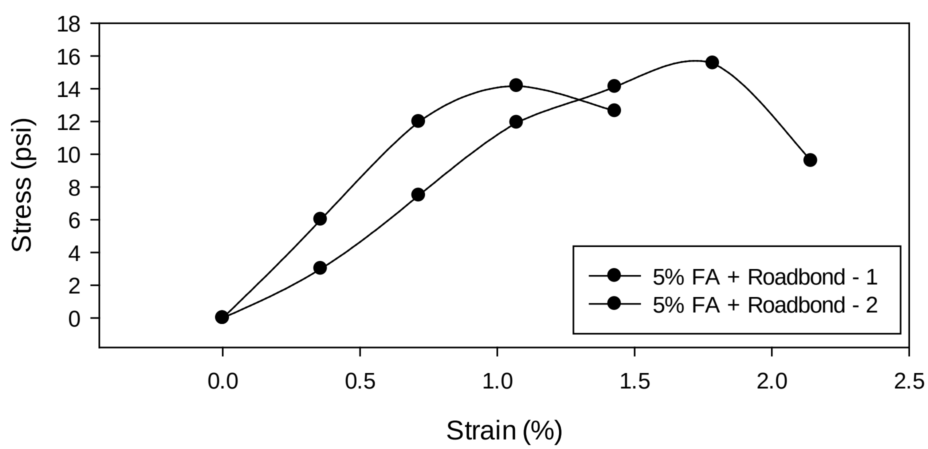

Figure 55: Lela Clay with Fly Ash 5% and Roadbond EN1 0.015% 28-Day Curing

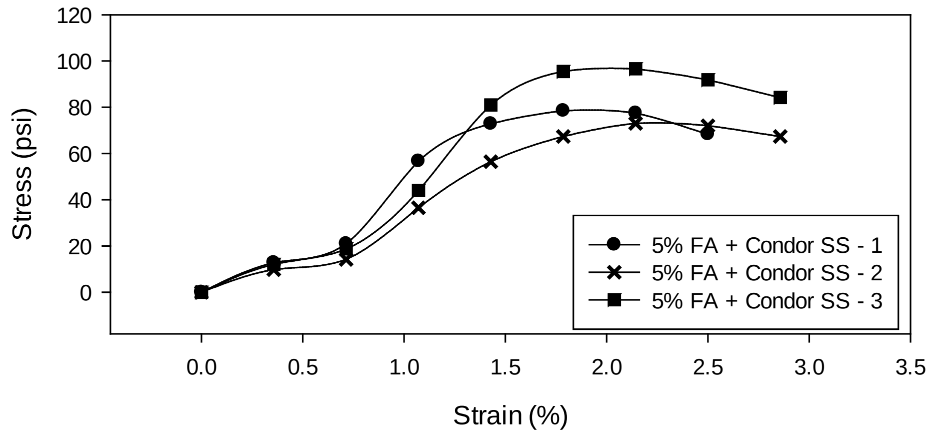

Figure 56: Lela Clay with Fly Ash 5% and Condor SS 0.015% 28-Day Curing

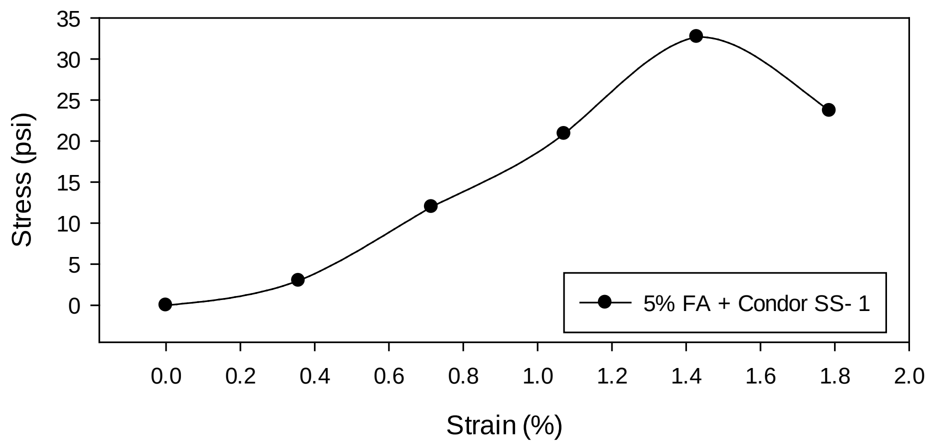

Figure 57: Lela Clay with Fly Ash 5% and Condor SS 0.015% 28-Day Curing Soaked

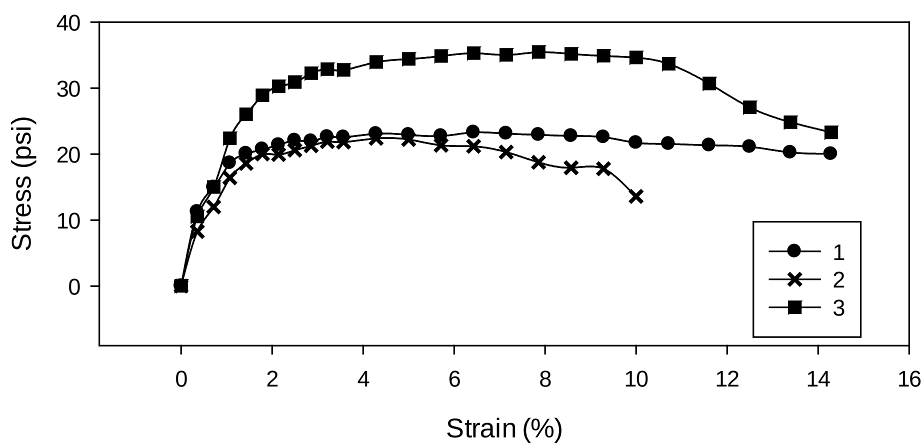

Figure 58: Renfrow Clay Untreated 14-Day Curing

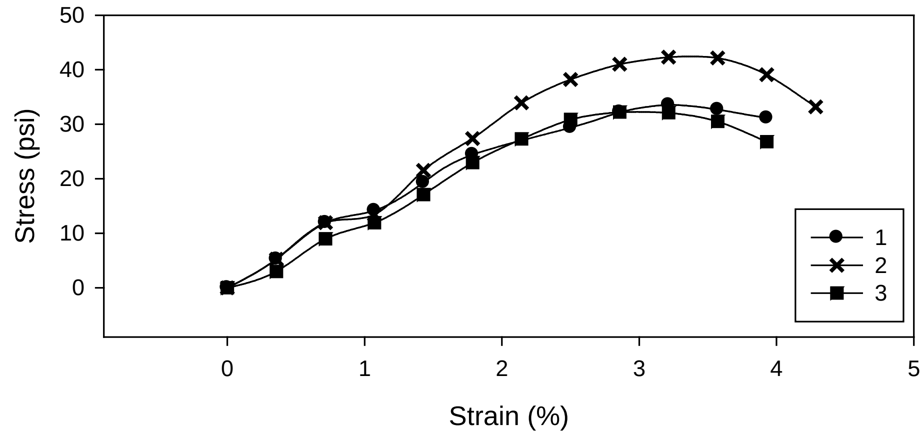

Figure 59: Renfrow Clay with Roadbond EN1 6% 14-Day Curing

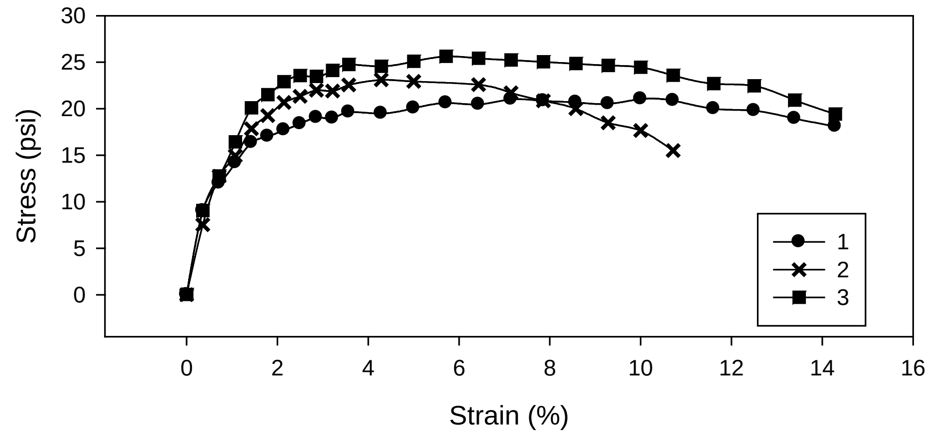

Figure 60: Renfrow Clay with Roadbond EN1 0.13% 14-Day Curing

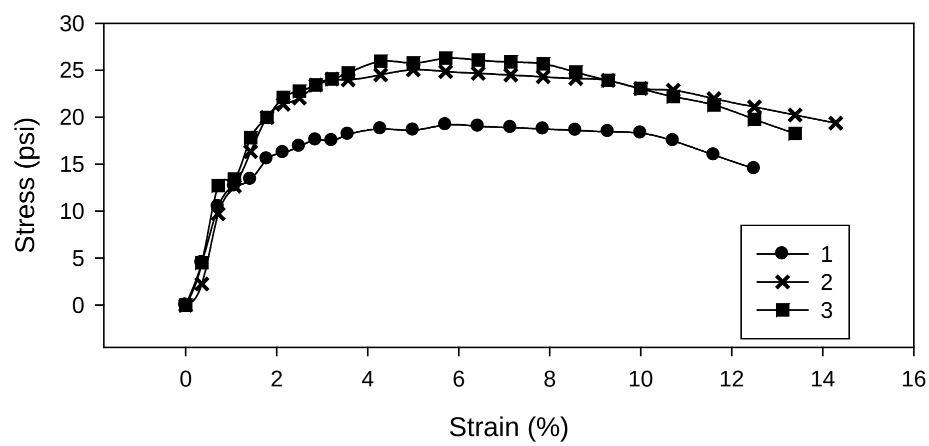

Figure 61: Renfrow Clay with Roadbond EN1 0.07% 14-Day Curing

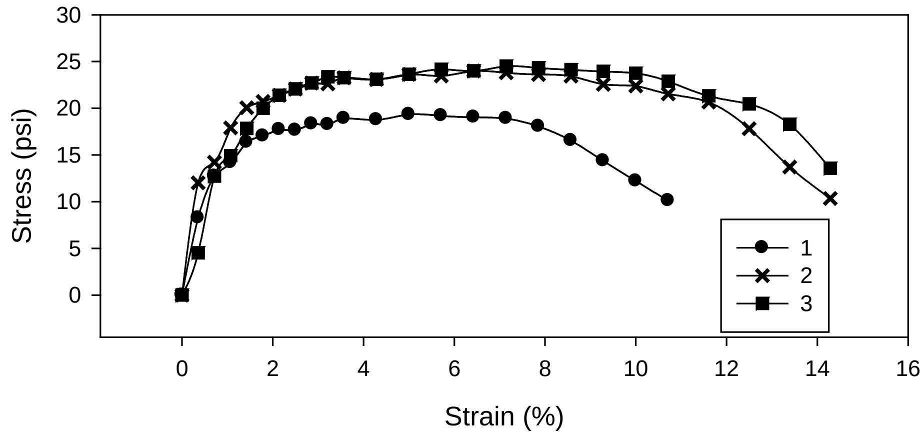

Figure 62: Renfrow Clay with Roadbond EN1 0.004% 14-Day Curing

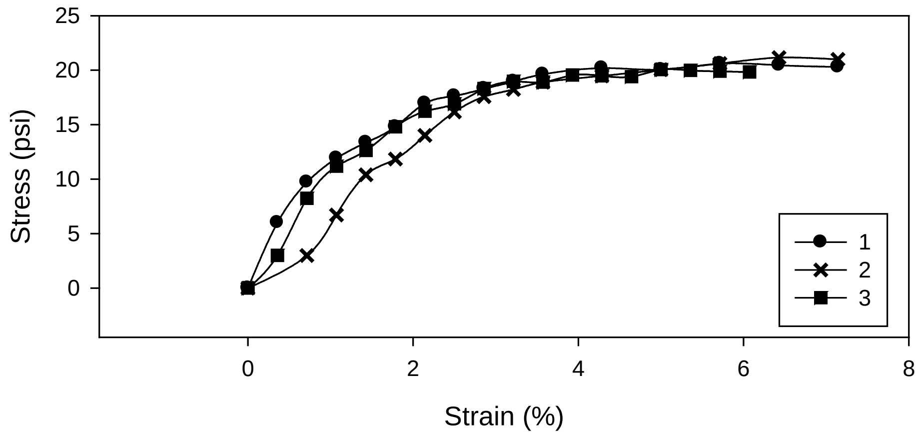

Figure 63: Renfrow Clay with Condor SS 6% 14-Day Curing

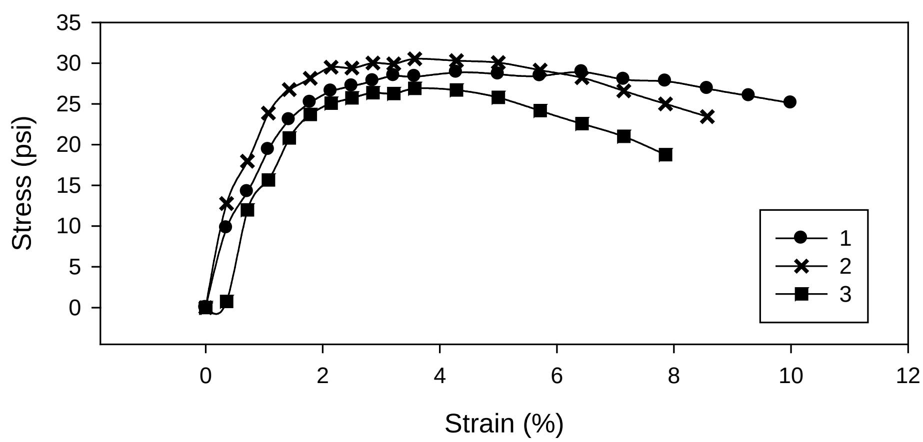

Figure 64: Renfrow Clay with Condor SS 0.13% 14-Day Curing

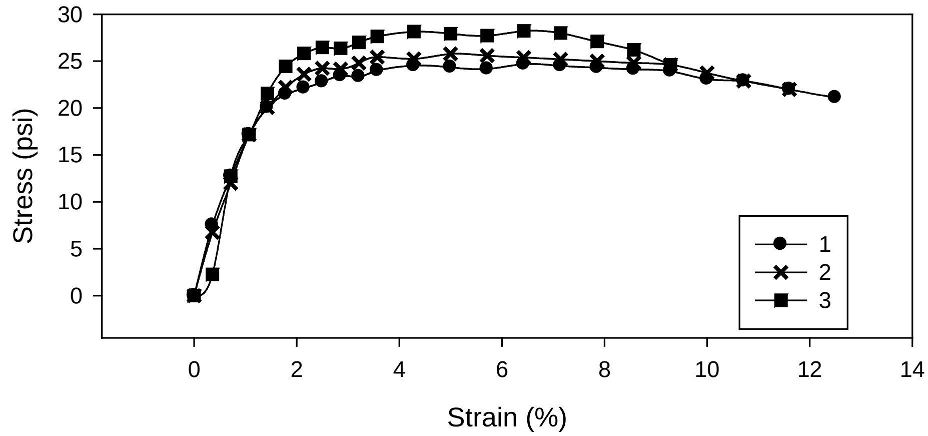

Figure 65: Renfrow Clay with Condor SS 0.04% 14-Day Curing

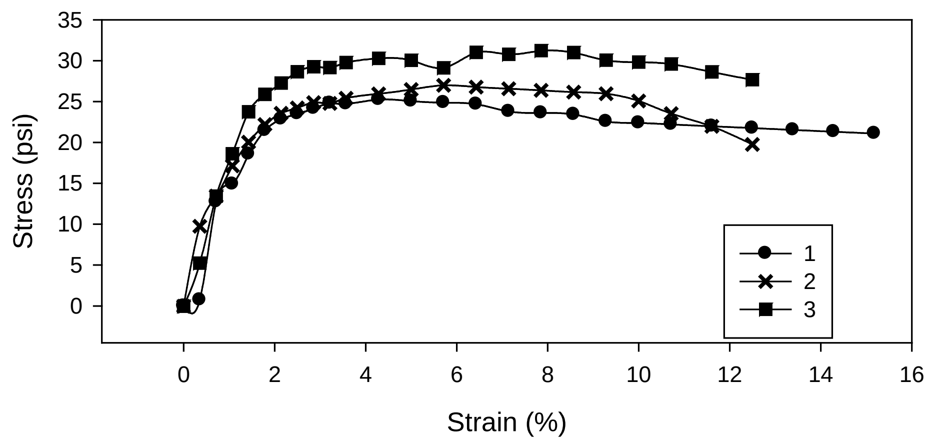

Figure 66: Renfrow Clay with Condor SS 0.003% 14-Day Curing

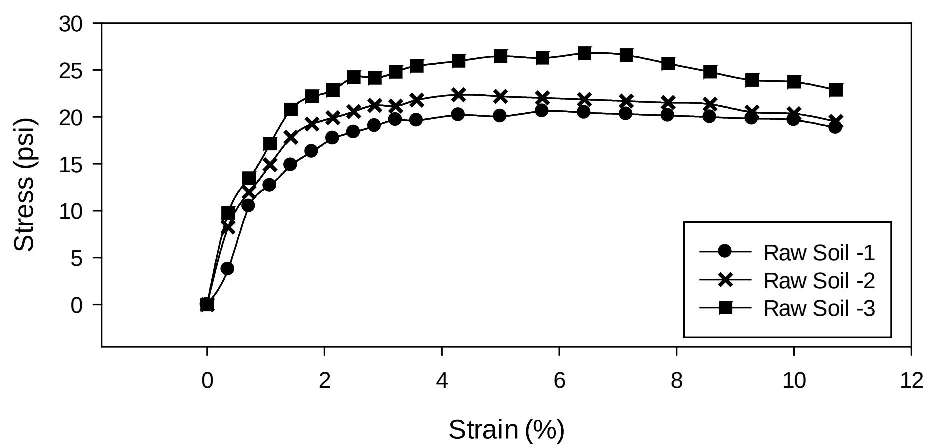

Figure 67: Renfrow Clay Untreated 28-Day Curing

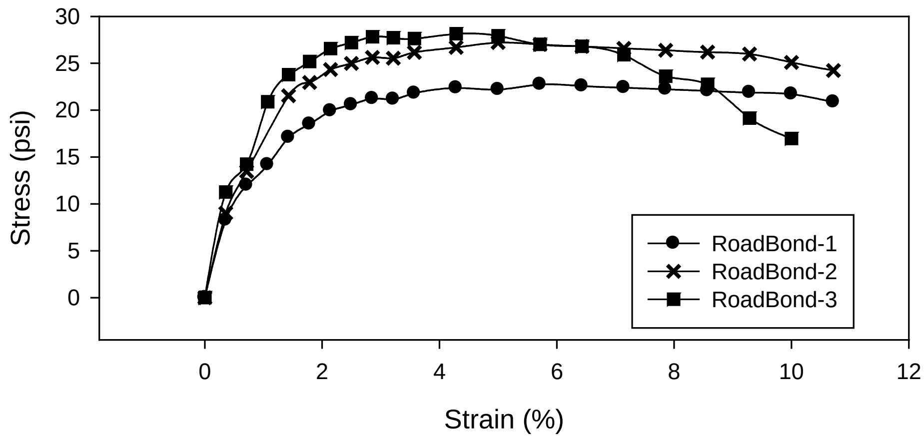

Figure 68: Renfrow Clay with Roadbond EN1 0.13% 28-Day Curing

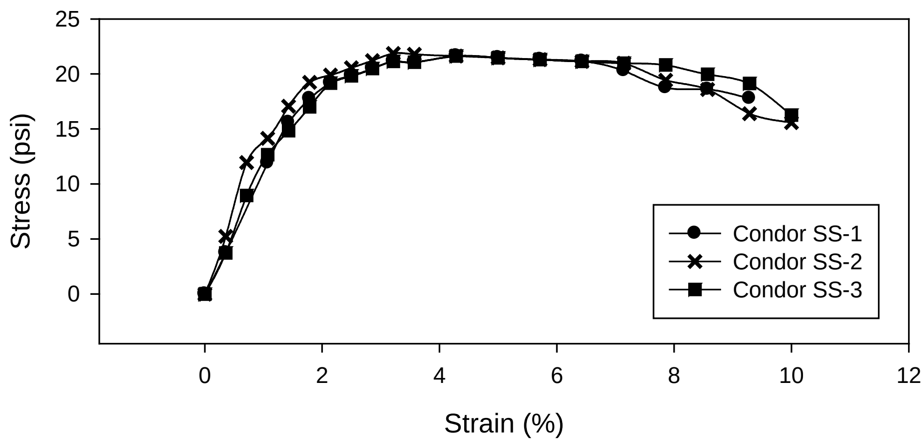

Figure 69: Renfrow Clay with Condor SS 0.13% 28-Day Curing

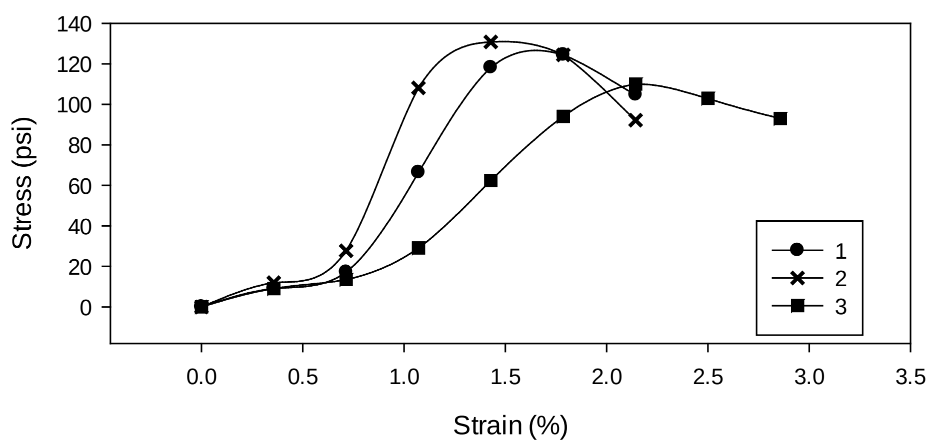

Figure 70: Renfrow Clay with Lime 6% 14-Day Curing

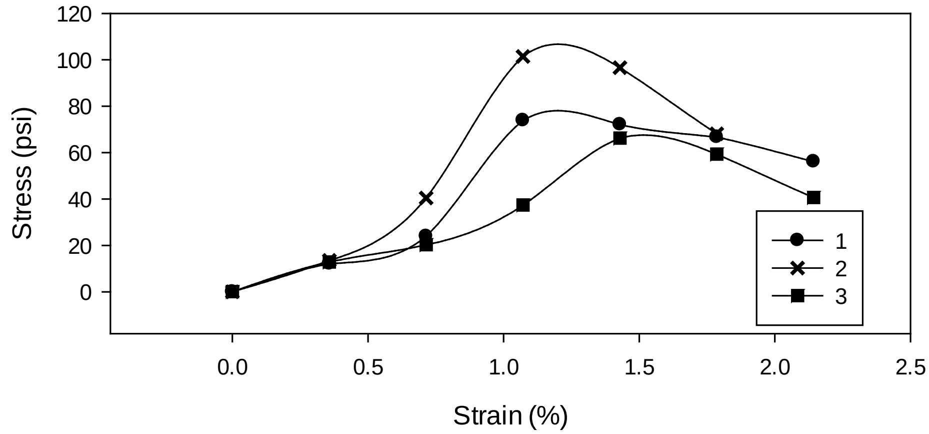

Figure 71: Renfrow Clay with Lime 6% 14-Day Curing Soaked 48 Hours

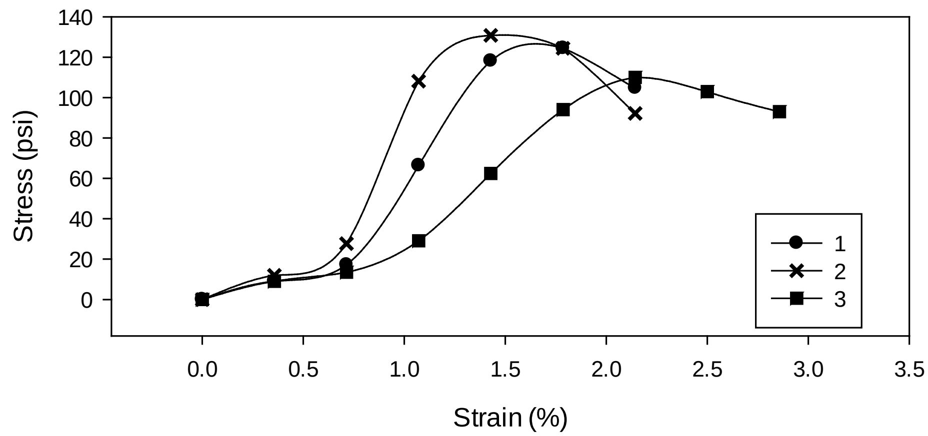

Figure 72: Renfrow Clay with Lime 6% 28-Day Curing

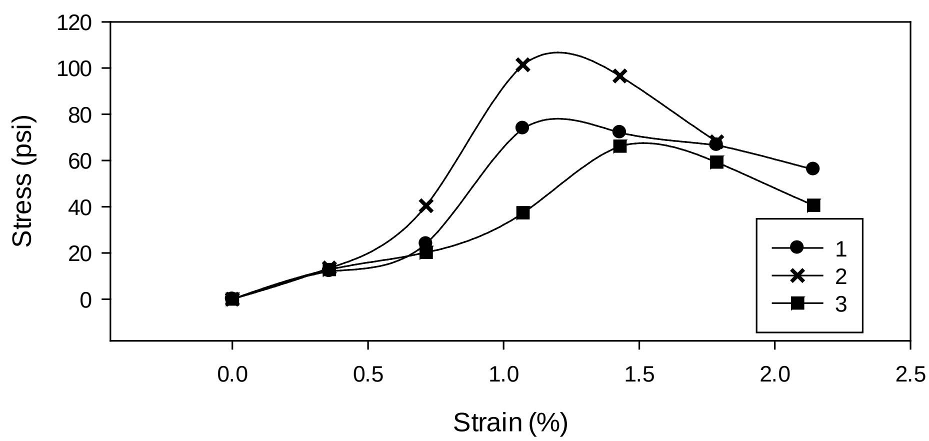

Figure 73: Renfrow Clay with Lime 6% 28-Day Curing Soaked 48 Hours

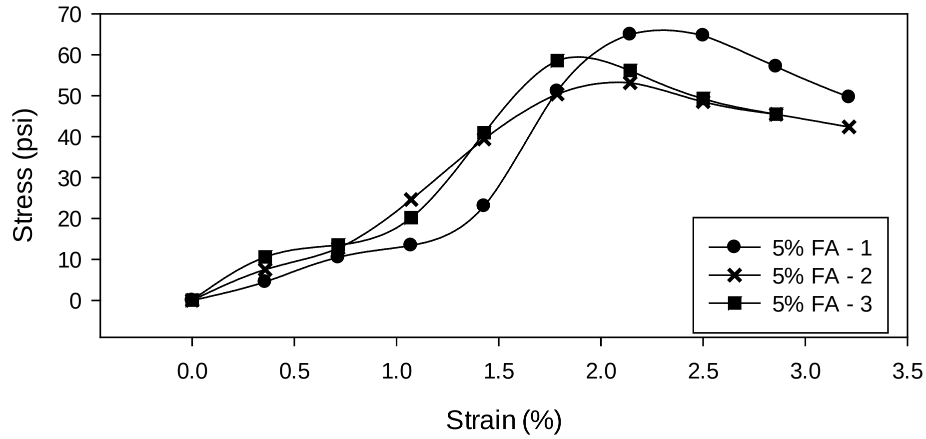

Figure 74: Renfrow Clay with Fly Ash 5% 14-Day Curing

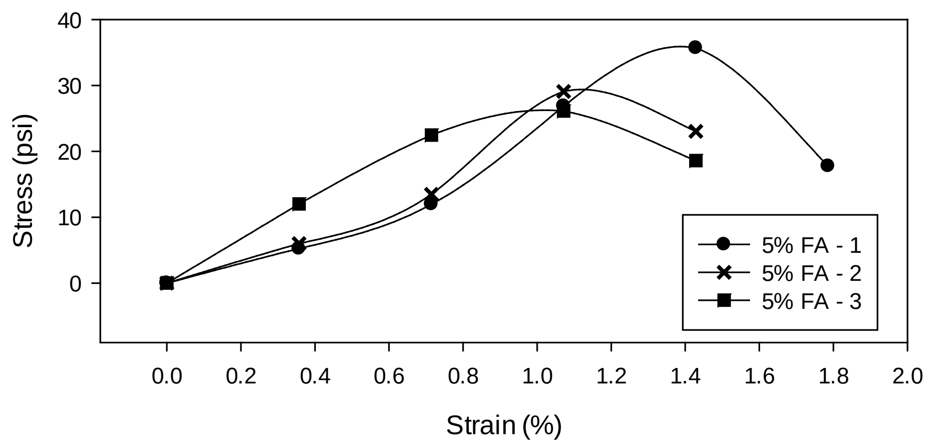

Figure 75: Renfrow Clay with Fly Ash 5% 14-Day Curing Soaked 48 Hours

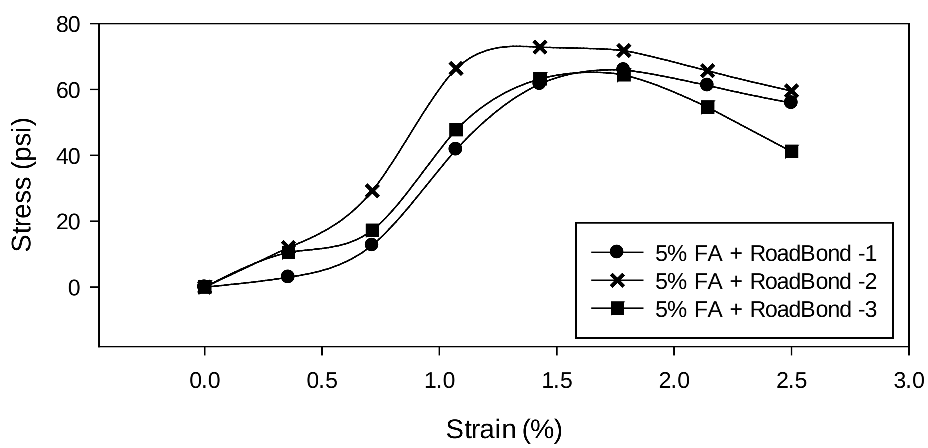

Figure 76: Renfrow Clay with Fly Ash 5% and Roadbond EN1 0.015% 14-Day Curing

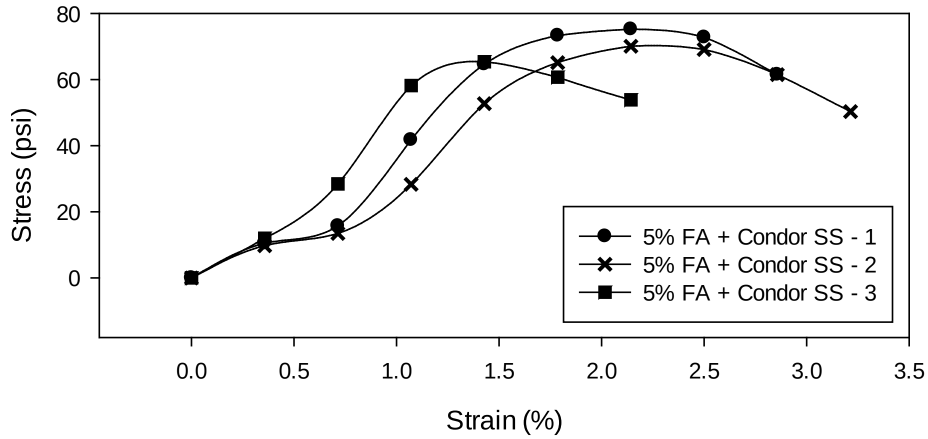

Figure 77: Renfrow Clay with Fly Ash 5% and Condor SS 0.015% 14-Day Curing

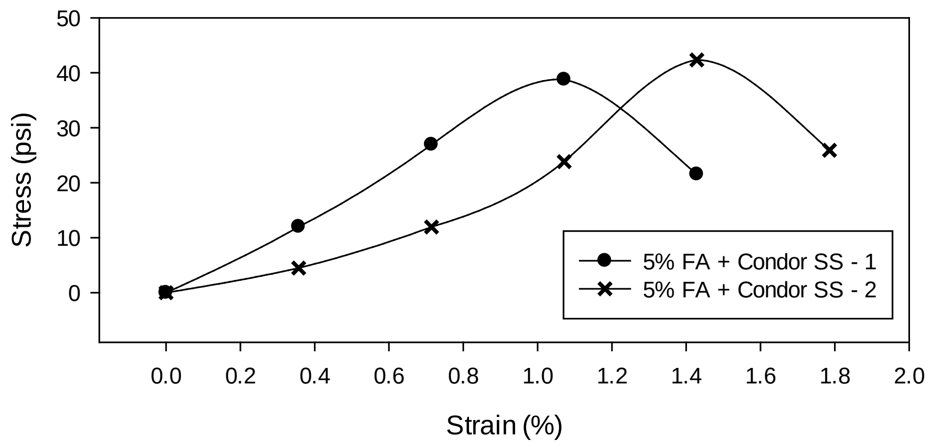

Figure 78: Renfrow Clay with Fly Ash 5% and Condor SS 0.015% 14-Day Curing Soaked 48 Hours

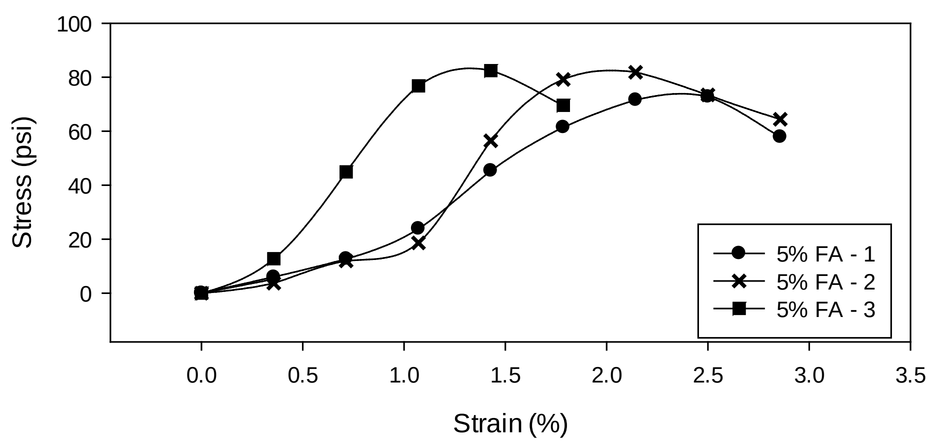

Figure 79: Renfrow Clay with Fly Ash 5% 28-Day Curing

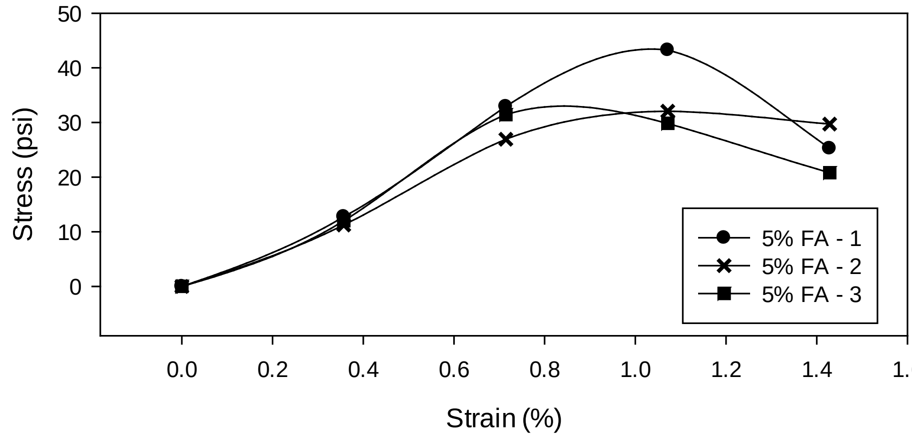

Figure 80: Renfrow Clay with Fly Ash 5% 28-Day Curing Soaked

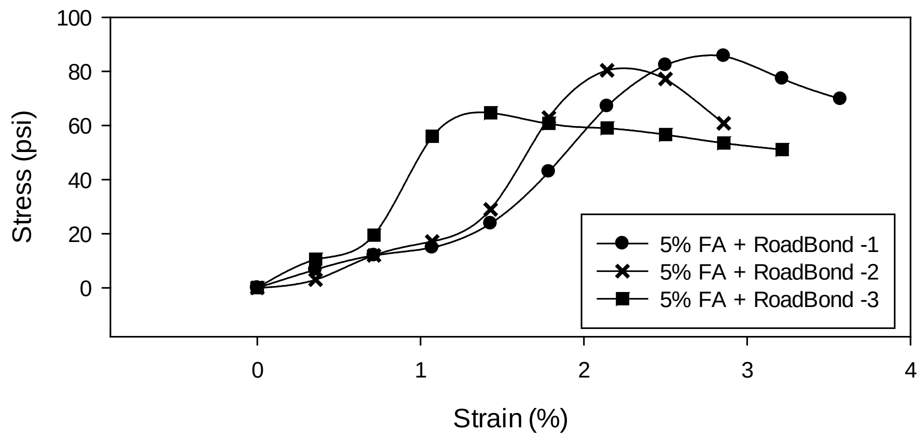

Figure 81: Renfrow Clay with Fly Ash 5% and Roadbond EN1 0.015% 28-Day Curing

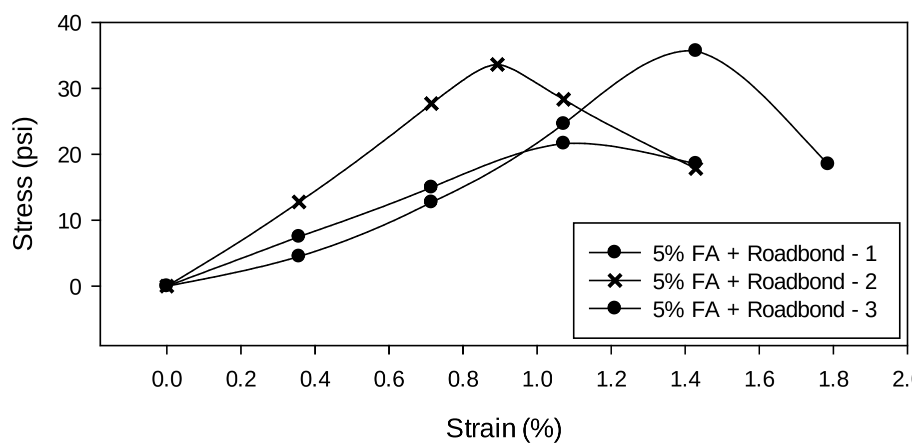

Figure 82: Renfrow Clay with Fly Ash 5% and Roadbond EN1 0.015% 28-Day Curing Soaked

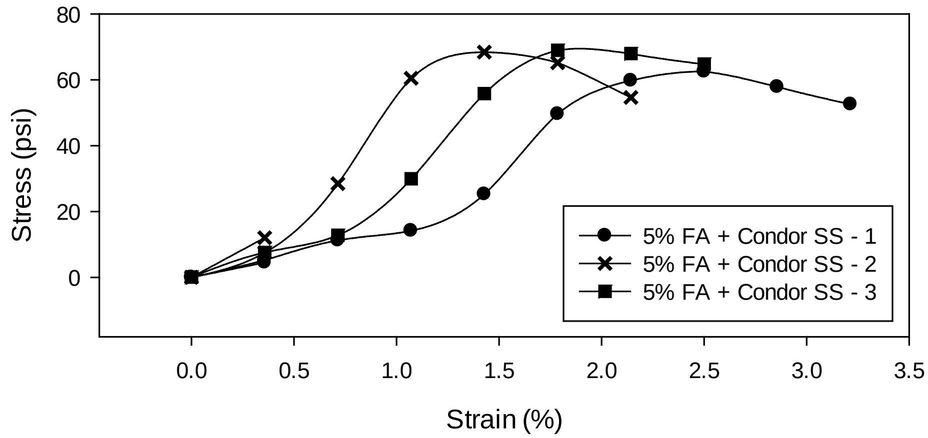

Figure 83: Renfrow Clay with Fly Ash 5% and Condor SS 0.015% 28-Day Curing

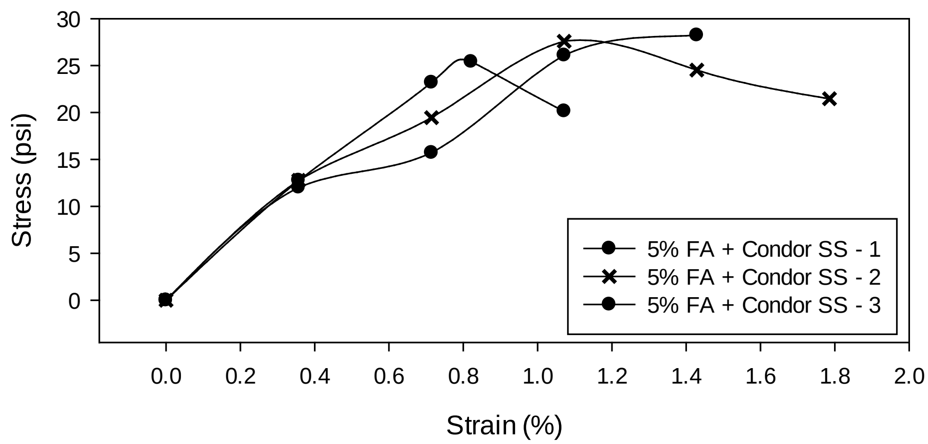

Figure 84: Renfrow Clay with Fly Ash 5% and Condor SS 0.015% 28-Day Curing Soaked

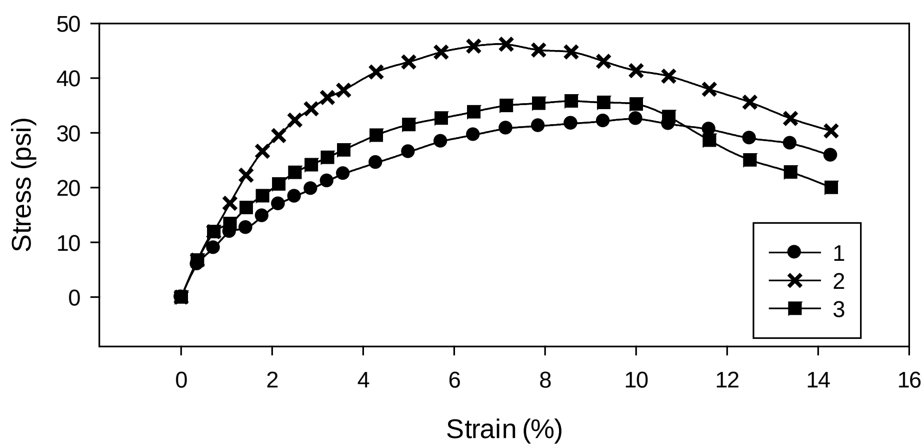

Figure 85: Vernon Soil Untreated 14-Day Curing

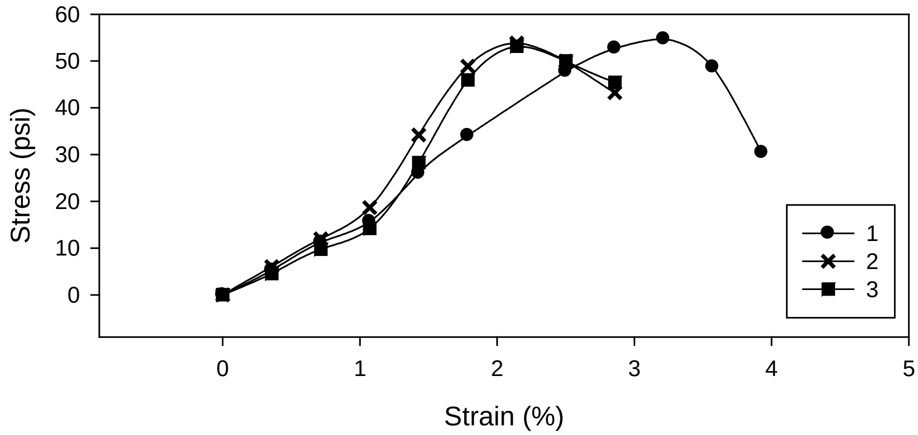

Figure 86: Vernon Soil with Roadbond EN1 6% 14-Day Curing

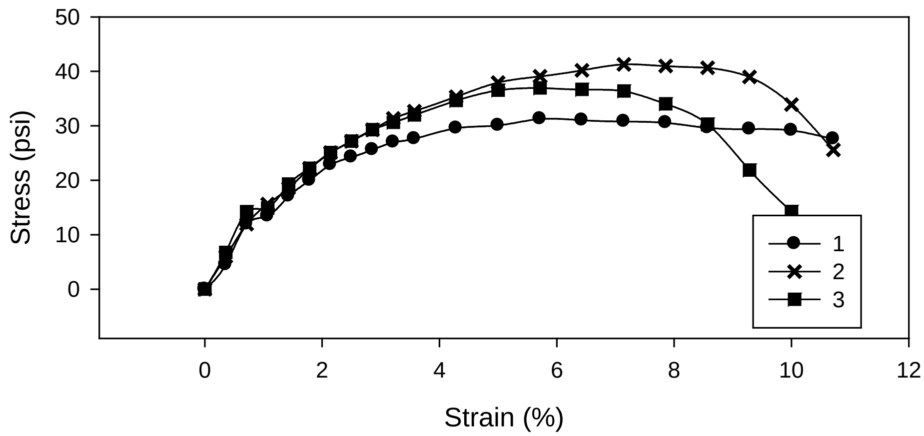

Figure 87: Vernon Soil With Roadbond EN1 0.2% 14-Day Curing

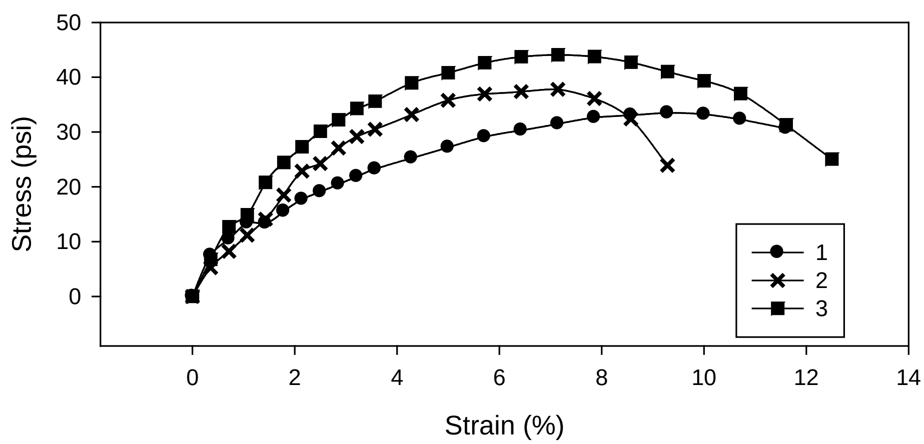

Figure 88: Vernon Soil With Roadbond EN1 0.1% 14-Day Curing

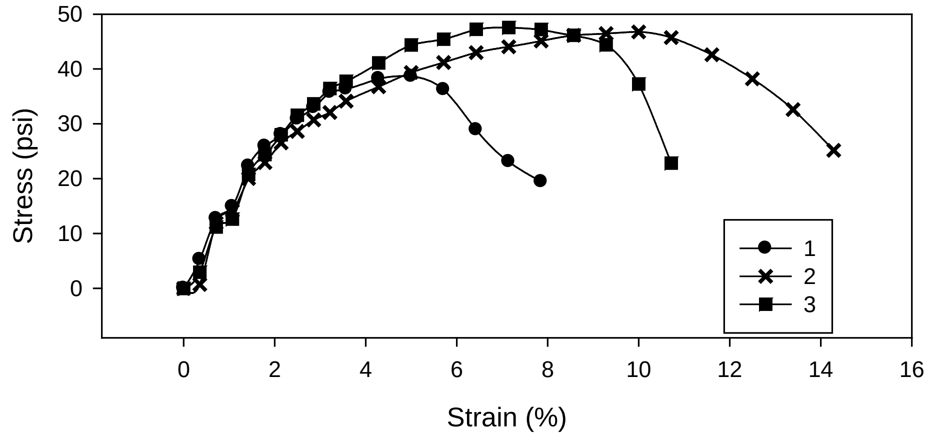

Figure 89: Vernon Soil with Roadbond EN1 0.06% 14-Day Curing

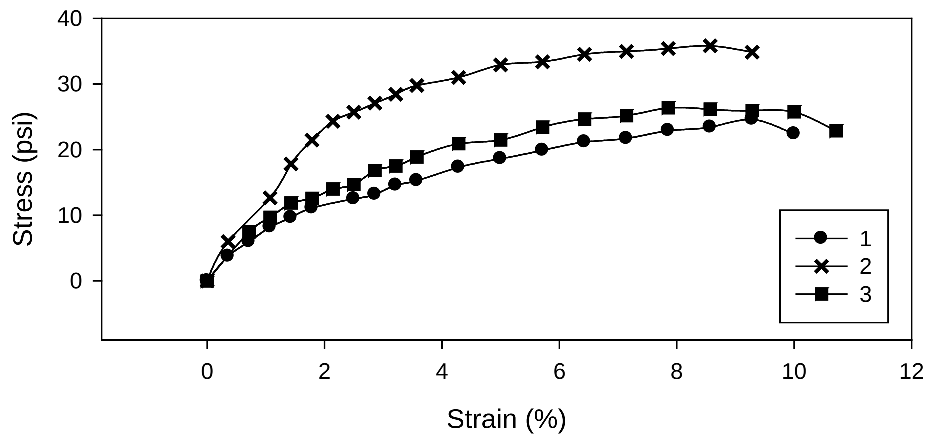

Figure 90: Vernon Soil with Condor SS 6% 14-Day Curing

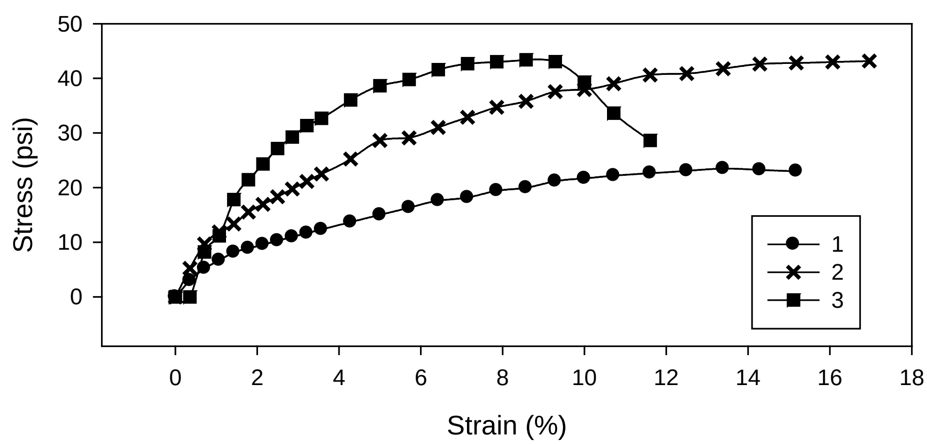

Figure 91: Vernon Soil with Condor SS 0.2% 14-Day Curing

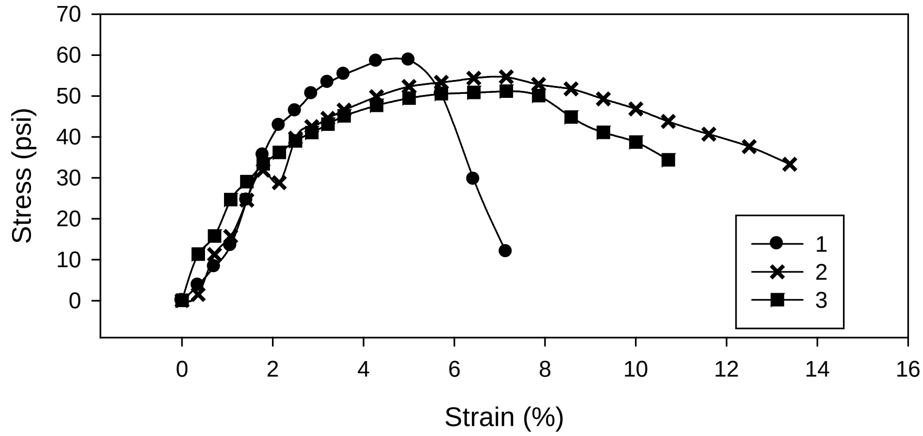

Figure 92: Vernon Soil with Condor SS 0.06% 14-Day Curing

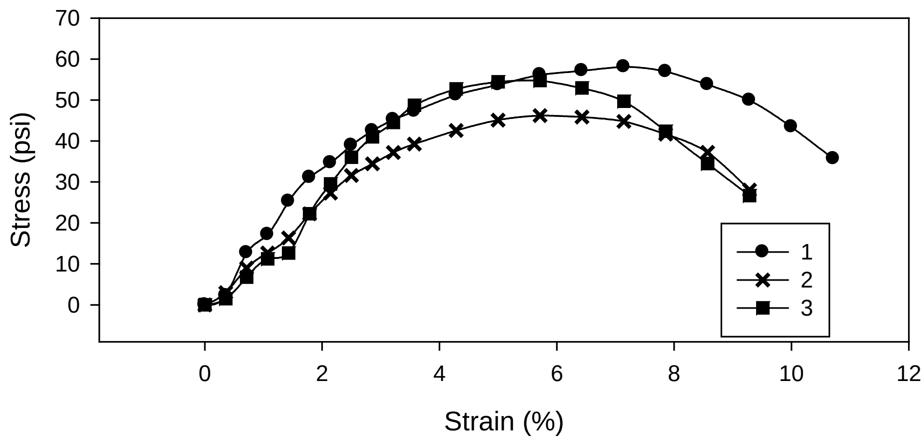

Figure 93: Vernon Soil with Condor SS 0.004% 14-Day Curing

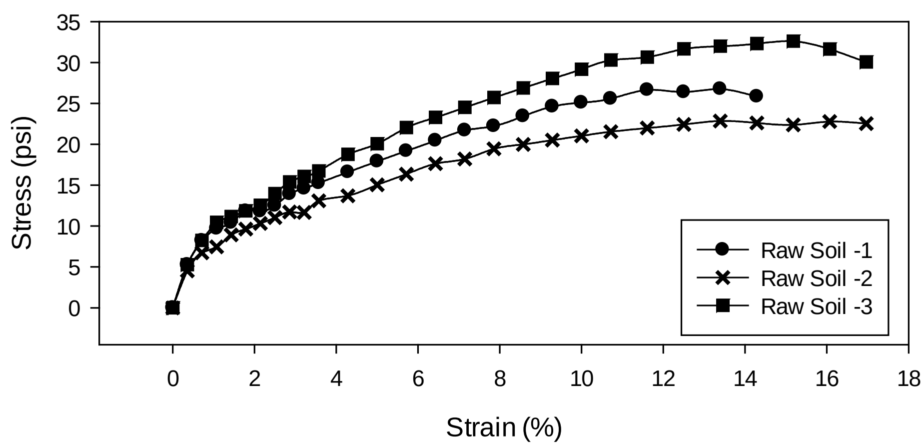

Figure 94: Vernon Soil Untreated 28-Day Curing

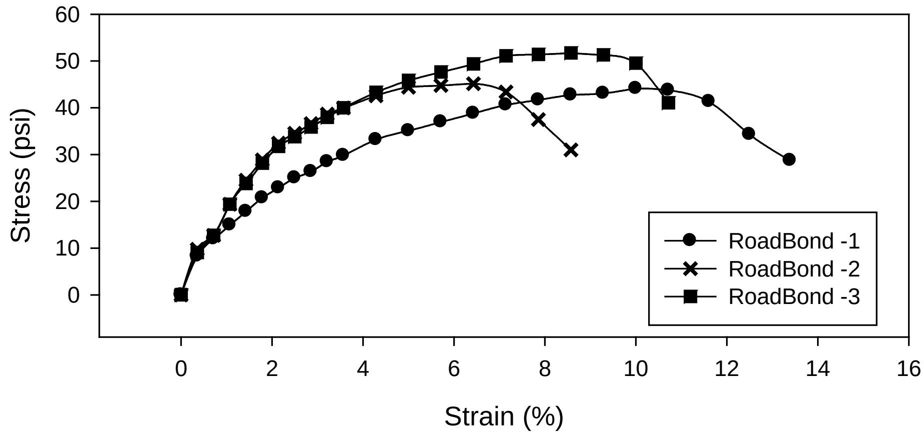

Figure 95: Vernon Soil with Roadbond EN1 0.2% 28-Day Curing

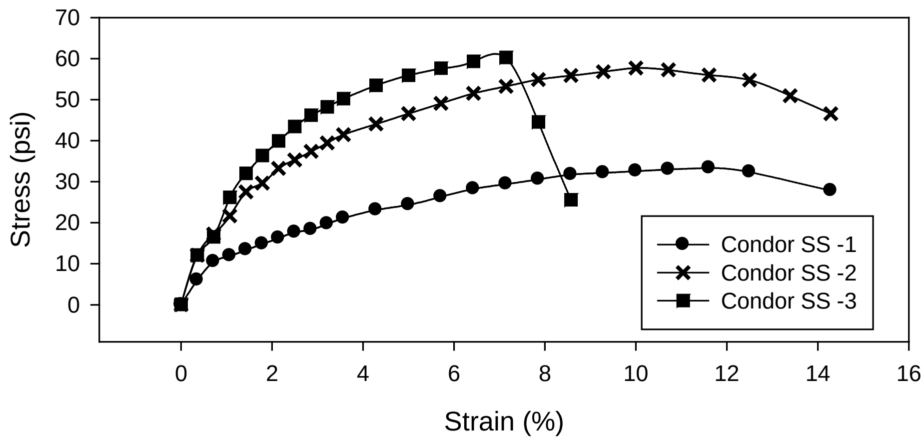

Figure 96: Vernon Soil with Condor SS 0.2% 28-Day Curing

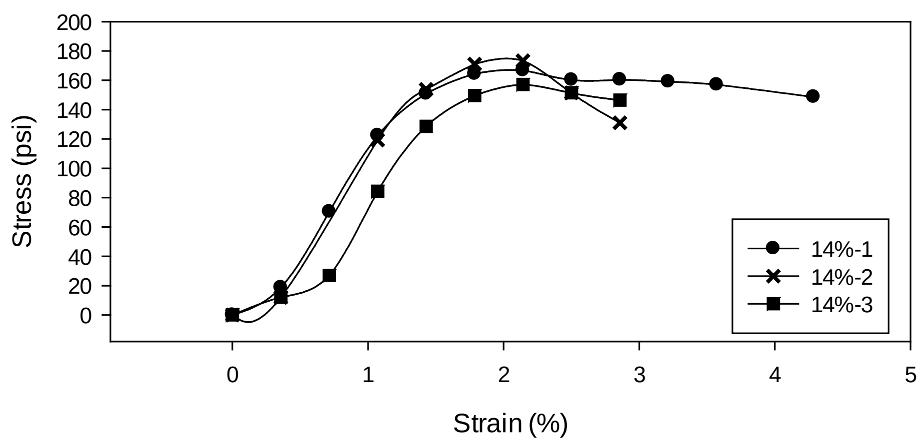

Figure 97: Vernon Soil with Fly Ash 14% 14-Day Curing

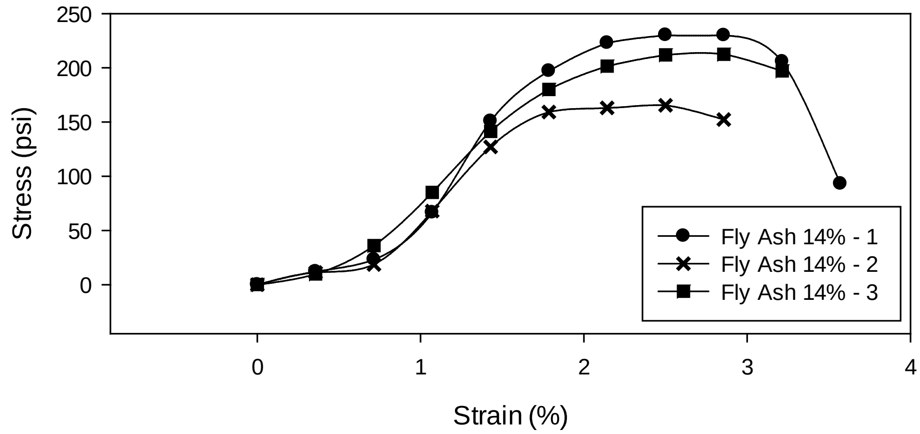

Figure 98: Vernon Soil with Fly Ash 14% 28-Day Curing

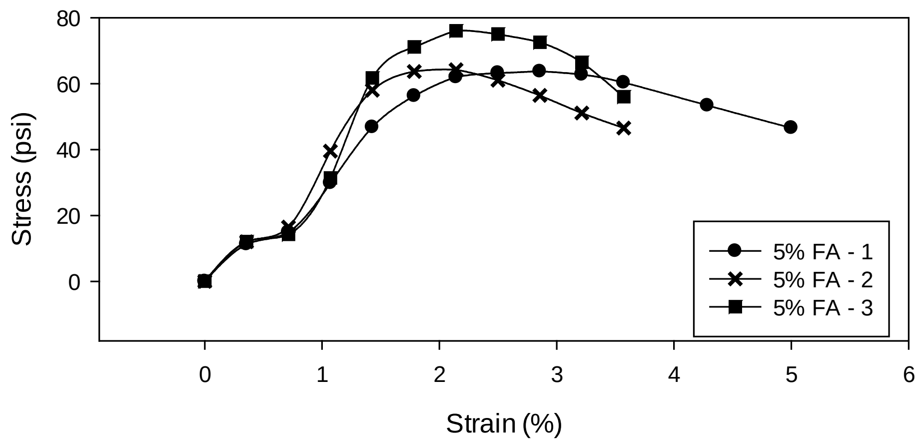

Figure 99: Vernon Soil with Fly Ash 5% 14-Day Curing

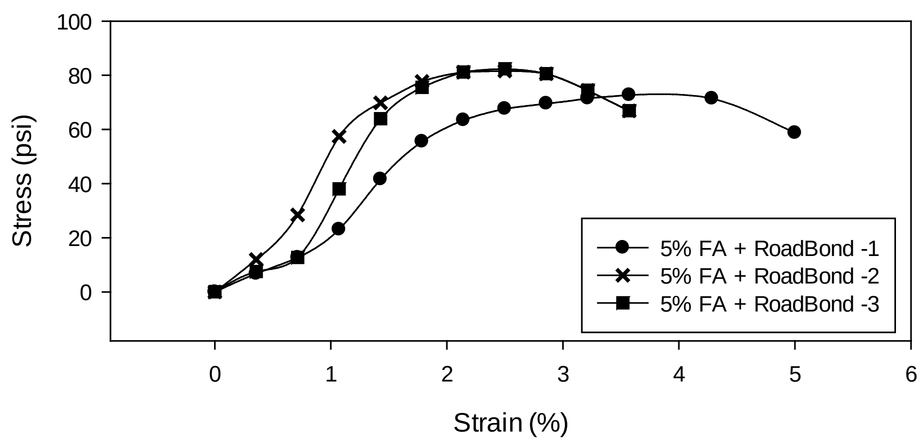

Figure 100: Vernon Soil With Fly Ash 5% and Roadbond EN1 0.015% 14-Day Curing

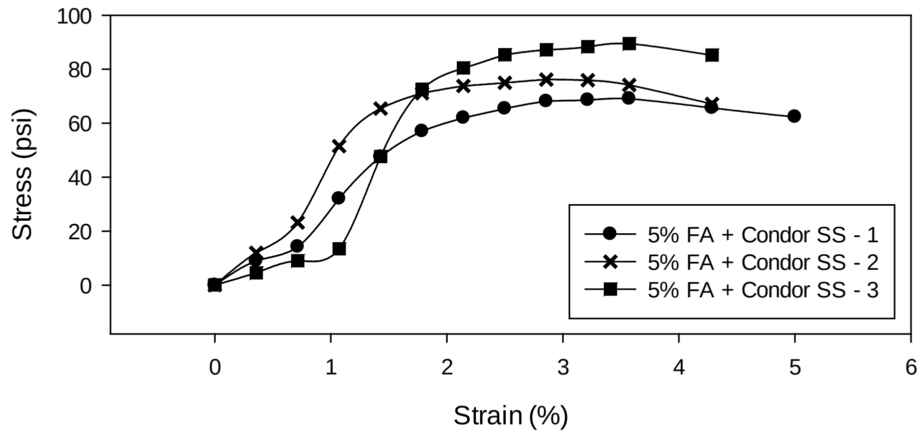

Figure 101: Vernon Soil With Fly Ash 5% and Condor SS 0.015% 14-Day Curing

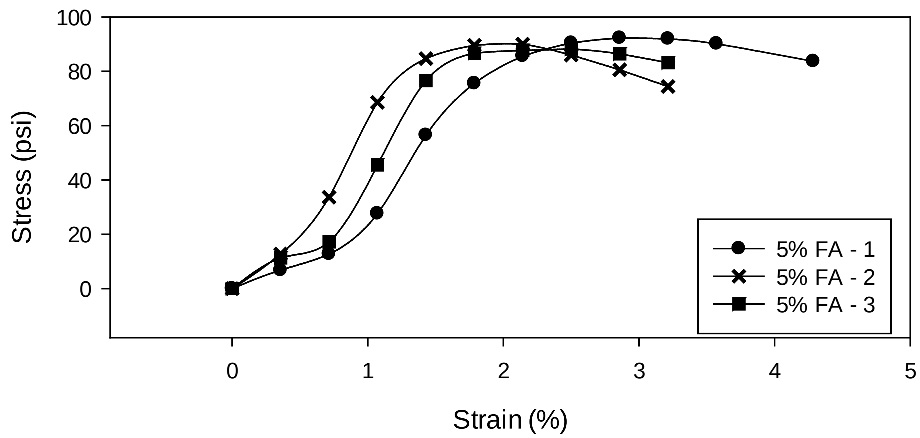

Figure 102: Vernon Soil with Fly Ash 5% 28-Day Curing

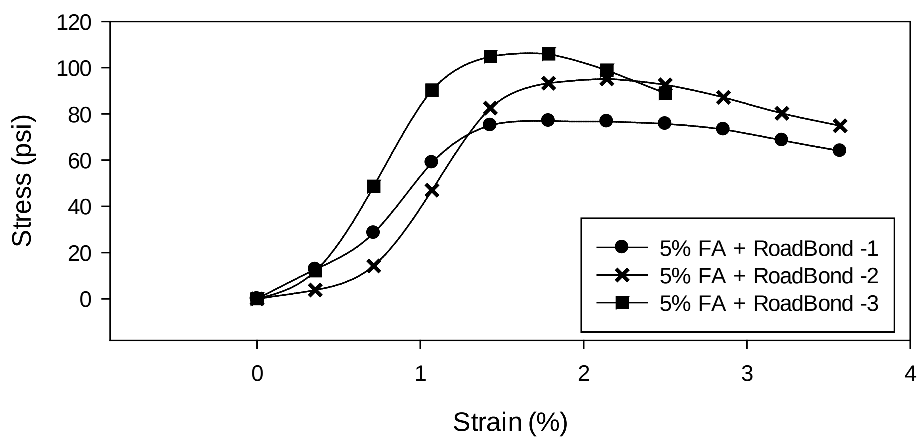

Figure 103: Vernon Soil With Fly Ash 5% and Roadbond EN1 0.015% 28-Day Curing

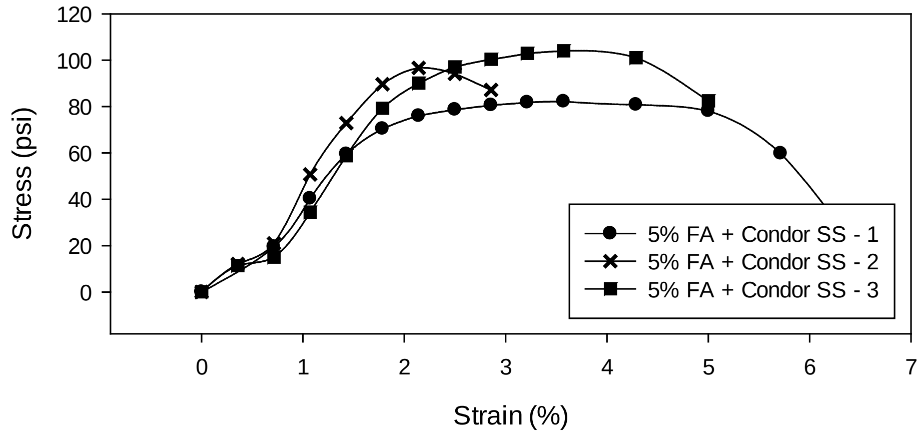

Figure 104: Vernon Soil With Fly Ash 5% and Condor SS 0.015% 28-Day Curing

APPENDIX B: SAMPLE WATER CONTENT AND DRY DENSITY

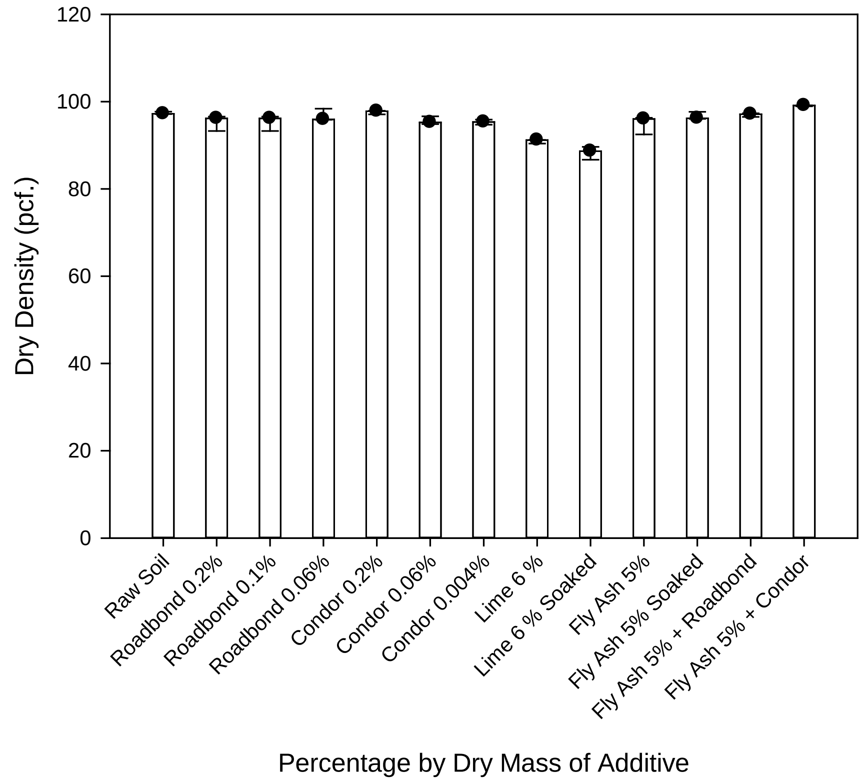

Figure 105: Lela Clay UCT Specimens Dry Density 14-Day Curing

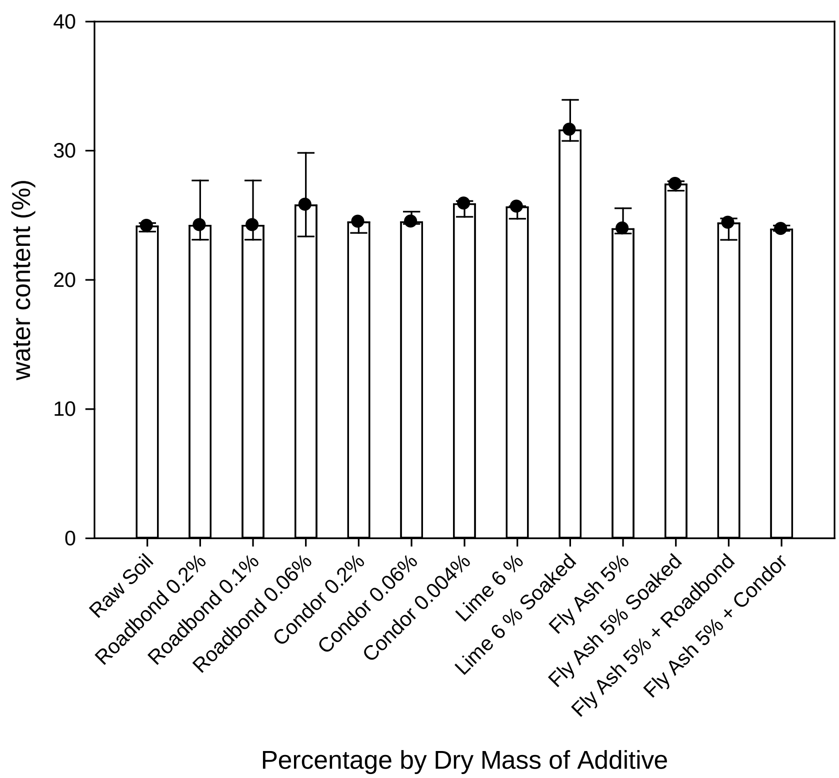

Figure 106: Lela Clay UCT Specimens Water Content 14-Day Curing

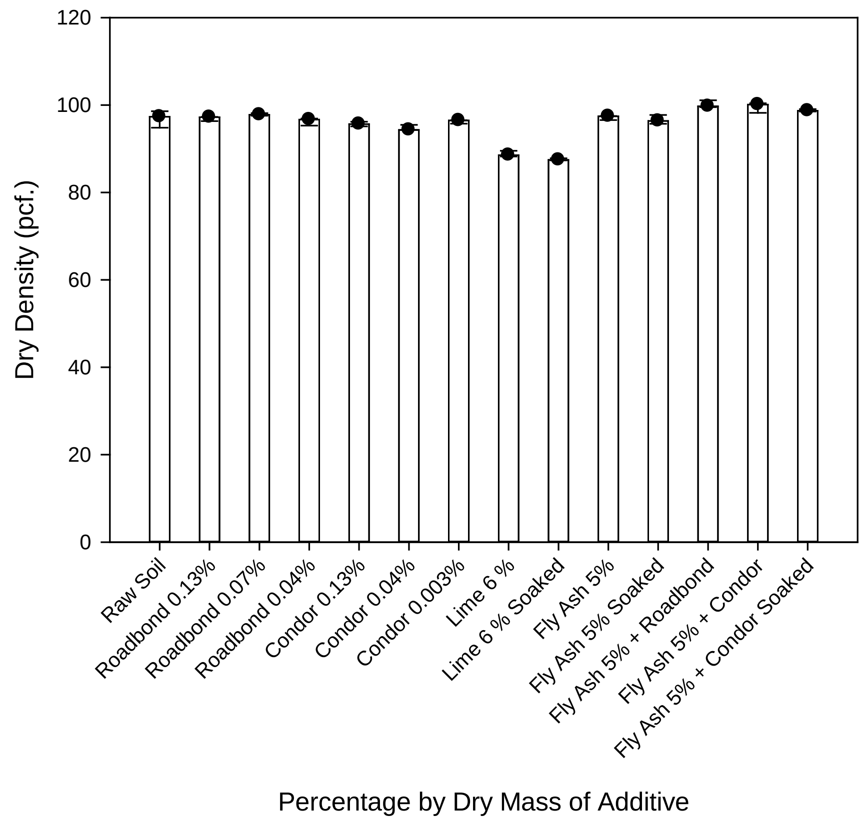

Figure 107: Renfrow Clay UCT Specimens Dry Density 14-Day Curing

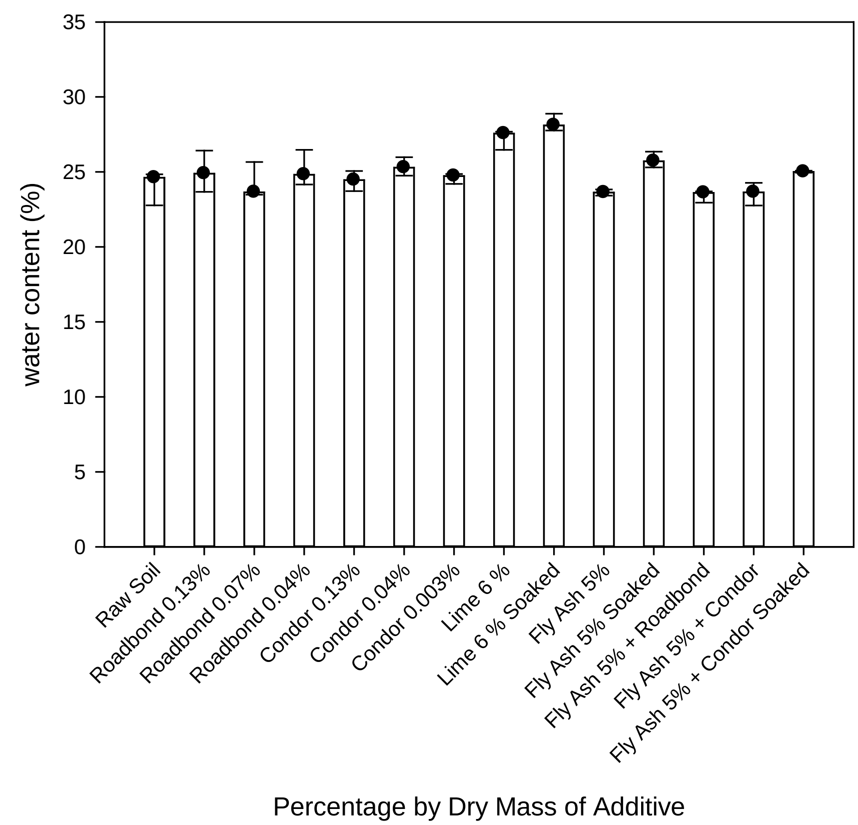

Figure 108: Renfrow Clay UCT Specimens Water Content 14-Day Curing

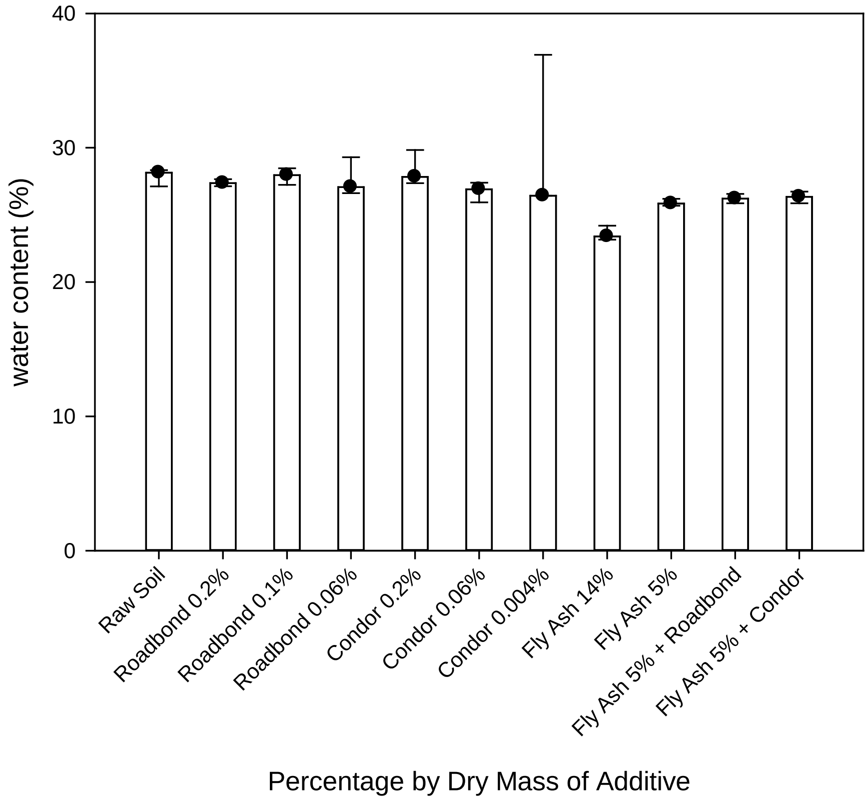

Figure 109: Vernon Soil UCT Specimens Dry Density 14-Day Curing

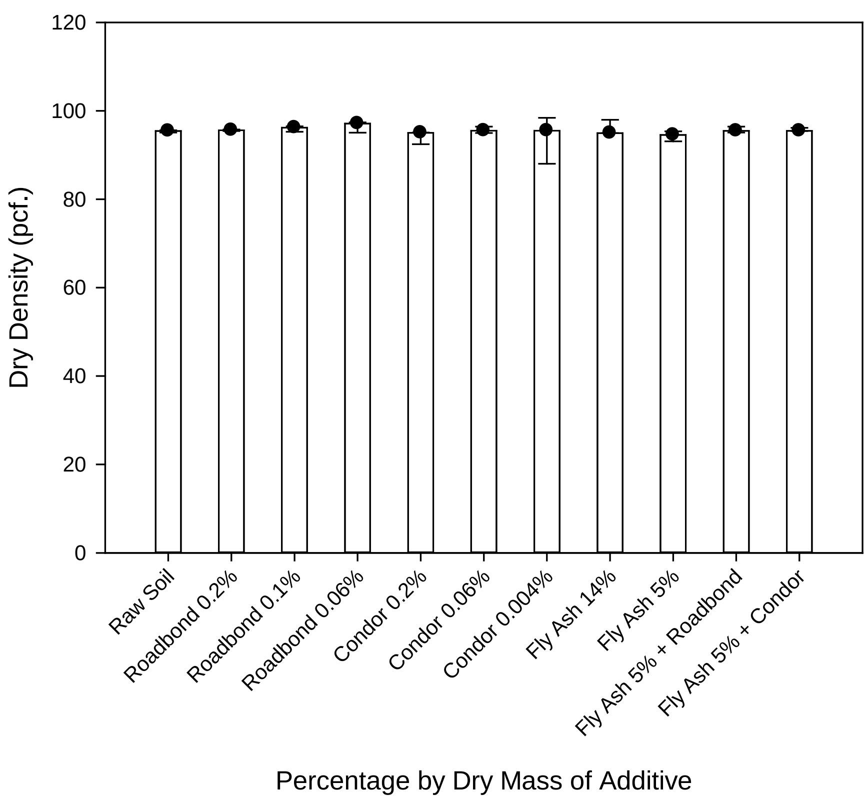

Figure 110: Vernon Soil UCT Specimens Water Content 14-Day Curing

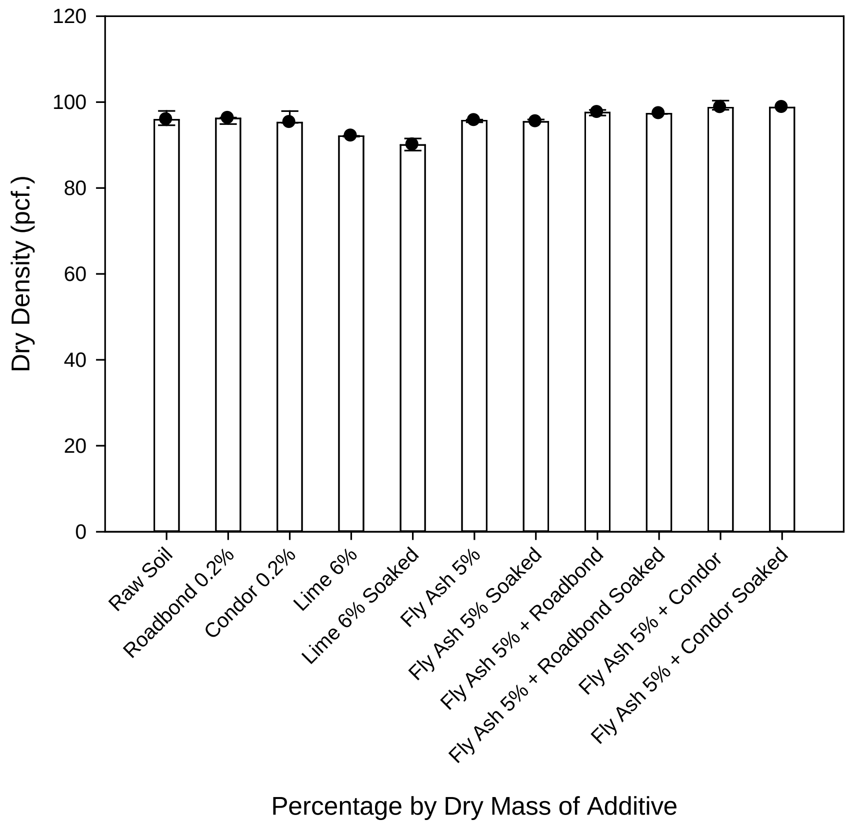

Figure 111: Lela Clay UCT Specimens Dry Density 28-Day Curing

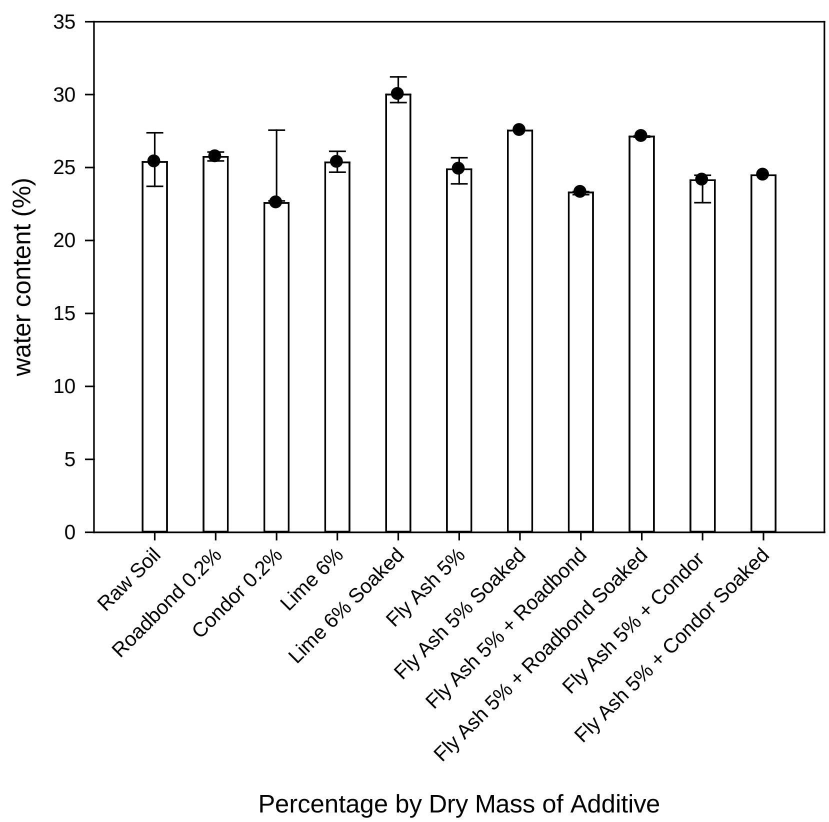

Figure 112: Lela Clay UCT Specimens Water Content 28-Day Curing

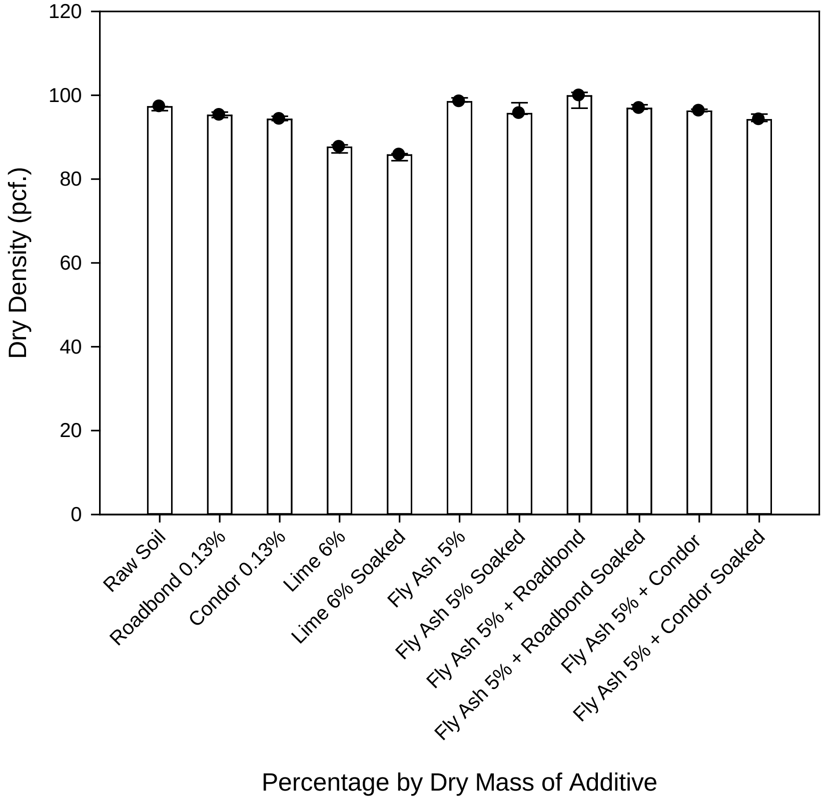

Figure 113: Renfrow Clay UCT Specimens Dry Density 28-Day Curing

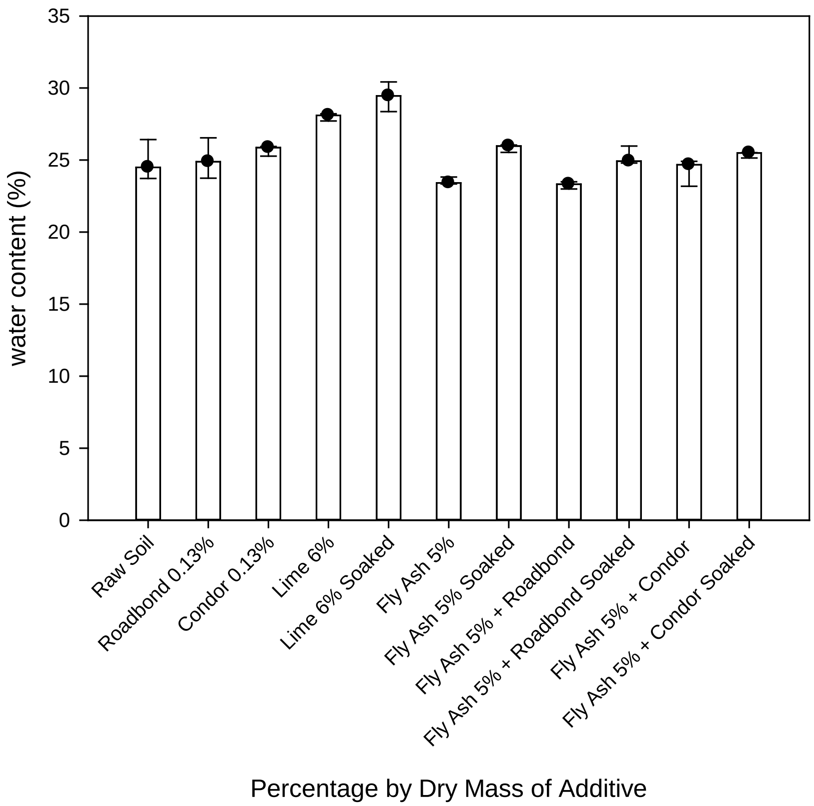

Figure 114: Renfrow Clay UCT Specimens Water Content 28-Day Curing

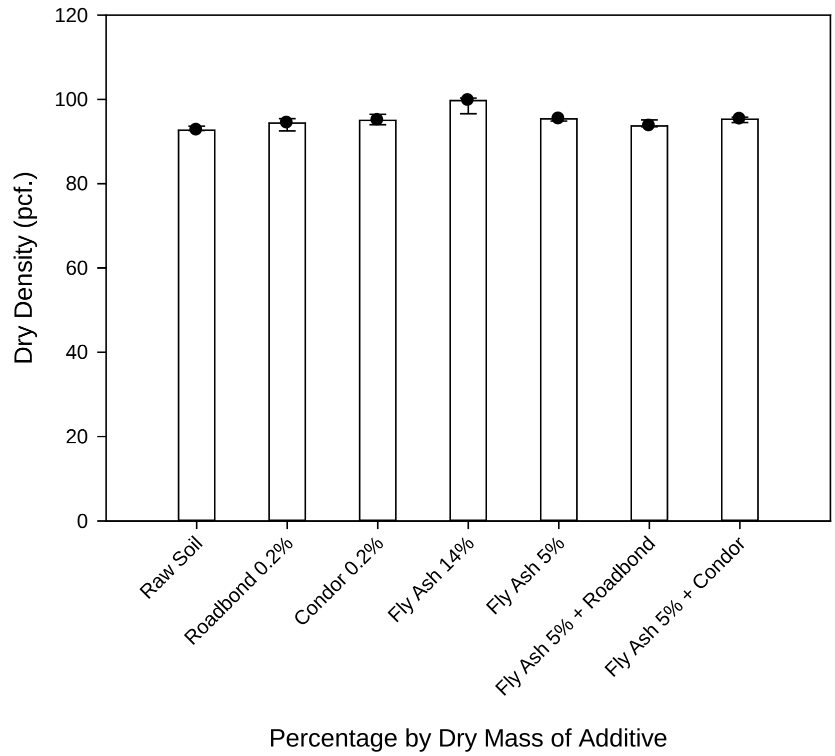

Figure 115: Vernon Soil UCT Specimens Dry Density 28-Day Curing

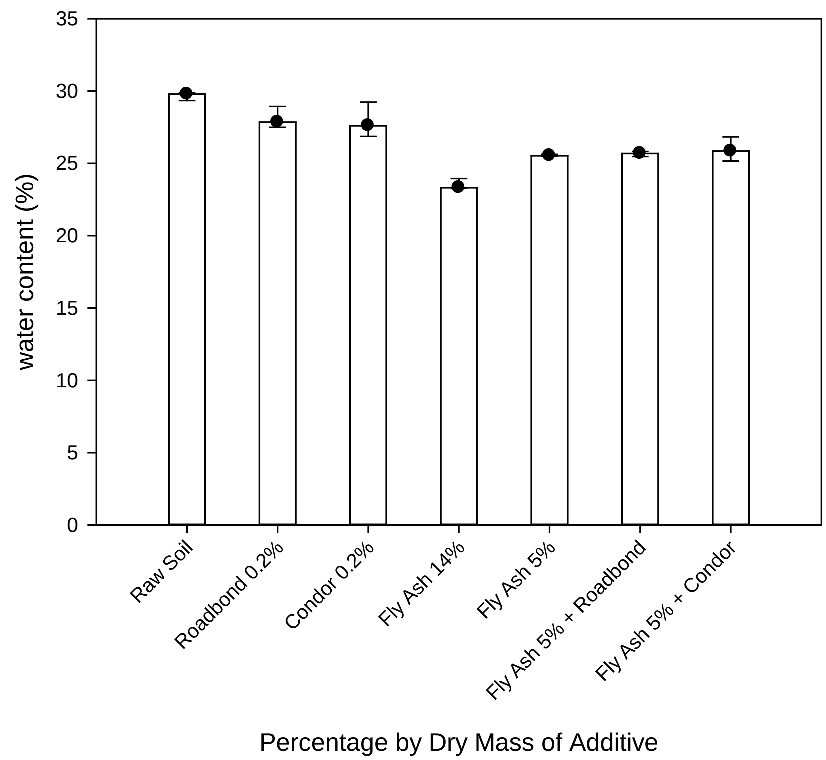

Figure 116: Vernon Soil UCT Specimens Water Content 28-Day Curing

Table 6: UCT Specimen Water Contents and Dry Densities

Soil	Additive	Concentration by Dry Mass	Curing Time (Days)	Sample #	Water Content (%)	Dry Density (pcf.)
Lela Clay	Untreated	-	14	1	24.4	97.1
				2	24.1	97.2
				3	23.7	97.7
			28	1	27.4	94.6
				3	25.4	95.9
				6	23.7	97.9
	Roadbond	0.20%	14	1	27.7	93.3
				5	24.2	96.5
				6	23.1	96.1
			28	1	25.7	96.2
				2	25.4	96.4
				5	26.1	94.9
		0.10%	14	2	44.6	84.9
				5	24.0	96.9
				6	23.1	97.2
		0.06%	14	3	25.8	95.9
				5	29.8	95.8
				6	23.4	98.4
	Condor SS	0.20%	14	1	24.5	97.8
				2	23.6	97.9
				3	24.5	97.1
			28	1	27.6	95.2
				4	25.6	95.2
				6	22.7	97.9
		0.06%	14	1	24.3	96.6
				2	24.5	94.8
				3	25.3	95.2
		0.03%	14	1	24.9	95.9
				2	26.1	95.3
				3	25.9	94.7
	Lime	6%	14	2	25.7	91.2
				3	25.6	91.2
				6	24.7	90.4
			14 Soaked	1	30.8	88.6
				4	31.6	89.6
				5	33.9	86.7
			28	3	25.4	92.0

				4	26.1	92.0
				5	24.7	92.1
			28 Soaked	1	30.0	90.0
				2	29.4	91.5
				6	31.2	88.7
	Fly Ash	5%	14	1	25.5	92.5
				2	23.9	96.0
				3	23.6	96.3
			14 Soaked	4	26.9	97.6
				5	27.4	96.1
				6	27.6	96.2
			28	2	24.9	95.7
				3	23.9	95.3
				4	25.7	95.9
			28 Soaked	5	27.5	95.4
	Fly Ash + RB	5% Fly Ash + 0.015% Roadbond	14	1	24.8	97.1
				2	24.4	97.3
				3	23.1	96.5
			28	1	23.1	96.9
				2	23.3	97.5
				3	23.3	98.2
			28 Soaked	4	27.2	97.3
				5	27.1	97.3
	Fly Ash + Con SS	5% Fly Ash + 0.015% Condor SS	14	1	23.9	98.9
				2	24.2	99.1
				3	23.9	99.1
			28	1	24.2	98.6
				2	24.1	98.2
				3	22.6	100.3
			28 Soaked	4	24.5	98.7
Renfrow	Untreated	-	14	1	24.6	97.3
				2	24.8	94.8
				4	22.8	98.6
			28	1	26.0	95.1
				2	25.3	95.0
				6	23.7	95.7
	Roadbond	0.13%	14	1	26.4	96.3
				2	24.5	97.2
				3	23.7	97.3

			28	1	26.5	94.7
				4	24.9	95.2
				5	23.7	96.0
		0.07%	14	1	25.7	97.5
				2	23.6	98.1
				4	23.5	97.8
		0.04%	14	1	26.5	95.3
				2	24.8	96.6
				3	24.2	96.9
	Condor SS	0.13%	14	1	25.1	95.6
				2	23.7	96.2
				3	24.4	95.1
			28	1	25.3	95.0
				2	25.9	94.2
				3	25.9	94.0
		0.04%	14	1	26.0	94.3
				2	25.3	95.5
				6	24.7	94.3
		0.00%	14	1	24.7	95.7
				2	24.2	96.5
				5	24.9	96.4
	Lime	6%	14	1	26.5	89.5
				4	27.7	88.5
				6	27.5	88.2
			14 Soaked	2	27.8	87.8
				3	28.1	87.3
				5	28.9	87.5
			28	1	28.4	86.0
				2	30.4	85.7
				6	29.4	84.4
			28 Soaked	3	27.7	86.2
				4	28.2	88.2
				5	28.1	87.6
	Fly Ash	5%	14	1	23.6	97.4
				2	23.8	97.5
				3	23.4	96.6
			14 Soaked	4	25.3	97.7
				5	25.7	96.4
				6	26.3	95.7
			28	1	23.8	98.4

				2	23.4	98.4
				3	23.3	99.4
			28 Soaked	4	25.5	98.2
				5	26.0	95.5
				6	26.0	95.6
	Fly Ash + RB	5% Fly Ash + 0.015% Roadbond	14	1	23.7	99.7
				2	23.0	101.1
				3	23.6	99.5
			28	1	23.5	100.7
				2	23.3	99.8
				3	23.0	96.9
			28 Soaked	4	24.9	97.7
				5	24.8	96.8
				6	26.0	96.7
	Fly Ash + Con SS	5% Fly Ash + 0.015% Condor SS	14	1	23.6	100.4
				2	24.3	100.1
				3	22.8	98.2
			14 Soaked	5	25.1	99.1
				6	24.9	98.5
			28	1	24.9	96.1
				2	24.7	96.2
				3	23.2	96.7
			28 Soaked	4	25.5	93.7
				5	25.1	95.5
				6	25.5	94.1
Vernon Soil	Untreated	-	14	1	28.3	95.4
				2	27.1	95.6
				5	28.1	95.1
			28	2	29.8	92.6
				4	29.9	92.7
				6	29.3	93.7
	Roadbond	0.20%	14	1	27.4	95.4
				3	27.1	95.8
				5	27.7	95.6
			28	2	28.9	92.5
				3	27.8	94.4
				4	27.5	95.4
		0.10%	14	1	28.5	95.3
				2	28.0	96.2
				3	27.2	96.5

		0.06%	14	1	29.3	95.0
				5	27.1	97.1
				6	26.6	97.4
	Condor SS	0.20%	14	1	29.8	92.4
				2	27.8	95.1
				3	27.4	95.0
			28	1	29.2	94.0
				5	27.6	96.5
				6	26.9	95.0
		0.06%	14	2	25.9	95.0
				4	26.9	96.4
				5	27.4	95.5
		0.00%	14	3	26.4	98.4
				4	26.4	95.5
				5	36.9	88.0
	Fly Ash	14%	14	1	24.2	98.0
				3	23.2	94.9
				5	23.4	94.9
			28	1	23.9	100.3
				2	23.3	99.7
				3	23.3	96.6
		5%	14	1	26.2	94.5
				2	25.7	93.1
				3	25.8	95.4
			28	1	25.6	95.4
				2	25.5	95.4
				3	25.5	94.9
	Fly Ash + RB	5% Fly Ash + 0.015% Roadbond	14	1	26.6	95.5
				2	25.9	96.4
				3	25.6	95.1
			28	1	25.5	93.5
				2	25.8	95.1
				3	25.7	93.7
	Fly Ash + Con SS	5% Fly Ash + 0.015% Condor SS	14	1	26.7	96.2
				2	26.4	95.5
				3	25.9	95.4
			28	1	26.8	95.8
				2	25.2	94.5
				3	25.8	95.3

Table 7: Oedometer Specimen Water Contents and Dry Densities

Soil	Additive	Curing Time (Days)	Water Content (%)	Dry Density (pcf.)
Lela Clay	Untreated	0	23.6	97.1
		14	27.8	89.1
	Roadbond 0.2%	0	27.0	95.0
		14	26.8	93.0
	Condor SS 0.2%	0	20.7	100.0
		14	25.3	92.7
	Lime 6%	0	26.0	93.7
		14	26.0	100.7
Renfrow Clay	Untreated	0	25.4	95.6
		14	25.9	94.6
	Roadbond 0.13%	0	27.3	92.8
		14	24.8	97.5
	Condor SS 0.13%	0	25.4	95.6
		14	23.9	97.2
	Lime 6%	0	23.3	95.1
		14	26.0	93.0
Vernon Soil	Untreated	0	28.4	93.7
		14	30.0	94.3
	Roadbond 0.2%	0	30.1	94.8
		14	28.1	96.3
	Condor SS 0.2%	0	31.4	92.8
		14	27.7	96.6
	Lime 4%	0	27.0	94.0
		14	27.3	94.7
	Fly Ash 14%	0	24.2	99.3
		14	24.6	96.5

APPENDIX C: STANDARD PROCTOR AND HARVARD MINIATURE COMPACTION CURVES

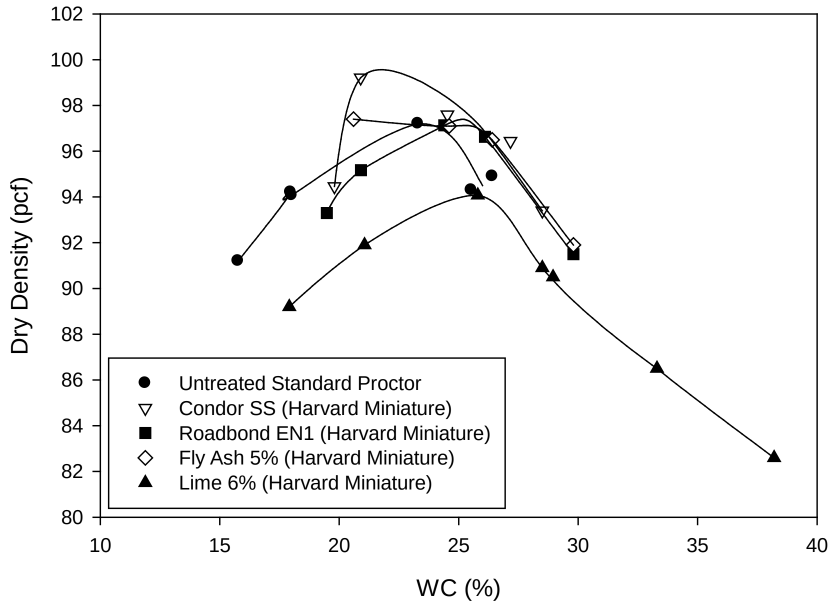

Figure 117: Lela Clay Compaction Curves

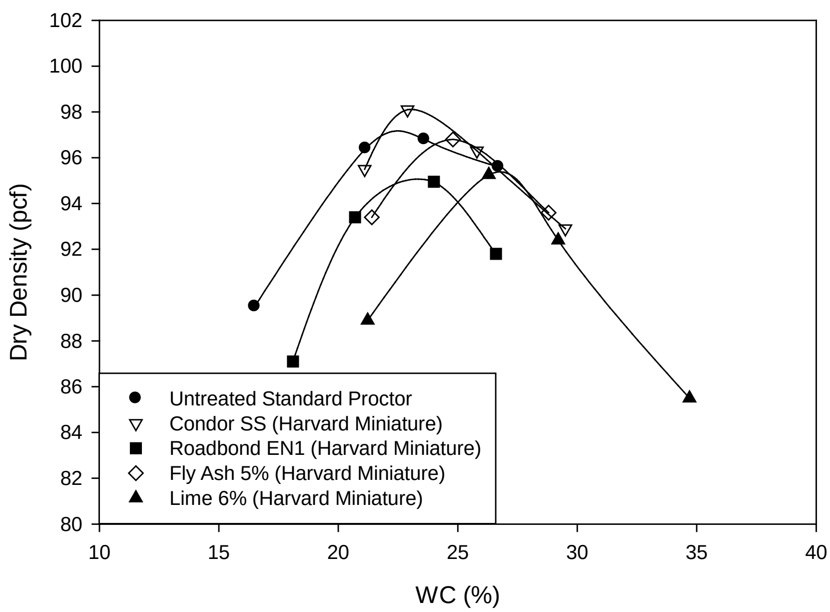

Figure 118: Renfrow Clay Compaction Curves

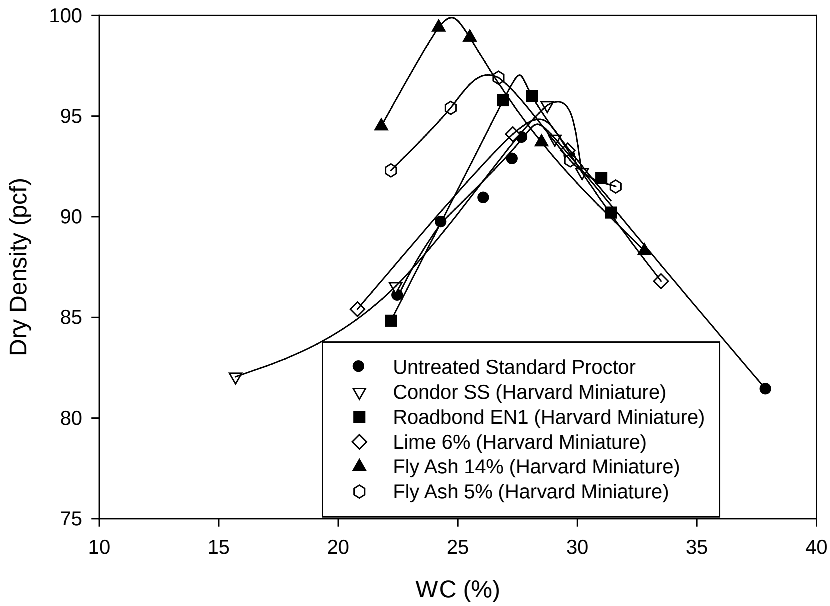

Figure 119: Vernon Soil Compaction Curves