VALIDATION AND REFINEMENT OF CHEMICAL STABILIZATION PROCEDURES FOR PAVEMENT SUBGRADE SOILS IN OKLAHOMA – VOLUME I

FINAL REPORT - FHWA-OK-11-02
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16. ABSTRACT

Additions of byproduct chemicals, such as fly ash or cement kiln dust, have been shown to increase the unconfined compression strength (UCS) of soils. To be considered effective, the soil must exhibit a strength increase of at least 50 psi. Many current design methods base chemical additive percentage recommendations on the results of Atterberg Limit tests which do not always properly characterize the soil stabilization response. For example, Atterberg limit tests may reveal the same AASHTO classification of soil at two different sites, but one site may require more than twice the additive percentage of a chemical to achieve the desired UCS increase.

This study examined the relationship between soil physico-chemical parameters and unconfined compression strength in various fine-grained soils to determine if other soil parameters have significant effects on predicting the strength of a soil treated with a given additive and additive content. The results of this study suggest that the surface area and shrinkage properties of the soil, combined with the Atterberg limit results, present a better picture of a given soil and will allow for better predictions of the amount of chemical stabilizer needed to adequately stabilize the soil.

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(Modern Metric) Conversion Factors

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)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
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	poundforce	4.45	newtons	N
lbf/in^2	poundforce 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	poundforce	lbf
kPa	kilopascals	0.145	poundforce 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

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the views of the Oklahoma Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. While trade names may be used in this report, it is not intended as an endorsement of any machine, contractor, process, or product.

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CHAPTER 1: INTRODUCTION

1.1 General

Stabilization of fine-grained soils is an alternative for geotechnical engineers considering the economics of construction with silt or clay soils. Mechanical stabilization, such as compaction, is an option; however many engineers have found it necessary to alter the physicochemical properties of clay soils in order to permanently stabilize them. The results presented in this report are part of a larger study that seeks to validate and/or refine the Oklahoma Department of Transportation's (ODOT) recommended additive contents for stabilizing fine-grained soils in Oklahoma. ODOT recently published their OHD L-50 Standard "Soil Stabilization Mix Design Procedure" which gives guidelines on additive percentages to be used with soils classified by AASHTO M145 (AASHTO 2010). Table 1 below shows the table from the OHD L-50.

Table 1: OHD L-50 Soil Stabilization Table (ODOT, 2009)

SOIL STABILIZATION TABLE												
ADDITIVE (Expressed as a percentage added on dry over basis)	**SOIL GROUP CLASSIFICATION – AASHTO M145**											
	A-1		A-2				A-3	A-4	A-5	A-6	A-7	
	A-1-a	A-1-b	A-2-4	A-2-5	A-2-6	A-2-7					A-7-5	A-7-6
PORTLAND CEMENT	4	4	4	4	4	4	5	√	√	√		
FLY ASH					12	12	13	14	14	14		
CEMENT KILN DUST (Pre-Calciner Plants)	5	5	5	5	5	5	6	√	√			
CEMENT KILN DUST (Other Type Plants)	10	10	10	11	11	11	12	12	12			
HYDRATED LIME*										4	5**	5**

A blank in the table indicates the additive is not recommended for that soil group. Recommended amounts include a safety factor for loss due to wind, grading, and/or mixing. Pre-calciner plants are identified on the Materials Division approved list for cement kiln dust.
√ = Mix Design Required
* = Reduce quantity by 20% when quick lime is used, i.e. 4% x 0.8 = 3.2%, 5% x 0.8 = 4.0%, 6% x 0.8 = 4.8%
** = Use 6% when liquid limit is greater than 50.

One of the concerns with these guidelines is that soils which fall into the same AASHTO category (e.g., A-6, A-7) may react differently to the same type and amount of additive listed in the table because of variations in mineralogical, physical and chemical constituents of the soil. Another concern is the length of time required for a traditional mix design approach used to select appropriate additive contents. In order to refine and optimize the recommendations in OHD L-50, various simple and inexpensive laboratory methods are being investigated for selecting additive contents.

This report presents the results of multiple laboratory tests on soils falling within the A-4, A-6 and A-7-6 AASHTO classifications, stabilized with increasing percentages of hydrated lime, cement kiln dust (CKD) and two types of Class C fly ash (from Red Rock and Muskogee, OK). The research described in this paper focused primarily on investigating the effects, if any, that other soil properties beyond Atterberg Limits have on predictions of increases in a soil's unconfined compression strength at varying chemical additive contents. This research may have an important effect on making chemical mix designs for pavement subgrades more efficient, as well as providing a better understanding of properties that significantly affect strength gains in soils.

1.2 Objectives

The goal of this research project was to assist the state in validating and improving the recommendations of OHD L-50 "Soil Stabilization Mix Design Procedure," as well as determine a correlation between stabilized soil strength gain and stiffness. In addition, the similarities and differences between predicted laboratory and stabilized soil strength gain and stiffness and actual field conditions were compared and contrasted. The proposed research primarily focused on AASHTO Soil Group Classifications falling under the fine-grained soil category (i.e. A-4 to A-7). It was expected that the results of testing on fine-grained soils may be intuitively extended to address variability found in fines of the A-2 soil classification. Granular soils in the A-1 category and fine sandy soils of the A-3 category were not included in this research. In addition to the exclusions mentioned above, soils containing appreciable levels of sulfate were excluded, as these soils are not recommended for stabilization using calcium-based chemical additives. Soils used in the currently proposed research were subjected to soluble sulfate testing and current research on sulfate soils helped to guide the selection of suitable soil candidates for the proposed research.

The overall objectives of this research project were as follows:

1) Refine and optimize the recommendations in OHD L-50 by examining potentially useful and quick methods for selecting additive contents,
2) Determine a correlation between stabilized soil strength gain and stiffness,
3) Understand the similarities and/or differences between predicted laboratory stabilized soil strength gain and stiffness and actual field conditions after construction and make necessary recommendations.

Because of the immense amount of data generated during this three year research project, this report is organized into two stand-alone volumes. Volume I covers Years 1 and 2 of this research project and Objective 1, while Volume II covers Year 3 and Objectives 2 and 3.

1.2.1 Specific Objectives of Volume I

Objective 1, noted above, was broken down further into smaller objectives and corresponding tasks to facilitate the successful completion of this research project.

A. Identify and investigate the variations in soil characteristics of Oklahoma Soils within each AASHTO Soil Group Classification (AASHTO M145).

A1. Examine the variability of surficial geologic materials, particularly along transportation corridors, using available published information including, but not limited to, soil surveys, geologic maps, and available records of subsurface exploration.

A2. Interview personnel from ODOT headquarters and residencies across the state to identify typical as well as unusual soil behavior and to identify soil stabilization case histories of interest.

A3. Collect three to five samples representing different soils within the same AASHTO M145 classification groups to represent the variations found in Oklahoma Soils.

B. Evaluate OHD L-50 "Soil Stabilization Mix Design Procedure" for the test soils and test additives identified.

B1. Determine testing schedule to optimize resources and time while considering the extent of soil and additive variability across Oklahoma.

B2. Determine basic physical and engineering index properties with standard laboratory tests.

B3. Determine moisture-density curves of raw and treated soil via the calibrated Harvard Miniature Procedure.

B4. Quantify change in plasticity of stabilized soil using Atterberg Limit Tests.

B5. Determine unconfined compressive strength of raw and treated soils to assess degree of stabilization achieved using the recommended ODOT additive quantities.

B6. Determine if the recommended additive contents meet the strength limits defined in ASTM D4609 and OHD L-50. Choose soils, including those that do not meet expectations, to perform further analyses as outlined in Objective E.

C. Thoroughly characterize the test soils identified to determine mineralogical, physical, chemical, and engineering index properties.

C1. Perform laboratory tests focused on physico-chemical understanding of soils including Specific Surface Area (SSA), powder X-Ray Diffraction (XRD), carbonate content, organic content, pH, electrical conductivity, iron content and Ion Chromatography (IC).

D. Refine and optimize the recommendations in OHD L-50 by examining potentially useful and quick methods for selecting additive contents.

D1. Use the linear shrinkage, SSA, pH and conductivity tests to determine protocols that would relate additive content to strength gain and take additive and soil variability (because tests are a function of mineralogy) into account.

1.2.2 Specific Objectives of Volume II

Volume II covers the third year and discusses Objectives 2 and 3 and the following specific tasks:

A) Select roadway projects in alignment characterization or grading and drainage stages which represent different subgrade soil types, chemical additive types, and climatic conditions across Oklahoma,

B) Collect representative soil samples from project locations for classification, quality control, and engineering property testing.

C) Collect representative chemically treated soil samples from construction project sites for engineering property testing.

D) Following compaction and acceptance of the chemically treated subgrade, conduct a time sequence (1, 3, 7, 14, 28 days) field evaluation of strength and stiffness using field test equipment, including the Dynamic Cone Penetration, PANDA Penetration Tests and Portable Falling Weight Deflectometer (PFWD).

E) Establish time rate of development and maximum level of strength gain relationships and compare to previous structural number correlations, then adjust design equation input parameters accordingly.

1.3 Report Layout

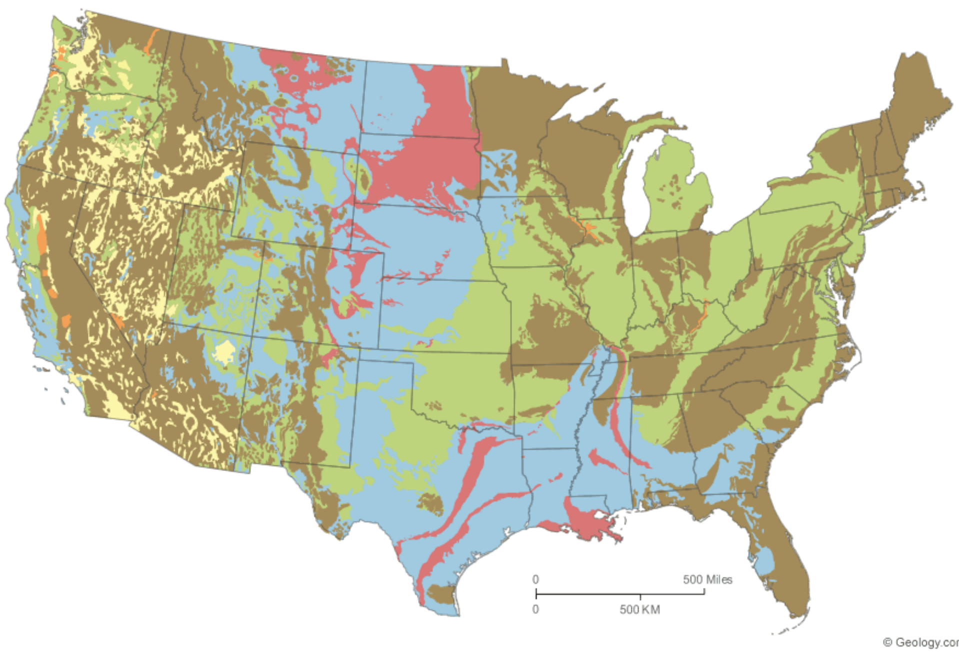
Volume I is organized into six chapters. Chapter 2 reviews published studies on chemical stabilization of soils and previous studies about soil properties that have significant effects on stabilizer effectiveness. Chapter 3 provides detailed descriptions of sample preparation, equipment, and testing used in this research study. Chapter 4 presents detailed descriptions of the soils used. Included in this chapter are the soil collection locations, the soil taxonomies, and soil properties that were found from the standard classification and physical property tests. Chapter 5 contains comparisons of the results of the statistical analyses performed on each soil. Lastly, the summary and conclusions of this study are presented in Chapter 6.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Many locations around the world, and especially many places in the United States, contain problematic soils such as expansive soils (Nelson and Miller 1992). Figure 1 shows the locations of swelling soil in the continental United States. In order to build on these soils, it is necessary to strengthen and stiffen these soils. Highly plastic soils, including many soils found in Oklahoma, are stabilized using chemical additives. These additives, used to stabilize soils, include hydrated and quick lime, fly ash, cement kiln dust, and Portland cement. Table 1 shows the “Soil Stabilization Table” from OHD L – 50 (2009) that was developed to provide a quick guide to what additive and how much to use for certain AASHTO M145 classified soils. One of the problems with relying solely on this table is that many times, similarly classified soils behave differently when stabilized with the same amount and type of stabilizer, and therefore, it is imperative to understand not only the cause of this different behavior but how our laboratory predicted behavior will differ from actual field performance.

To shed some light on these issues, a recently completed ODOT research study (Snethen et al. 2008), made some important discoveries that helped to shape the research objectives and direction of the current study. One of the conclusions was that that strength and stiffness values determined in a laboratory setting depended on how the specimens were prepared. The authors found that for field mixed samples (field mixed samples taken directly after chemicals were mixed in the field and compacted for testing), strength and stiffness values were 50% to 90% of the laboratory mixed samples (raw soil and chemical stabilizer sampled from the field and mixed and compacted in the lab). This is because of non-uniform field mixing, possibly less additive than specified being applied for stabilization, different curing temperatures, and variable water contents. The reduction in strength might also be attributed to delayed compaction effects. If there were significant delays in compaction of the test specimens from the time of mixing to the time of compaction (greater than 2 hours), then a reduction in strength is possible (e.g., Little, et al 2000 and Miller and Diaz 2002).



Over 50 percent of these areas are underlain by soils with abundant clays of high swelling

Less than 50 percent of these areas are underlain by soils with clays of high swelling

Over 50 percent of these areas are underlain by soils with abundant clays of slight to moderate swelling potential.

Less than 50 percent of these areas are underlain by soils with abundant clays of slight to moderate swelling potential.

These areas are underlain by soils with little to no clays with swelling potential.

Data insufficient to indicate the clay content or the swelling potential of soils.

Figure 1 - Map of Swelling Soils in United States (from Olive, et al, 1989)

To examine the influence of delayed compaction, Miller and Diaz (2002) mixed a clayey sand (LL = 29%, PI = 13.5%) with 10% CKD and compacted it after various elapsed times following the completion of mixing. For each delay, unconfined compression test specimens were prepared in triplicate following the specified elapsed times up to 48 hours. Following 14 days of curing after compaction, samples were subjected to unconfined compression testing. The results indicate that substantial reductions in strength occur after a compaction delay of about two hours (Figure 2). Apparently most of the beneficial stabilization reactions between the CKD and soil occur within the first couple of hours following mixing. This observation has important implications regarding field mixing; however, it is noted that the reactions will be a function of temperature, being faster at higher temperatures and slower at lower temperatures as compared to the laboratory temperature of about 22^{o}C

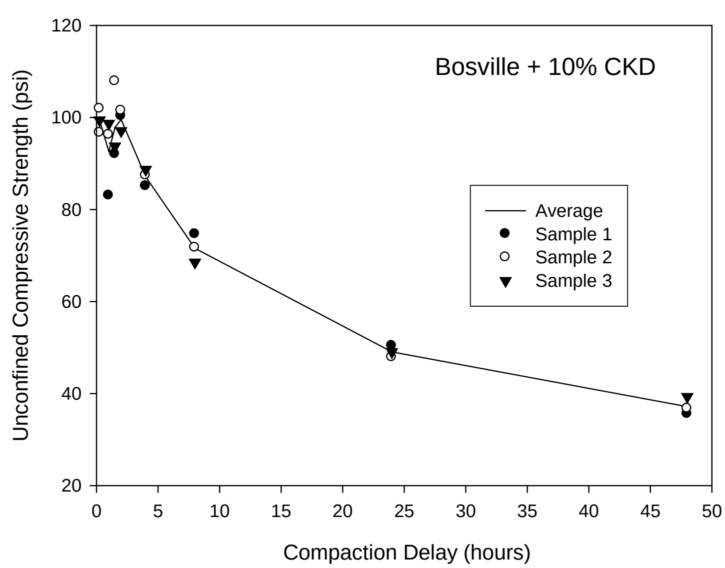


Figure 2: Reduction in Unconfined Compression Strength due to Compaction Delay (from Miller and Diaz 2002).

In the laboratory mixed samples, on the other hand, the amount of stabilizer and water used was carefully controlled. Temperature and cure time were also carefully controlled. It was from this finding that led the current research program to use X-ray Fluorescence on the field mixed samples to determine exactly how much stabilizer was present in the field and to use this amount in mixing laboratory specimens.

Another important conclusion from Snethen et al. 2008, was that the Dynamic Cone Penetrometer (DCP) and the PANDA Penetrometer provided good measures of long term performance of stabilized soil layers and show good potential for use as quality control tools. It was from this finding that the decision was made to use the DCP, PANDA and Portable Falling Weight Deflectometer (PFWD) in quantifying predicted laboratory strength and stiffness with actual field strength and stiffness, which will be discussed in detail in Volume II.

Solanki et al. 2009 reported on results from their study on stabilized subgrade soils for pavement design for ODOT, and found that lime, CFA and CKD, were effective in reducing the plasticity of soils, with lime-stabilization more effective as compared to CFA and CKD-stabilization in PI reduction. They found that increasing the additive content increased the unconfined compressive strength and reduced the failure strain and modified several existing log-log and semi-log models with measured properties (e.g., UCS, pH, dry density, LOI, etc.) to predict MR values of CFA, CKD and hydrated lime stabilized soils.

Pinilla et al. (2011) investigated the influence of soil properties, additive type and curing time on the resilient modulus of chemically stabilized soils. Regression equations were developed so MR development with time could be numerically described. After 28 days of curing time, tested soils showed improved MR values ranging from 7 to 46 times larger than those of untreated soil. Rates of improvement were characterized using a power-type regression analysis. Correlations between improvement rate (Rt) and raw soil properties including fines fraction, pH, and to a lesser extent, specific surface area (SSA) and cation exchange capacity (CEC) indicate these factors show promise as predictors of MR improvement with time.

2.2 Research into Effective Stabilizer Percentages

2.2.1 Lime

For this study, hydrated lime was one of the three chemical stabilizers chosen for the laboratory study, however, quicklime was utilized on two sites in the field study to be discussed in Volume II. Of the three chemicals, it is the only one that is not a byproduct of an industrial process, which makes lime comparatively more expensive to use. As a stabilizer, lime increases the workability of a soil and reduces the plasticity, especially through the first 3% (by dry weight) added (e.g., Snethen et al. 1975, Nelson and Miller 1992, Das 2007). Also noted in Snethen et al. 1975, is adding lime to clay soils causes cation exchange and flocculation-agglomeration, two physico-chemical reactions. Flocculation-agglomeration causes the individual particles to agglomerate, or stick together and form bigger particles, which leads to several changes in the soil properties, most notably texture, a reduced plasticity index, an increased shrinkage limit, and a higher strength.

The primary test for determining the necessary amount of lime to add to stabilize a soil is the pH test (ASTM D 6276). The standard states that the minimum effective lime additive content is that which raises the pH of the soil-additive mixture to 12.4, the pH of a saturated lime solution. However, the standard also says that unconfined compression tests should be used to assure that the chosen lime percentage causes the desired strength gain. As lime is a basic substance (calcium oxide, CaO, pH of 12.4) and most soils have pHs ranging from approximately 7 to 9, effective lime modification generally occurs with only 2% to 3% lime by dry weight. The Armed Forces of the

United States use a very similar procedure for their pavement designs (U.S. Army, U.S. Air Force, and U.S. Navy 2005). The first step in their five step procedure is to mix several test batches of soil with increasing lime percentages to determine which percentage first causes a soil to reach a pH of 12.4. That percentage is then used to create UCT samples to evaluate if the percentage is sufficient in terms of the strength gained. If the strength is not acceptable, the next higher percentage is subjected to the same tests until the strength requirement is met.

Another important aspect of choosing the appropriate lime additive percentage is the degree of pulverization of the soil. According to Bozbey and Garaisayev (2009), the higher the percentage of soil particles that pass a #4 sieve, the more efficient lime stabilization treatments will be. Their study focused on the differences between high-quality pulverized samples (100% passing a #4 sieve) versus poor-quality pulverized samples representing common field conditions (40% passing a #4 sieve) (Bozbey and Garasayev 2009). In terms of the unconfined compression strength results, the study showed that non-mellowed, high-quality samples treated with 6% lime showed much higher strengths than poor-quality samples with the same conditions. Only at 9% lime did the soil have similar strength values, showing that samples tested at “ideal” laboratory conditions may under-predict the actual additive amount needed to achieve the same desired results in field applications.

2.2.2 Cement Kiln Dust

Cement kiln dust (CKD) is a byproduct from the production of Portland cement. As it is a byproduct from an industrial process and each cement plant is different, the properties of CKD vary widely from one source to another. This makes it difficult to standardize the effects of soil stabilization with CKD. According to Miller and Zaman (2000), CKD is an effective soil stabilizer for both cohesive (clays and some silts) and non-cohesive soils (some silts and sands). This phenomenon was tested in this study, as both expansive clays and silts were tested with cement kiln dust. Their study also compared the effectiveness of CKD from three different sources. They ultimately determined that CKD from different sources results in different strength gains.

Unlike lime treatments, which primarily base a stabilizer's effectiveness on pH, soils treated with CKD are best judged by the UCS changes after stabilization (Si and Herrera 2007), although other methods are used. Their study investigated the strength properties of a medium-PI soil classified as A-6 (16) treated with CKD from 2% up to 10% of the dry weight of the soil. They also investigated the effects of curing times on the compression strength of the stabilized soil. They determined that not only did the higher percentages of CKD yield higher unconfined strengths, a longer curing time (5-months versus 7-days) also resulted in higher strengths; the 5-month cured samples exhibited more than 2 times the strength of the 7-day cured samples.

While the Si and Herrera study found 10% CKD was the optimum additive content for their clay sample, a separate study by Mohamed (2002) on a non-plastic silty sand determined that 6% CKD is effective for stabilization based on a peak shear strength at 6% CKD followed by a reduction in strength at higher additive contents. An alternate method to choosing the correct CKD percentage to treat a soil is to base the calculations on the recommendations for treating a soil with Portland cement. Miller, et al (1997) pointed out that since CKD reacts with soil in a similar manner as Portland cement, but contains about 50% less calcium oxides, a reasonable method to choose a CKD content is to find the appropriate Portland cement content and double it to find the CKD content.

Another aspect of soil stabilization treatment that affects the percentage of CKD required to achieve a necessary strength gain is the compaction delay time. This was tested in a study by Brooks, et al (2009). Using a medium-PI (18%) clay, the researchers tested the effects of compaction delays on different soil parameters including the UCS and the California Bearing Ratio (CBR). They determined that the as long as the compaction occurred within three hours of mixing, strength changes were negligible; but as the delay increased beyond three hours, the soil showed considerable UCS and CBR value reductions. ODOT has language in Section 307 of the 2009 Specification book to “compact the soil-additive mixture immediately after final mixing. Complete compaction on the same day as the mixing.”

2.2.3 Fly Ash

Fly ash is a byproduct of the combustion of lignite coal in coal-fired power plants. When used as a soil stabilizer, fly ash is divided into two categories based on the calcium content. Ashes with high calcium contents are labeled as Class C fly ash, and ashes with low calcium contents and higher amounts of silica and/or alumina are called Class F fly ash (Turner 1997). In his study, Turner compared the effectiveness of the two types of fly ash on several different Wyoming soils. He ultimately found that the compression strengths of the Class C fly ash stabilized soils were higher than those soils stabilized with Class F fly ash.

Class C fly ash is a self-cementing material, meaning that it contains some amount of free lime along with silica and alumina. Fly ash also has the ability to be used with sandy and silty soils due to its cementitious properties, unlike lime which typically does not react well with those types of soils (IDOT 2005). Unfortunately, the proportion of free lime in fly ash can vary from source to source. The percentage of lime can be as low as 0 to 7% (ASTM D 5239) or up to 25% and higher (Das 2007). Despite the presence of this extra lime, soil stabilization applications that call for fly ash generally use relatively higher percentages by dry weight than applications with lime or CKD, with percentages ranging up to 12% or 15% or higher (Mackiewicz and Ferguson 2005).

As with CKD stabilization, fly ash stabilization does not have any specific methods for choosing the correct additive percentage. Laboratory testing of the unconfined compression strength after stabilization is still the best method of choosing the fly ash content. However, several different methods are commonly used to choose the additive percentage when fly ash is the recommended additive. One of these methods is to base the fly ash percentage from the amount of lime that would be used for the particular soil. In the *Design, Construction, and Materials* manual, the Illinois Department of Transportation (IDOT) recommends as the fly ash content to use two to three times the percentage of lime (IDOT 2005). A separate study investigated the optimum fly ash content using a free swell oedometer. Çokça (2001) tested fly ash percentages up to 25% on an expansive soil and found that the swell potential was barely reduced from 20 to 25% fly ash, implying that 20% fly ash is the optimum additive content, at least for that soil.

When fly ash is used in field applications, there are two major aspects of construction that do have specific guidelines. One aspect is the maximum compaction delay from the time of soil-water mixing (Little, et al 2000). As the hydration reactions begin as soon as the water is added to the fly ash and soil mixture, it is imperative that compaction begins within one to two hours to take full advantage of the cementing abilities of the fly ash. The cementitious materials bond the soil particles rapidly upon mixing, so any compaction delays can potentially disrupt these bonds and cause the final soil strength to be less than expected. The other important construction aspect is moisture control. If the moisture content of the soil at mixing is higher than the optimum moisture content, "the strength of the stabilized material can be reduced by 50 percent or more if the moisture content exceeds the optimum for maximum strength by 4 to 6 percent" (Little, et al 2000). ODOT specifications limits the moisture to within 2 percentage points of optimum (ODOT 2009, pp 173).

2.3 Soil Properties of Interest

It was expected that several different soil properties would affect the efficiency of chemical stabilizers used in fine-grained Oklahoma soils. Studies have already been performed on stabilizers and researchers have found many factors that influence the compressive strength of the soil (e.g., Snethen et al. 2008). The Oklahoma Department of Transportation (ODOT), for example, uses the Atterberg Limits to determine the modification to use in their mix designs; however, they have found instances where this does not accurately predict the stabilized strength even though the soils may be classified identically by AASHTO classifications. In other words, while convenient for classification, Atterberg Limits are not adequate in all cases for determining the amount of stabilizer to use for roadway subbase design because they alone do not always explain soil behavior. It is likely that other properties may have significant effects as well.

2.3.1 Soil pH

Miller and Azad (2000) performed a study on the influence of a soil's type on stabilization attained using cement kiln dust. Their study investigated several parameters, including the pH of the soil. Using data gathered from pH tests performed one hour after mixing a soil with cement kiln dust, they found that "Results of unconfined compression tests…indicate that the pH response can be used to predict relative performance of CKD-treated soils" (Miller and Azad 2000). Enough research has also been done on the subject of the pH response of soils mixed with lime that the ASTM Standards Manual contains a specific test procedure (ASTM D 4609) on how to determine the optimum lime additive content based on the pH (ASTM 2010). The standard states that once the recorded pH of the soil-additive mixture reaches 12.4, the additive content at which this occurs is the minimum lime content at which modification may occur. While the pH may ultimately be a contributing factor in more accurately predicting the soil strength gain, the ASTM standard recommends testing the unconfined strength of the optimum additive content to ensure the strength reaches the minimum threshold.

2.3.2 Cation Exchange Capacity

The cation exchange capacity (CEC) is a useful parameter for predicting the soil strength gains with different additives. Gill and Reaves (1957) presented SSA versus CEC with a correlation coefficient of $r^2 = 0.95$, which is similar to Mortland's (1954) and Reeve's et al. (1954) findings. Farrar and Coleman (1967) presented results for 19 British Clays, which show a relatively linear correlation between CEC and SSA as well as LL and CEC. All of these equations can be found in Table 2.

Table 2. Correlation Equations for Relationships Between CEC and Surface Area, Liquid Limit and Plasticity Index.

CEC=0.15SA-1.99	Southestern US Clay	Gill and Reaves (1957)
CEC=0.28SA+2	British Clay Soils	Farrar and Coleman (1967)
CEC=0.12SA+3.23	Israel soils	Banin and Amiel (1970)
CEC=0.14SA+3.6	Osaka Bay Clay	Tanaka (1999)
CEC=0.55LL-12.2	British Clay Soils	Farrar and Coleman (1967)
CEC=1.74LL-38.15	Clays from Israel	Smith et al. (1985)
CEC=3.57PL-61.3	Clays from Israel	Smith et al. (1985)

It should be noted that these correlations are soil specific. These same soil specific trends are what Cerato (2001) found after testing soils of various geologic origin. Cerato (2001) found that while there was a strong relationship between CEC and total SSA

(EGME Method) within specific geologic deposits (e.g., Figure 2), no global relationship was found between CEC or SSA (Figure 3) and the Atterberg Limits (Figure 4 and 5) for the soils tested. Cerato (2001) found, however, that there was a weak correlation between CEC, SSA and Atterberg Limits within specific geologic groups (Figure 4).

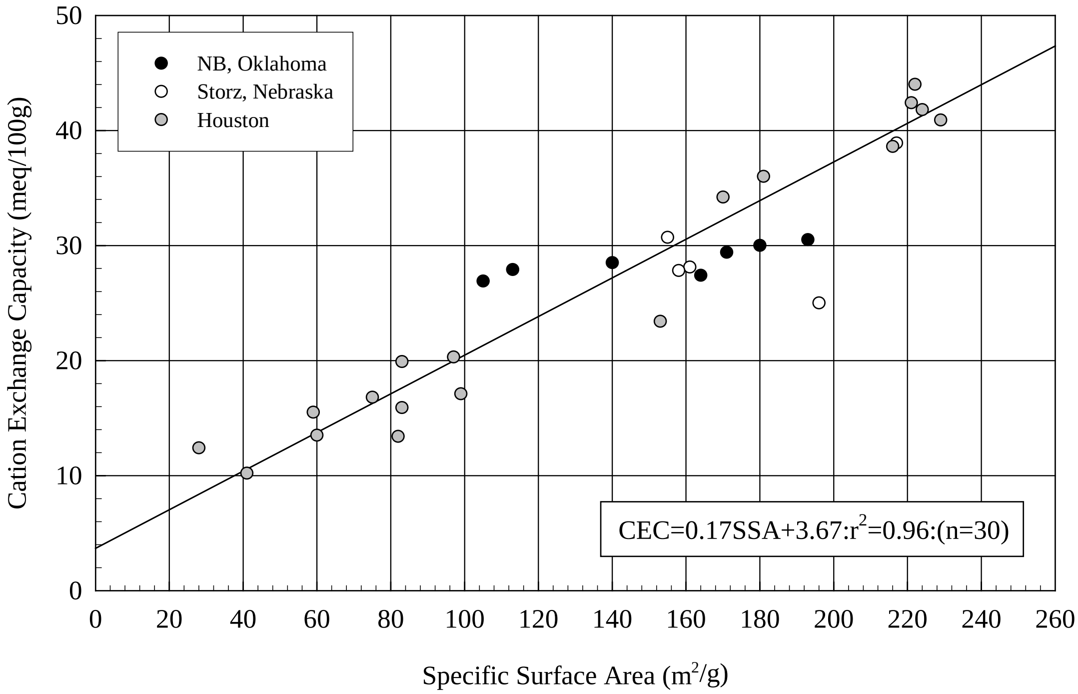


Figure 3: CEC versus SSA for Alluvial Deposits (from Cerato 2001).

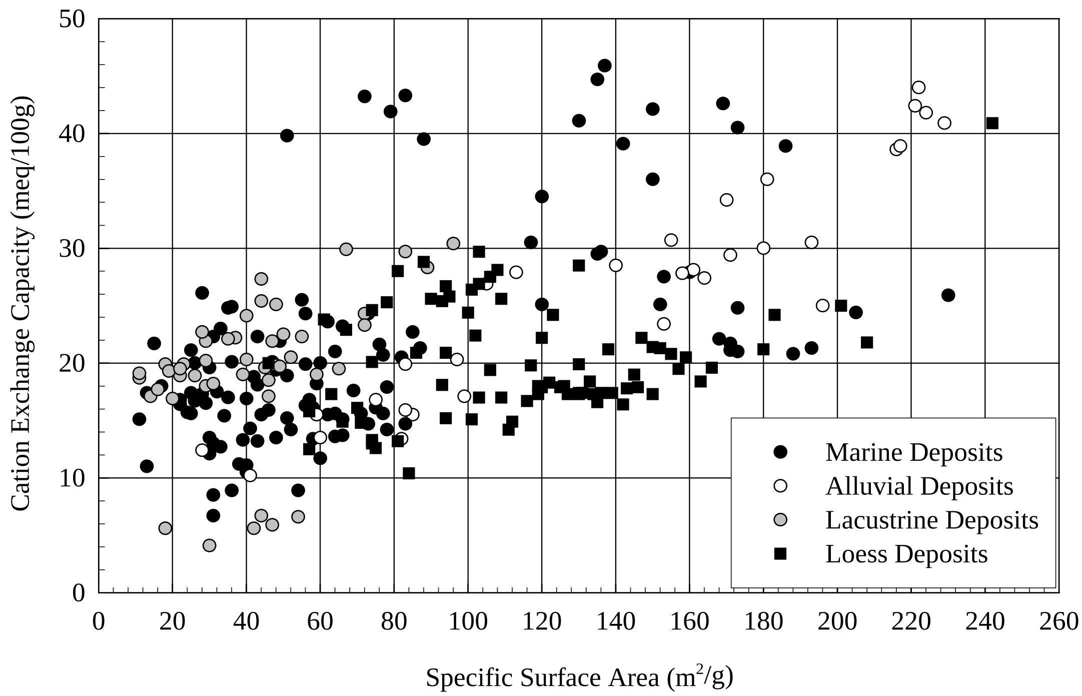


Figure 4 Cation Exchange Capacity versus Surface Area (from Cerato 2001).

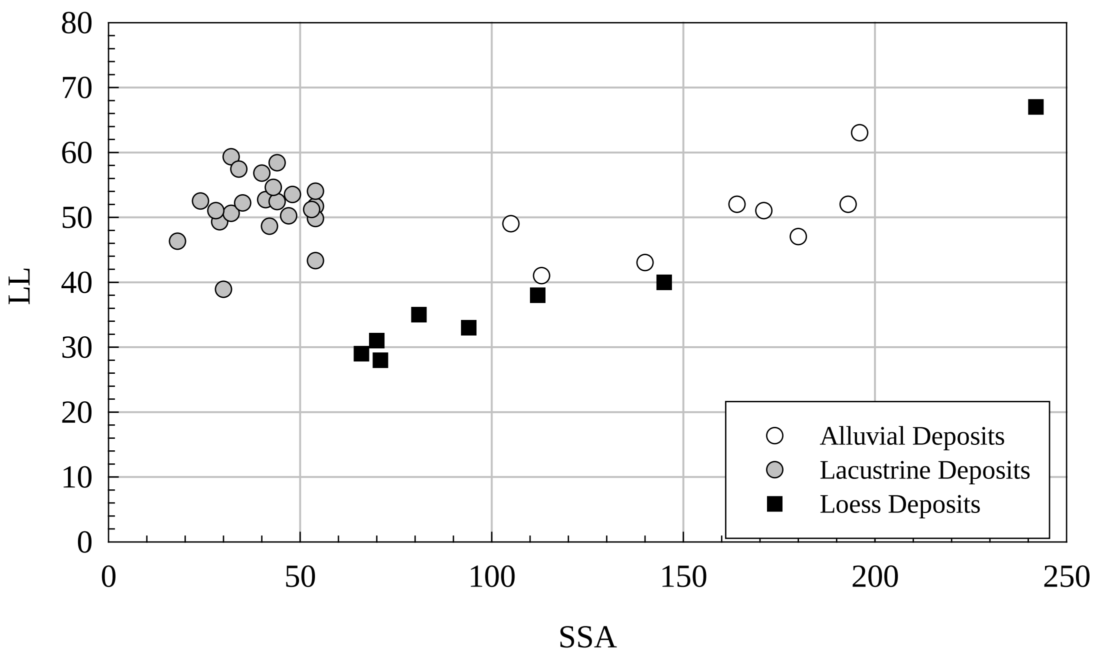


Figure 5: Soil Type Dependent Relationship Between LL and SSA (from Cerato 2001).

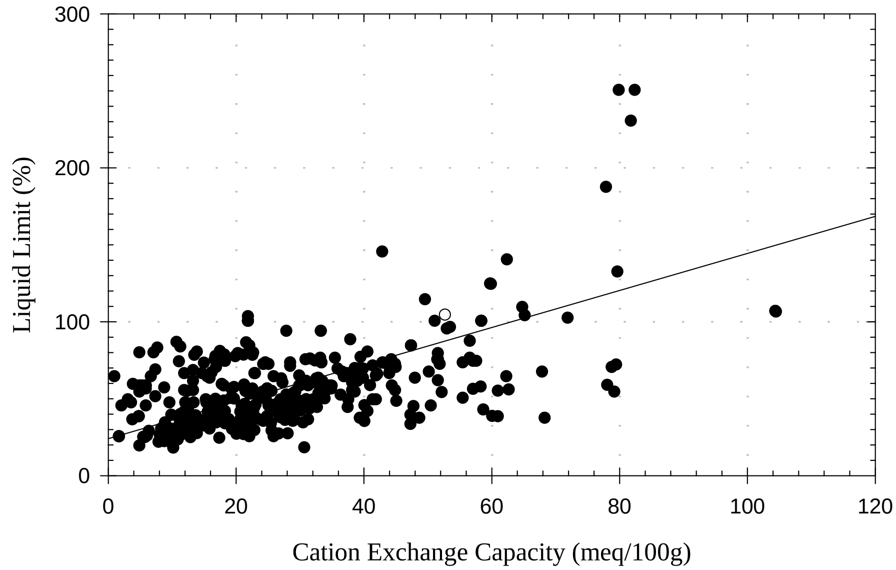


Figure 6: Global Relationship Between LL and CEC of Alluvial, Lacustrine, Marine and Loess Soils (from Cerato 2001).

Other researchers have shown that surface area and cation exchange show a linear relationship (e.g., Banin et al. 1970; Tanaka 1999) (Figure 7 and 8) within specific soil deposits of Clay soils of Israel and Osaka Bay clay, respectively.

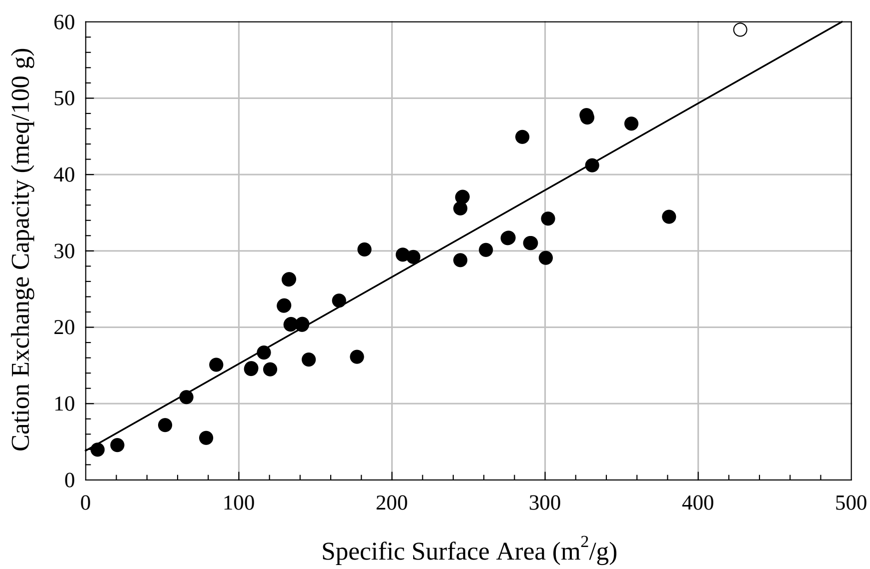


Figure 7: Correlation Between CEC and SSA for Clay Soils of Israel. (after Banin and Amiel 1970)

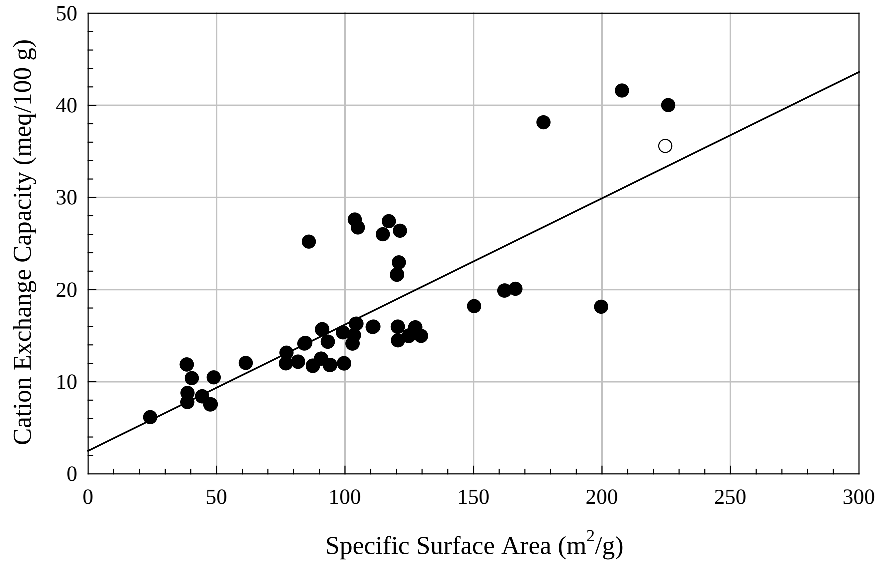


Figure 8: Correlation Between CEC and SSA for Osaka Bay Clay. (after Tanaka 1999)

Figure 9 illustrates the relationship between plasticity index and cation exchange capacity of Keuper Marl compared with Iowa loess. Because of the cementation effects in some of the marls, high exchange capacity values do not necessarily result in corresponding high plasticity indices (Kolbuszewski et al. 1965).

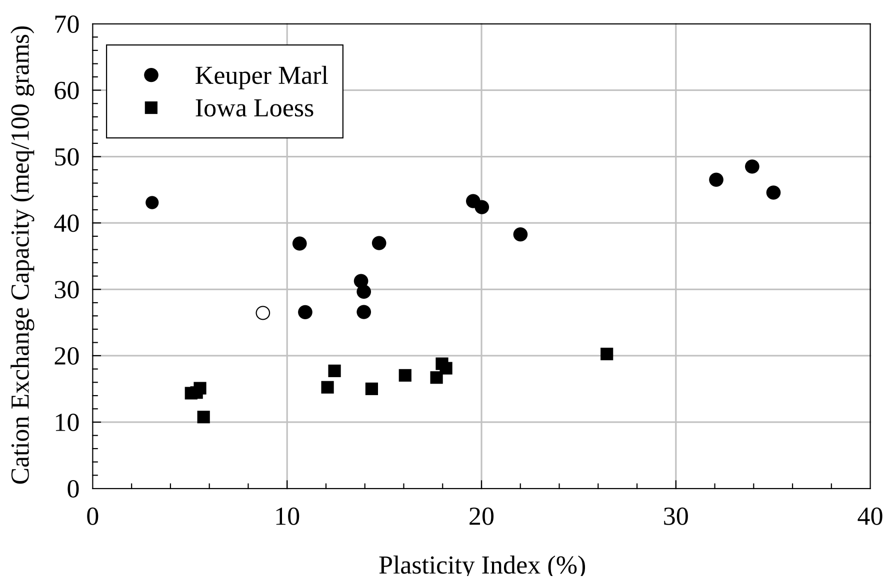


Figure 9: Cation Exchange Capacity versus Plasticity Index. (after Kolbuszewski et al. 1965)

Sheerer and Davidson (1952) performed tests on Wisconsin Loess in southwestern Iowa. They show the relationship between CEC and Plasticity Index, Liquid Limit and Clay Fraction to have a linear to curvilinear positive correlation, whereas the relationship between CEC and Plastic Limit and Shrinkage Limit show a negative linear correlation, Figures 10 through 14.

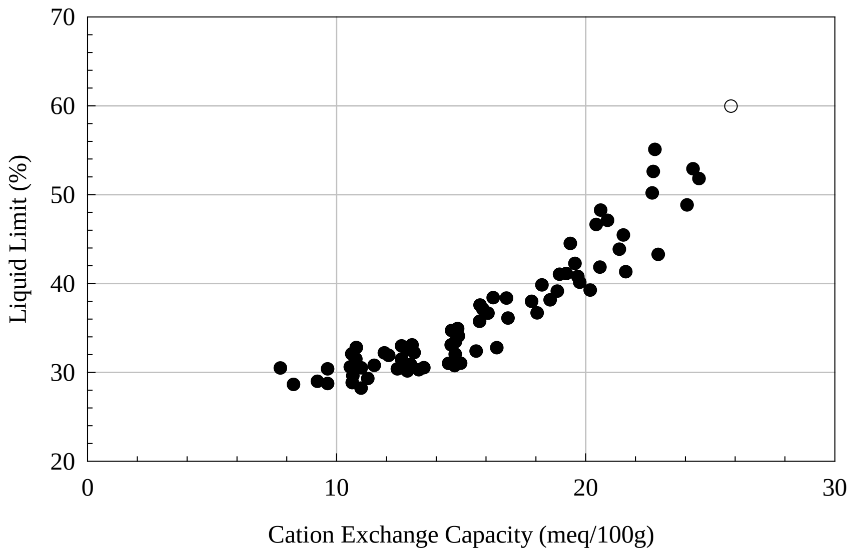


Figure 10: Relationship Between Cation Exchange Capacity and Liquid Limit. (after Davidson et al. 1952)

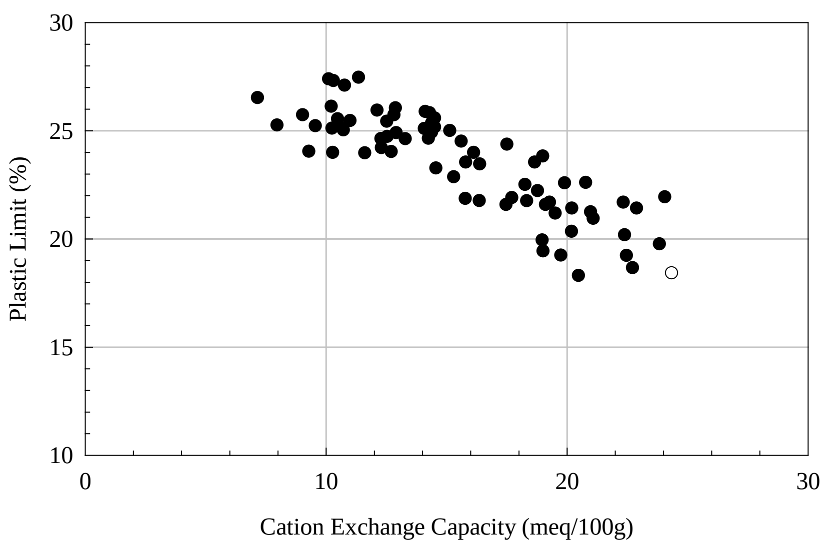


Figure 11: Relationship Between Cation Exchange Capacity and Plastic Limit. (after Davidson et al. 1952)

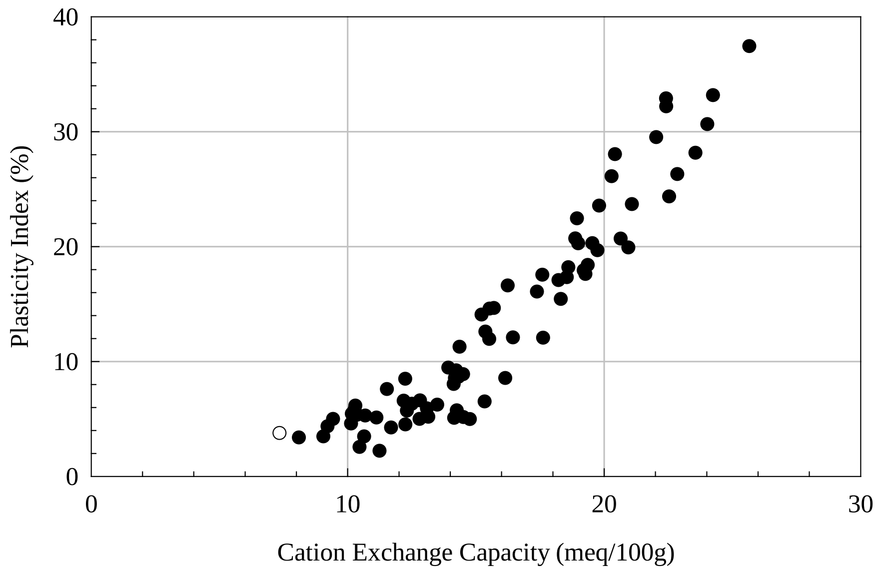


Figure 12: Relationship Between Cation Exchange Capacity and Plasticity Index (after Davidson et al. 1952)

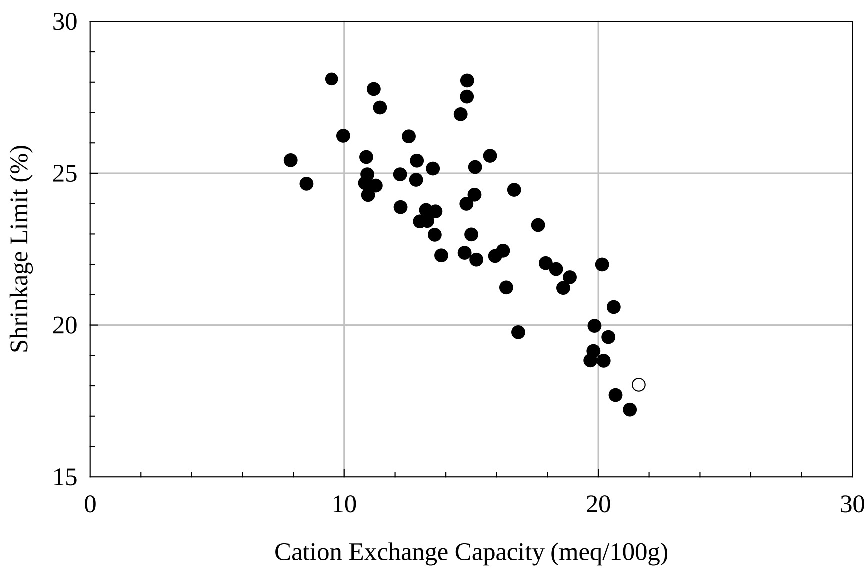


Figure 13: Relationship Between Cation Exchange Capacity and Shrinkage Limit. (after Davidson et al. 1952)

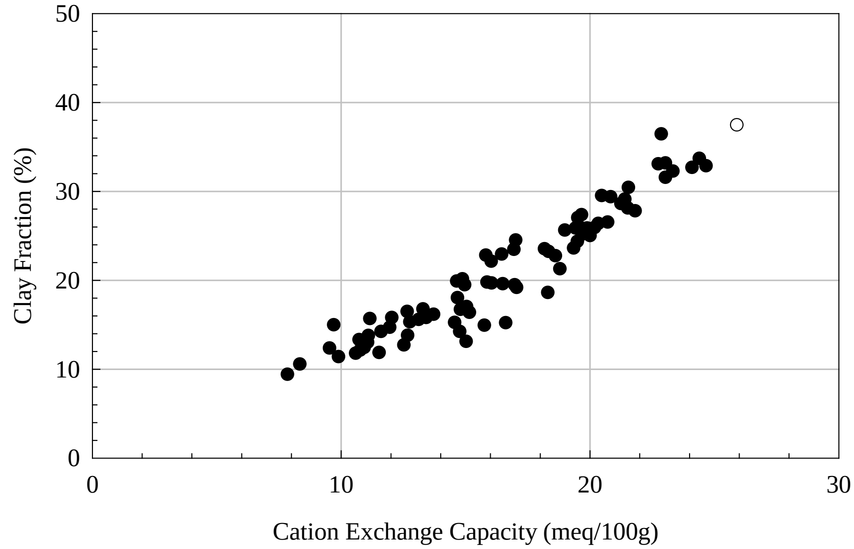


Figure 14: Relationship Between Cation Exchange Capacity and Clay Fraction. (after Davidson et al. 1952)

A study by Yukselen and Kaya (2006) investigated the correlations between cation exchange capacity and various other soil properties. Their study found strong relationships between the CEC and the EGME surface area values, the Liquid Limit, and the Plastic Limit. As soil stabilization already relies heavily on the data provided through Atterberg Limits in terms of placing soil in classification groups, and CEC has been found to show some correlations within specific soil types with these Atterberg Limit values, it stands to reason that the CEC may be one of the additional soil properties that can help explain the differing behavior of soils classified in the same soil group by Atterberg Limits.

2.3.3 Specific Surface Area

The specific surface area of clay can tell a great deal about the expansion potential of the soil. "There is strong evidence in the literature that indicates that specific surface area may be the single most important contributing factor that controls the engineering behavior of fine-grained soils" (Cerato and Lutenegger 2002). In a separate study by

Buhler and Cerato (2007), it was determined that for highly plastic soils treated with lime and Class C fly ash, higher specific surface areas coincided with higher amounts of shrinkage as determined with linear shrinkage tests. When treated with chemical stabilizers, higher stabilizer contents result in lower specific surface areas.

The Plastic limit has been correlated with Specific Surface Area (Smith et al. 1985; Gill and Reaves 1957; Farrar and Coleman 1967; Odell et al. 1960), as seen in Table 3, for specific soil deposits and the LL has been correlated with SSA within specific soil groups as shown in Figure 4, however, no global trend was noted.

Table 3: Correlation Equations for Relationships Between Plastic Limit and Surface Area.

$PL=0.43SA_{ext.}+16.95$	South African/Georgia/Missouri Clays	Hammel et al. (1983)
$PL=0.064SA+16.60$	Clays from Israel	Smith et al. (1985)

CHAPTER 3: MATERIALS AND TEST PROCEDURES

3.1 Introduction

This chapter details the soils chosen for the study, as well as the methods of investigation used to determine properties of the various soil samples. The laboratory test program consisted of general classification tests, Harvard Miniature compaction tests, and chemical property tests. The test soils selected for this study were subjected to standard classification, physical property, and chemical property tests, including tests of: grain size distribution (ASTM 422-00), specific gravity (ASTM D 845-00), Harvard Miniature compaction (ASTM D 4609-01), unconfined compression strength (ASTM D 2166-06), Atterberg Limits (ASTM D 4318-00), linear shrinkage (BS 1377: 1990, Test 5), shrinkage limit (ASTM D427), specific surface area (Cerato and Lutenegger 2002), carbonate content (Dreimanis 1962), sulfate content (ODOT 2005), pH (ASTM D 4972-01), direct current electrical conductivity, and cation exchange capacity (Rhoades 1982) tests. These tests were performed to classify the soil based on USCS and AASHTO classifications, to characterize the compaction properties, and gather input parameters for the statistical analysis.

3.2 Test Soils

The soil samples for this study were taken from different sites across Oklahoma and were chosen to represent the AASHTO-classified A-4, A-6, and A-7-6 soils. A total of eight soils were used in the study: three silts (A-4, ML or CL), three lean clays (A-6, CL), and two fat clays (A-7-6, CH). Once removed from the field, the soils were sealed in plastic buckets and kept in a humidity-controlled room to maintain the natural water contents. Figure 15 shows the locations of each soil and Table 4 provides a legend for Figure 15. Figure 16 provides images of each soil.

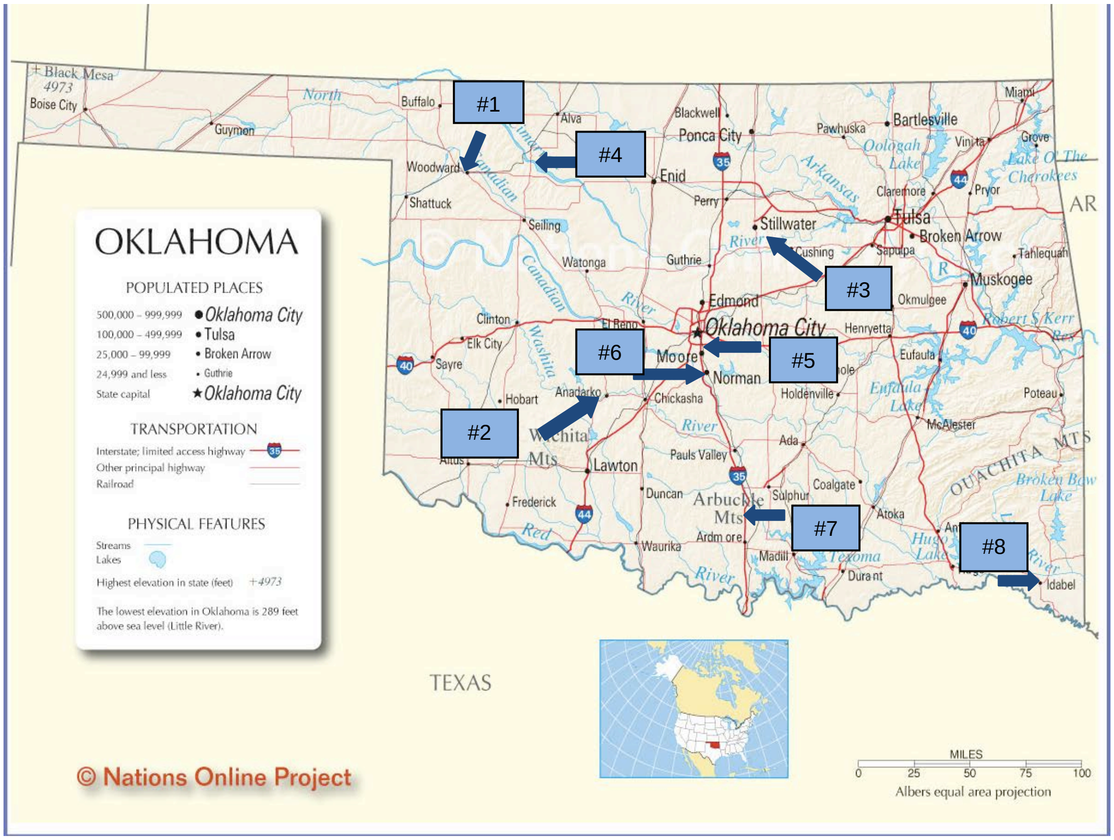
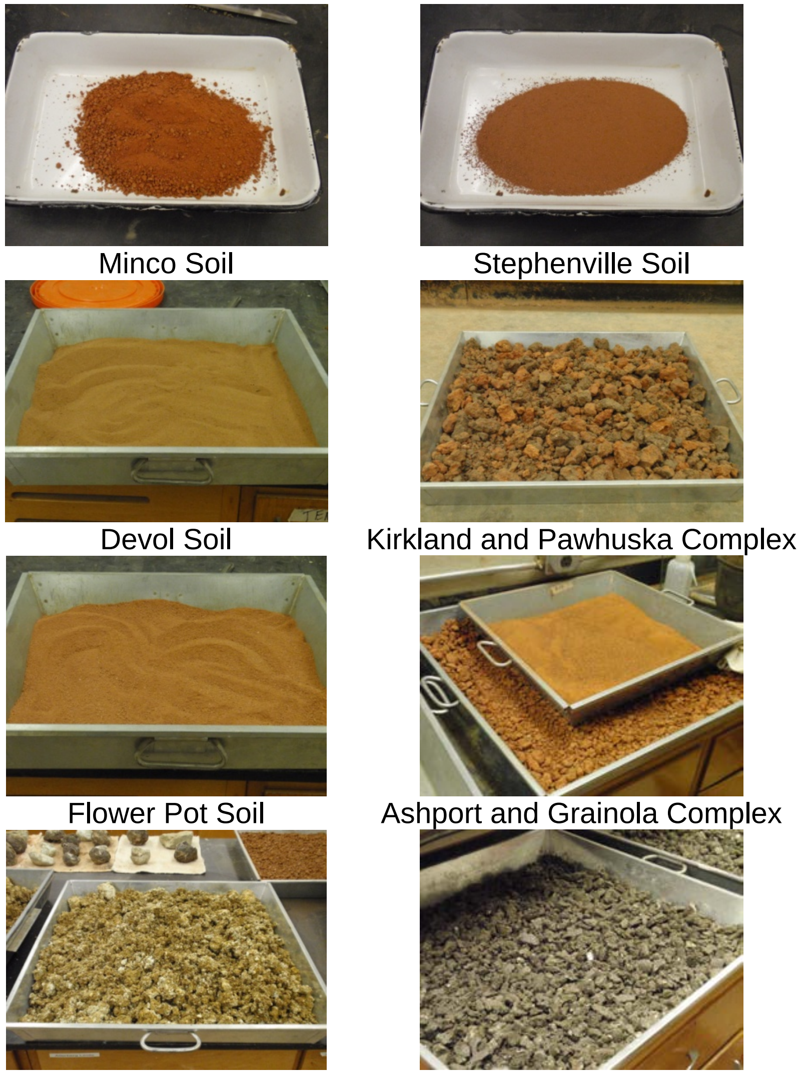


Figure 15 - Locations of Test Soils in Oklahoma

Table 4 - List of Soil Locations and Classifications

Soil No.	Soil Name	AASHTO Class.	USCS Class.	Location
1	Devol	A-4 (0)	ML	US 183, Woodward, OK
2	Minco	A-4 (0)	ML	US 62, East of Anadarko, OK
3	Stephenville	A-4 (2)	CL	Country Club Road, Payne Co., OK
4	Flower Pot	A-6 (18)	CL	Cimmaron River, East of Woodward, OK
5	Kirkland/Pawhuska Complex	A-6 (13)	CL	Sante Fe & South of 19th Moore, OK
6	Ashport/Grainola Complex	A-6 (9)	CL	24th E Robinson St., Norman, OK
7	Heiden Clay	A-7-6 (39)	CH	I-35 and Ardmore, OK, near Turner Falls
8	Hollywood	A-7-6 (45)	CH	Route US 70 & St. Rt. 7., Idabel, OK



Minco Soil | Stephenville Soil

Devol Soil | Kirkland and Pawhuska Complex

Flower Pot Soil | Ashport and Grainola Complex

Hollywood Soil | Heiden Clay

Figure 16- Pictures of Test Soils

3.3 Classification and Physical Property Tests

3.3.1 Grain Size Distribution

This test procedure was performed in accordance with the ASTM D 422-00 “Standard Test Method for Particle-Size Analysis of Soils” (ASTM 2010).

3.3.2 Specific Gravity

This test procedure was performed in general accordance with ASTM D 854-00 “Standard Test Method for Specific Gravity of Soils” (ASTM 2010).

3.3.3 Harvard Miniature Compaction

Compaction tests were performed according to the ASTM D 4609-01 “Evaluating Effectiveness of Chemicals for Soil Stabilization” (ASTM 2010), with major modifications. The biggest modification was the method of compaction. Instead of the spring-loaded, kneading compaction method, a miniature drop hammer, calibrated for each soil to the Standard Proctor (ASTM D 698-91) compaction curves, was used. This compaction hammer was developed to produce constant compaction energy for the Harvard Miniature (HM) mold that could be calibrated to the compaction characteristics of the Standard Proctor compaction method (Khoury and Khoury 2008). The primary reason for using the drop hammer was to minimize operator variability among the various students working on the project. Past experience has shown that compaction resulting from use of the spring-loaded tamper is significantly dependent on the operator. The diameter of the rammer was chosen so that the ratio of the diameter of the rammer to the diameter of the mold is approximately the same as the ratio in the standard Proctor test. The guide sleeve has vent holes from both ends with different diameters to prevent any pressure build up. The free fall distance of the rammer (0.863 lbs) was kept constant at 12 inches (30.48 cm), similar to the distance in the ASTM D 698-91 test method. Khoury and Khoury (2008) performed tests on 4 different soils and determined the best match to the Standard Proctor was using 10 drops per five compacted layers with the small drop hammer. Once the fifth layer was compacted, extra soil was trimmed from the top and bottom of the mold and used to determine the moisture content of the sample as a whole. The soil was then removed from the mold with a mechanical extractor.

This HM compaction method was calibrated to the Standard Proctor curves for each raw soil in this study (e.g., Figure 17, and Appendix A, Figures A.1-A-5). Once the raw soil Standard Proctor curve was matched with the HM compaction method, a few individual test points were checked on stabilized soil curves, although no full curves for each additive and quantity were performed. The individual test points chosen for a HM calibration check on the stabilized soils (typically the maximum dry density and OMC point on the Standard Proctor curve) matched well with the Standard Proctor curves. Throughout this research it was assumed that the calibration was valid for all the stabilized soils at all stabilizer quantities. Most of our soils fell within the 9-10 blows per layer range, with the Hollywood and Heiden clays needing only 5-6 blows per layer to match the Standard Proctor curves. Once this method was calibrated for each raw soil, the unconfined compression test specimens were made.

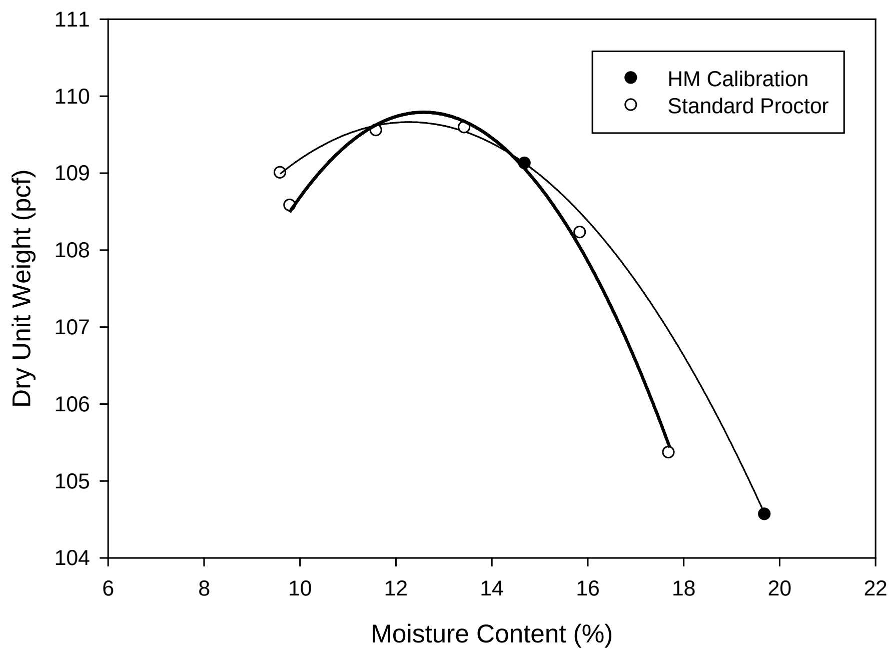


Figure 17: Calibration Curve for Devol (HM Samples using 10/blows per layer).

For preparation of each compaction specimen in this study, 140 g of air-dried soil was measured into a mixing bowl. The appropriate additive weight was calculated based on the dry weight of the soil and was added and mixed into the air-dried soil. Once the soil and additive were mixed, deionized water was added to the bowl to raise the moisture content to the desired level. The soil was then placed in the Harvard

Miniature mold and compacted using a manual rammer. The soil was compacted in five layers with the calibrated number of blows/layer for each specific soil (5-10/blows per layer). This process was repeated to create multiple-point moisture-density curves used to determine the optimum moisture content (OMC) of each soil-additive mixture.

3.3.4 Unconfined Compression Strength

Unconfined compression strength (UCS) testing followed the guidelines in ASTM D 2166-06 "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil" (ASTM 2010). Based on the OMC curves determined from the Harvard Miniature compaction tests, samples for UCS testing were prepared at the OMC of each soil-additive combination. The samples were prepared with the Harvard Miniature apparatus following the procedure outlined previously. Once the sample was removed from the mold, it was wrapped with plastic wrap and sealed in a plastic bag and placed in a 100% humidity room to cure for 14 days. Three samples were molded at each additive percentage for each soil. To be considered eligible for UCS testing, samples were required to be within 0.5% of the target moisture content and the range of moisture contents of the three samples could be no greater than 0.75%.

After curing, samples were tested using strain-control at a testing rate of 2% strain per minute. The values of load and deformation were analyzed to create stress-strain curves. After the samples failed in compression, they were air-dried and saved for testing the Atterberg Limits.

3.3.5 Atterberg Limits

The Atterberg Limits were conducted according to ASTM D 4318-00 "Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils" (ASTM 2010). Approximately 200 grams of soil were used to perform the Atterberg Limits tests. The soil sample was mixed with deionized water to bring the water content to a point where the blow count equaled 15 or less. Then the soil sample was kept in a plastic bag and placed in a humid chamber for at least 16 hours to temper. Once the soil tempered, the soil sample was divided into two parts. Approximately 20 grams of soil were used to perform the Plastic Limit test and the rest was used for the Liquid Limit test.

3.3.6 Shrinkage

3.1.1.1 Linear Shrinkage

This test method was first introduced by the Texas Highway Department in 1932 (Heidema 1957) and currently appears as a British Standard, BS 1377 (1990) and a TxDOT Standard, TEX-107-E (1999). The difference between the two standards is the shape of the linear shrinkage mold; the British Standard uses a half of a brass pipe with boxed edges and the TxDOT standard uses a square box mold. The BS was used at OU and the TxDOT standard was used at OSU. Approximately 150 grams of soil passing a #40 sieve were used to perform the test procedure. First, the soil sample was mixed with deionized water to approximately the Liquid Limit. A portion of the soil was placed in either a semi-circular linear bar mold approximately 6 inches long and 1 inch in diameter (BS 1377) or 5 inches long by 0.75 inches in width and height (TEX-107-E). The soil was placed in three layers and tapped against a flat surface in between the layering to remove air bubbles. The mold was allowed to air dry. Typically, no length and mass readings are taken until the sample has been oven-dried, however, if the shrinkage limit value is required, it is necessary to take intermediate readings in order to determine where volume change ceases, while water content is still decreasing. Therefore, mass and length measurements were taken several times a day until the length did not change measurably. At that point, the mold was oven-dried for 24 hours at 110 ± 5°C. After drying, the mass and length measurements were taken once more. The length of the soil sample was measured three times by using a digital caliper. The average length was used to calculate the linear shrinkage. The linear shrinkage was calculated by the following equation:

$$LS = 100 * \left(1 - \frac{L_{avg}}{L_o}\right) \qquad [1]$$

Where:

LS = Linear shrinkage (%),

L_{avg} = Average final length of the soil inside the linear bar mold (in),

L_o = Original length of the linear bar mold (in).

3.1.1.2 Shrinkage Limit

The linear shrinkage measurement of soil was used to determine the shrinkage limit. The test method was performed in general accordance with the British Standard (BS 1377: 1990, Test 5), which is an alternative to the Mercury Method (ASTM D 427- 00) “Standard Test Method for Shrinkage Factors of Soils by the Mercury Method.” This test was also performed in conjunction with the Linear Shrinkage test detailed previously. The changes in length measured during the air-drying period were plotted versus the water content, where the shrinkage limit was described as the first water content at which no variation in the length of the soil sample was observed. The determination of the shrinkage limit from the linear shrinkage is presented in Figure 18.

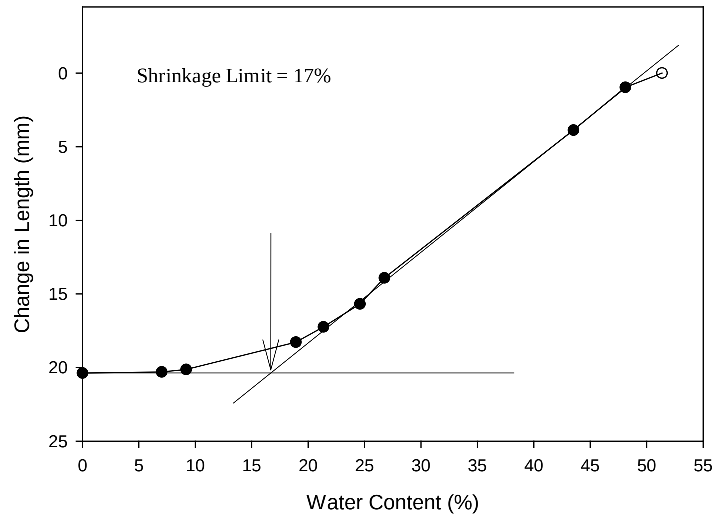


Figure 18 - Determination of the Shrinkage Limit

3.2 Mineralogical Property Tests

3.2.1 Specific Surface Area

3.2.1.1 Ethylene Glycol Monoethyl Ether (EGME) Method

This test method for the total surface area follows the methodology presented by Cerato and Lutenegger (2002) in their study “Surface Area and Engineering Properties of Fine-Grained Soils.” This test method was conducted on oven-dried soil. All soils were pulverized and then processed over a standard #40 sieve. Approximately one gram of oven-dried soil was spread on the bottom of an aluminum tare with 3 inches (76 mm) diameter and 1 inch (25 mm) height. Two aluminum tares were used for each soil sample. The mass of the soil was determined by using an electronic analytical balance with an accuracy of 0.0001 grams. Approximately 3 ml of Ethylene Glycol Monoethyl Ether (EGME) was added to the soil and gently mixed by hand to create a homogenous slurry. The slurry was allowed to equilibrate for 20 minutes and then the tares were placed in vacuum desiccators. A vacuum pump with 30 inches (762 mm) Hg was used to evacuate the desiccators. Initially, after 18 hours, the tares were removed from the desiccators and weighed. After the first measurement, the tares were weighed every 4 hours till the mass did not vary more than 0.001 grams. The total surface area was calculated by the following equation:

$$Total\ SSA = \frac{W_a}{(W_s * 0.000286)} \qquad [2]$$

Where:

W_s = Initial weight of soil sample used

W_a = Final weight - W_s

3.2.1.2 BET Method

This test procedure is used to determine the external specific surface area of soils (Brunauer et al. 1938). The Quantachrome Corporation's MONOSORB, a direct reading dynamic flow surface area analyzer, was used for this test. The principle of this test method is to measure the amount of adsorbate gas adsorbed on a solid surface by sensing the change in the thermal conductivity of a flowing mixture of adsorbate and an inert carrier gas. The adsorbate is nitrogen and the inert gas is helium. All soils were pulverized and processed over a standard #40 sieve, and then oven-dried at 110 ± 5°C for 24 hours. Approximately 0.1 grams of oven dried soil was placed in a sample tube and then put in the cell holder. A Dewar flask was filled with liquid nitrogen and brought up until the liquid nitrogen covered the top of the cell by 0.5 inches. Nitrogen then begins to flow and the soil adsorbs the gas. The Dewar flask lowered when the nitrogen flow stops and the gas adsorption begins on the soil. When the adsorption was complete, the integrator displayed a number which represented the sample surface area in square meters. The external surface area was determined by dividing that number by the mass of the soil.

3.2.2 Carbonate Content

This test method was performed using the Chittick Apparatus developed by Dreimanis (1962). The Chittick Apparatus measures the amount of carbonates in the soil by measuring the amount of carbon dioxide that evolves from carbonates reacting with dilute hydrochloric acid. The soil sample was crushed and passed over a standard #40 sieve. The soil was then oven-dried at 110 ± 5°C for 24 hours. Approximately 1.7 grams of the oven-dried soil was placed in a 250-ml Erlenmeyer flask with a plastic coated stirring magnet.. The hydrochloric acid solution was made by mixing 109.4 mL of concentrated hydrochloric acid in 1000 mL of distilled water. A pipette was filled with 20 ml of the 6N hydrochloric acid solution. Initially, the reservoir was raised to be in the same level of the annulus and this initial reading was recorded. Then a stop watch was started and the acid pipette valve was opened to allow 20 mL of acid to flow into the Erlenmeyer flask within a period of approximately 45 seconds. After one minute, the reservoir level was adjusted to be even with the level of the annulus and the first reading was taken. The temperature in the beaker and barometric pressure were recorded. The second reading was taken after twenty minutes, where the reservoir was again raised and leveled with the annulus and a second reading was taken. The temperature and barometric pressure were also recorded again. Using these readings and a table of correction factors, the calcite and dolomite percentages were determined using the calculation procedure described in Dreimanis (1962). The calcite digests in about 30 seconds and the dolomite digests in about 20 minutes. The total amount of calcite and dolomite was described as the total amount of carbonate content.

3.2.3 Sulfate Content

The sulfate content of the eight natural soil samples was determined according to the procedure established by the Oklahoma Department of Transportation (ODOT) OHD L-

49 "Method of Test for Determining Soluble Sulfate Content of Soil" (ODOT 2009). Air-dried soil was crushed and sieved over a standard #10 sieve to collect a mass of at least 30 grams. This sample was then oven-dried for 24 hours at 110 ± 5°C. Five grams of oven-dried soil was added to a plastic bottle with 200 g of deionized water and the slurry was shaken with a mechanical shake table for 15 minutes and then allowed to soak for at least 16 hours. The liquid in the bottle is then poured over a filter paper cone into a beaker. A 10 mL sample is extracted with a pipette from the filtered liquid and placed into a small glass vial. The vial is placed into a digital colorimeter and three sulfate content readings (ppm) are recorded. The sulfate content is determined using the following equations:

$$D = {}^{W_w}/_{W_s} \qquad [3]$$

Where:

D = Dilution ratio of soil slurry

W_w = Mass of water added to slurry

W_s = Mass of oven-dried soil in slurry

$$C = RD \qquad [4]$$

Where:

C = Sulfate concentration in ppm

R = Colorimeter reading in ppm

D = Dilution ratio

3.2.4 Soil pH

The pH curve of the eight soil samples with each desired chemical additive was determined using a test procedure based on the ASTM D 4972-01 "Standard Test Method for pH of Soils" (ASTM 2010). Enough soil was crushed from each sample to test ten additive percentages to construct a pH curve. Table 5 shows the tested additive percentages based on the additive type being used. The testing percentages for lime were weighted slightly more toward the early percentages because the lime pH curve develops rapidly at low contents.

Table 5 - Additive Testing Percentages for pH and Conductivity Tests

Additive Type	Percentages Tested to Prepare Curves
Lime	0, 0.5, 1, 2, 3, 5, 10, 15, 25, 100
CKD	0, 1, 2, 3, 5, 7, 10, 15, 25, 100
Red Rock Fly Ash	0, 1, 2, 3, 5, 7, 10, 15, 25, 100
Muskogee Fly Ash	0, 1, 2, 3, 5, 7, 10, 15, 25, 100

First, enough air-dried soil was measured out to have a mass of 25 g of oven-dried soil. The desired additive amount was added based on the 25 g dry mass and was thoroughly mixed in a clean plastic bottle. 100 mL of deionized water was added to the bottle and the bottle was placed on a mechanical shaker to shake for 30 seconds. The shaking was repeated every 10 minutes for one hour to ensure a well-mixed sample for testing. After the shaking was completed, a calibrated digital pH meter was used to determine the pH of the sample. Each additive percentage was tested three times to ensure accurate results.

3.2.5 Direct Current Electrical Conductivity

The conductivity of the soil-additive combinations was determined following the same basic procedures outlined in the pH testing section above. The tests were also performed in conjunction with the pH tests. Table 5 shows the testing percentages. After testing the pH of the soil-additive slurry in a bottle, a calibrated digital conductivity meter was used to measure the electrical conductivity of the slurry. As with the pH tests, three tests were done at each additive percentage for accuracy purposes.

3.2.6 Cation Exchange Capacity

The cation exchange capacity of each soil and additive combination was determined by Harris Laboratory, Inc., Lincoln, Nebraska using a 1N ammonium acetate extraction method (Rhoades 1982).

CHAPTER 4: RESULTS OF CLASSIFICATION, PHYSICAL, AND MINERALOGICAL PROPERTY TESTS

4.1 Introduction

Eight soil samples were collected from various locations around Oklahoma for this research study. All eight soils were tested and classified using the tests described in Chapter 3. This chapter presents the property test results.

4.2 Soil Sources

As seen in Table 4, a total of eight Oklahoma soils were chosen for this project. According to the AASHTO classification system, the soils were classified in three groups; A-4, A-6, and A-7-6. According to the USCS classification system, the soils were classified in three classification; ML, CL, and CH. The A-4 soils were three low plasticity or non-plastic soils: a Devol soil from near Woodward, OK, a Stephenville soil from Payne, OK and a Minco Silt from Anadarko, OK. The three A-6 soils were Flower Pot clay from along the Cimarron River north of Route 412, an Ashport and Grainola complex from Norman, OK, and a Kirkland and Pawhuska complex from Moore, OK. Two soils were from the A-7-6 classification: a Hollywood soil, from near Idabel, OK and a Heiden clay, from near Turners Falls, OK.

4.3 Physical and Mineralogical Test Results

The soils in this study were tested using procedures selected to provide important properties for later use in the analysis of the chemical stabilizer effectiveness. Physical property test results are shown in Table 6 and mineralogical test results are shown in Table 7.

4.3.1 Harvard Miniature Compaction Results

The Harvard Miniature compaction apparatus was used to determine the optimum moisture content (OMC) of each raw soil and, later, of each soil and additive combination. The OMCs were used to prepare the UCT samples for strength testing. A summary of the compaction results appears in Table 8. The OMC curves for each soil-additive combination can be seen in Appendix A in Figure A.6 through Figure A.27 and Table A-1 through Table A-8.

Table 6 - Physical Properties of the Raw Test Soils

Soil Name	Specific Gravity	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Linear Shrinkage (%)	Shrinkage Limit (%)	Clay Fraction (%<2μm)	*Activity (A)
Devol	2.72	26.0	NP	NP	3.0	2.5	7.1	n/a
Minco	2.70	NP	NP	NP	2.0	4.5	14.9	n/a
Stephenville	2.70	24.0	14.0	10.0	9.0	9.5	31.4	0.32
Flower Pot	2.80	36.7	17.3	19.4	10.7	15.0	62.1	0.31
Kirkland / Pawhuska	2.74	38.8	16.3	22.5	12.3	15.0	28.6	0.79
Ashport / Grainola	2.77	36.8	17.7	19.1	11.8	12.0	27.5	0.70
Heiden	2.77	66.9	22.8	44.1	19.4	17.0	50.1	0.88
Hollywood	2.78	54.0	19.6	34.4	16.4	11.0	61.5	0.56

*Activity = PI/CF

Table 7 - Mineralogical Properties of the Raw Test Soils

Soil Name	Cation Exchange Capacity (meq/100g)	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)	Sulfate Content (ppm)	Calcite Content (%)	Dolomite Content (%)	*Carbonate Content (%)	pH	Conductivity (**mS)
Devol	5.5	30.0	8.4	21.6	213	3.6	1.6	5.2	9.08	37.81
Minco	8.2	40.5	1.5	39.0	230	2.3	1.6	3.9	7.50	262.20
Stephenville	14.0	50.0	18.8	31.2	1013	1.4	1.5	2.9	7.80	358.00
Flower Pot	44.1	85.5	50.6	34.9	4133	4.3	2.3	6.6	8.41	546.00
Kirkland / Pawhuska	37.7	120.5	47.9	72.6	4118	5.6	3	8.6	8.65	1205.33
Ashport / Grainola	21.9	90.5	34.2	56.3	223	2.7	6.6	8.3	9.30	265.67
Heiden	50.7	229.0	51.5	177.5	335	12.1	2.3	14.4	8.93	300.00
Hollywood	26.4	145.5	40.3	105.2	247	3.1	0.9	4.0	7.65	190.67

*Carbonate Content = Calcite Content + Dolomite Content

**mS = microSiemens

Table 8 - Compaction Properties of the Raw Test Soils

Soil Name	Maximum Dry Unit Weight γ_d (pcf)	OMC (%)
Devol	109.6	12.30
Minco	112.3	13.30
Stephenville	116.2	13.60
Flower Pot	106.4	20.90
Kirkland / Pawhuska	108.5	17.30
Ashport / Grainola	114.4	15.54
Heiden	98.6	24.20
Hollywood	106.4	20.60

CHAPTER 5: THE EFFECTS OF CHEMICAL STABILIZERS ON SOIL PARAMETERS AND SOIL STRENGTH

5.1 Unconfined Compression Test Results

The minimum strength gain for a soil to be considered effectively stabilized, as specified in ASTM D 4609, is 50 psi (345 kPa) above the raw soil strength. All eight soils were tested at several different additive percentages, bracketing the current recommendations of OHD L-50. Table 9 shows the results of the UCS tests for the raw soils at maximum dry density and optimum moisture content. The results of all eight soils stabilized with the four chemical stabilizers in varying amounts can be seen in Figure 19 through Figure 28, and in Appendix A, Table A-9.

Table 9 - Unconfined Compression Strengths of the Raw Test Soils

Soil Name	Average Maximum UCS (psi)	*Standard Deviation (psi)
Devol	18.7	2.1
Minco	15.6	0.5
Stephenville	32.9	3.4
Flower Pot	42.2	3.6
Kirkland / Pawhuska	36.2	3.8
Ashport / Grainola	31.5	1.3
Heiden	45.3	3.7
Hollywood	53.0	1.3

*Standard Deviation was calculated for 3 or more samples. This is not the range.

Figure 19 presents the UCS strengths of A-4 soils stabilized with CKD. All three soils are stabilized in terms of the 50 psi strength gain over the raw strength at 8% CKD, whereas the current OHD L-50 standard recommends 12%. However, the strength of Minco and Stephenville soils decreases from an additive content of 10% to 12% and the Devol soil gains much less strength with increasing additive than the Minco and Stephenville soils.

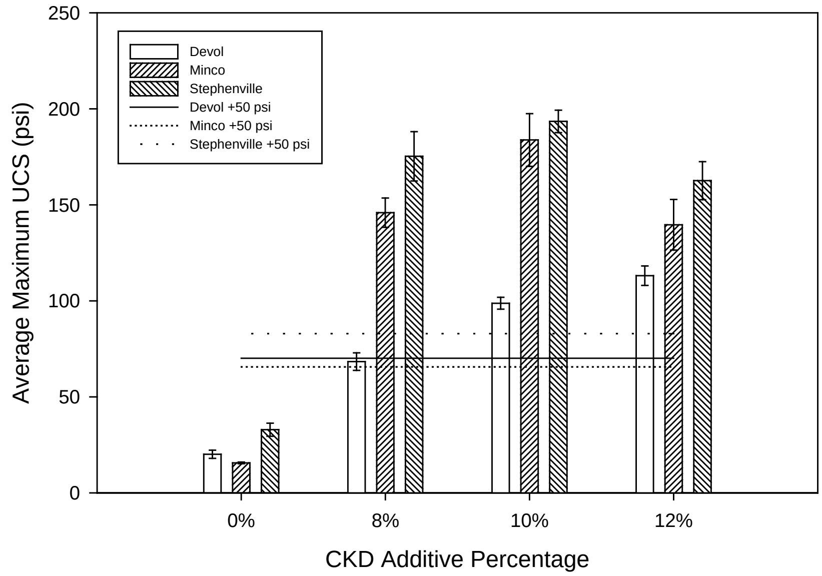


Figure 19: UCS Plots for A-4 Soils with CKD

When the A-4 soils were stabilized with Red Rock Fly Ash (Figure 20), only one of the three soils gained the required 50 psi strength (Stephenville), which occurred at 9% additive. The current OHD L-50 standard recommends 14% FA for A-4 Soils.

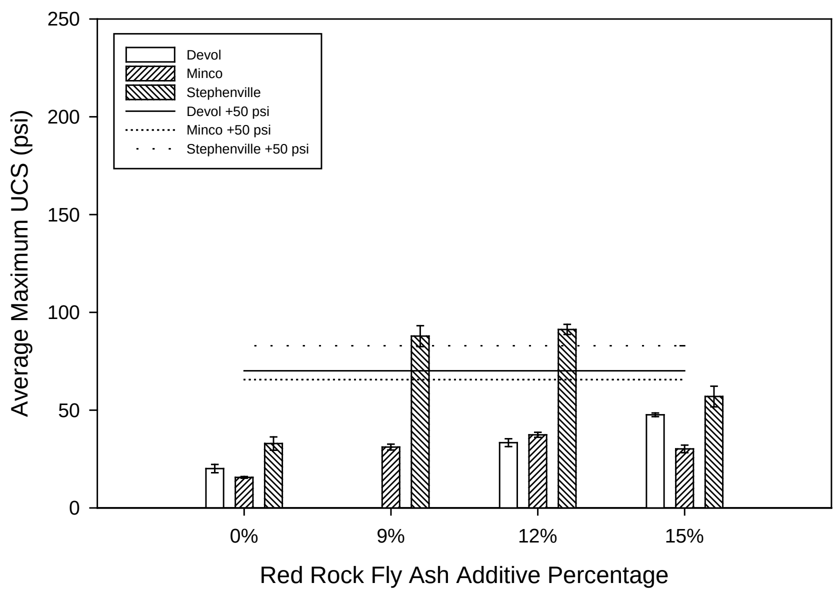


Figure 20: UCS Plots for A-4 Soils with Red Rock FA

The three A-6 soils gained the required 50 psi strength at 9% CKD additive (Figure 21). The current OHD L50 standard does not include a recommendation for A-6 soils and CKD, however, from the results of this laboratory study, it looks like CKD may be a viable stabilizer for soils classified as A-6. The differences in strength among the three soils at the same additive percentages are not as great as with the A-4 soils. No peak and then subsequent decrease in strength was seen with increasing additive content.

OHD L-50 recommends 4% lime be used to stabilize A-6 soils, and as can be seen, 3% works for the Flower Pot (two other soils were not tested at this percentage) and all three soils have the additional 50 psi strength at 4% (Figure 22). In this case, there is peak strength for Kirkland-Pawhuska, at 4%, after which the strength decreases. The other two soils do not show a peak strength.

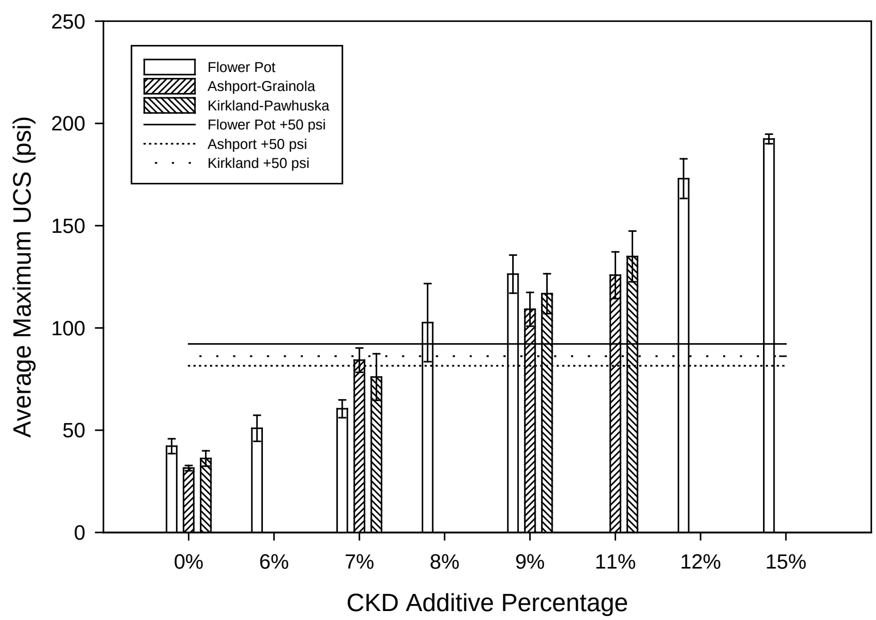


Figure 21: UCS Plots for A-6 Soils with CKD

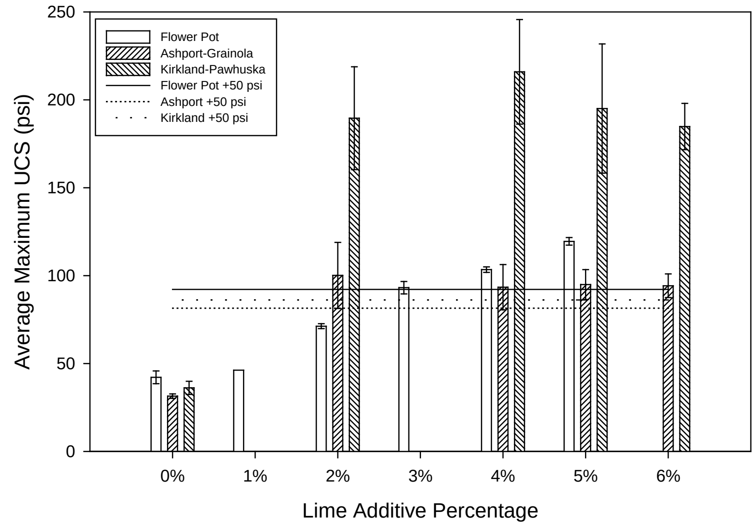


Figure 22: UCS Plots for A-6 Soils with Lime

A-6 soils stabilized with Red Rock Fly Ash showed the required 50 psi strength gain at 6%, and the strength kept increasing with increasing additive content (Figure 23). OHD L-50 recommends using 14% FA in the field. Flower Pot, although gaining the 50 psi in strength at 6% FA content, did not gain as much strength with increasing additive content, as the other two A-6 soils.

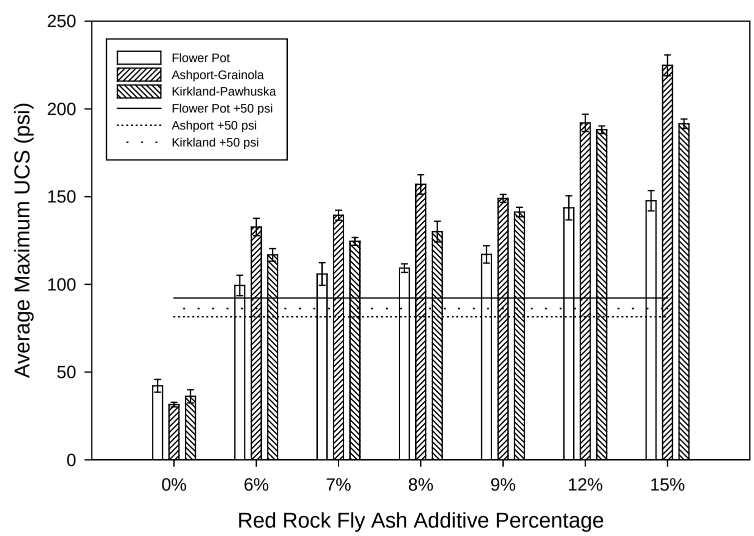


Figure 23: UCS Plots for A-6 Soils with Red Rock FA

Results of the A-6 soils stabilized with Muskogee FA were similar to those of the A-6 soils stabilized with RRFA as shown in Figure 24. All three soils gained the 50 psi strength at 6 % and the strength kept on increasing with increasing additive content, while Flower Pot did not gain as much strength as the other two soils.

OHD L-50 does not currently recommend using CKD with A-7-6 soils, however, with the two A-7-6 soils tested in this study, the required 50 psi strength gain occurred at 9% CKD content. Both soils behaved similarly with each other and increased in strength with increasing additive content.

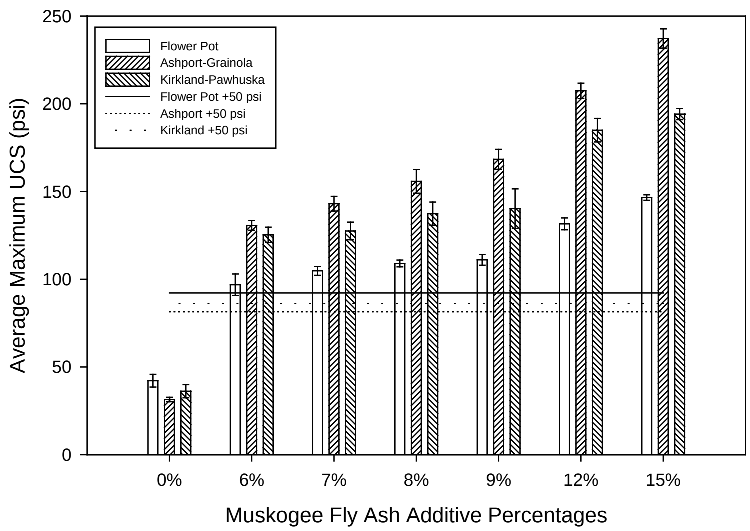


Figure 24: UCS Plots for A-6 Soils with Muskogee FA

The current OHD L-50 standard recommends using 5% hydrated lime to stabilize A-7-6 soils, unless the Liquid Limit is greater than 50, at which time, 6% is recommended. In this study, it was found that both A-7-6 soils exhibited the 50 psi strength gain at 3%, however, the Hollywood soil showed much lower strengths than the Heiden soil at increasing additive content. Peak strengths were seen at 3% additive content for Heiden and 4% additive content for Hollywood.

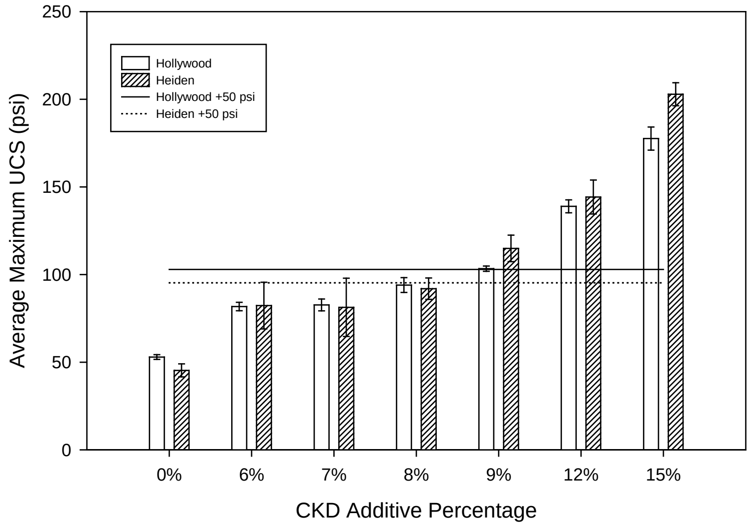


Figure 25: UCS Plots for A-7-6 Soils with CKD

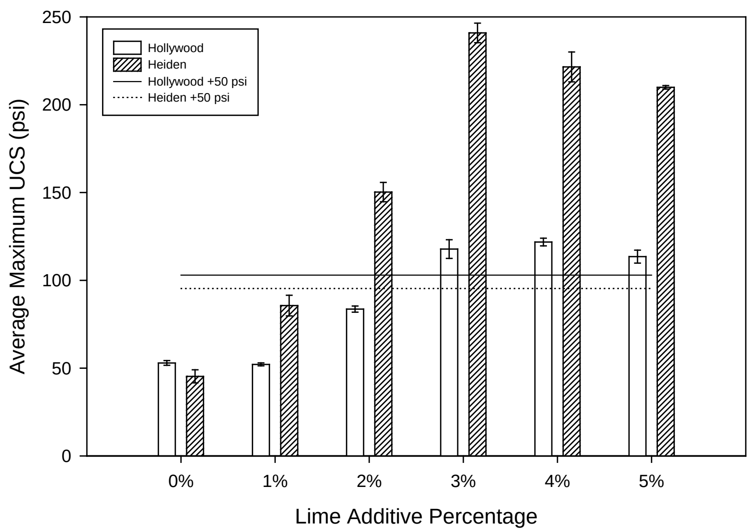


Figure 26: UCS Plots for A-7-6 Soils with Lime

Fly ash is not currently recommended as a stabilizer for use with A-7-6 soils, however, it can be seen that at 9%, with both types of FA, the soils show an increased strength of 50 psi (Figure 27 and Figure 28).

From the results of the UCS tests of all eight soils with four different stabilizers at varying amounts, many of the soils classified similarly and stabilized with the same type and amount of stabilizer, behave differently. In addition, the results found in this laboratory study show that the soils reach the minimum 50 psi strength gain at a much smaller additive amount than is currently recommended in OHD L-50. In the case of the A-4 soils stabilized with FA, only 2 of the 3 soils actually exhibit any type of strength increase. When those same A-4 soils were stabilized with CKD, they showed the 50 psi strength increase at 8%, however, the strength magnitudes were much different between the three soils. This is similar to what was seen with the A-6 soils stabilized with FA and Lime and A-7-6 soils stabilized with lime.

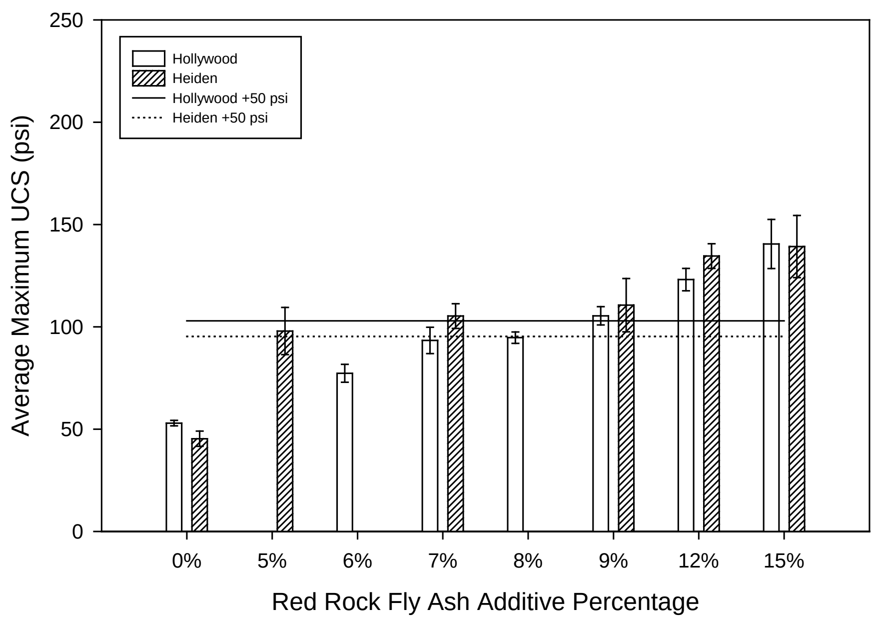


Figure 27: UCS Plots for A-7-6 Soils with Red Rock FA

From these results, it can be seen that Atterberg Limits alone do not explain the optimum additive content. If adequate strengths are to be achieved in the field, it is imperative to understand what about these similarly classified soils causes the differences in behavior, quantified by strength, when the same type and amount of stabilizer is added. Alternative soil parameters to Atterberg Limits may more accurately indicate the stabilizer amount that would provide adequate strength gain. Therefore, a number of different mineralogical and physico-chemical tests were performed on soil-additive mixtures.

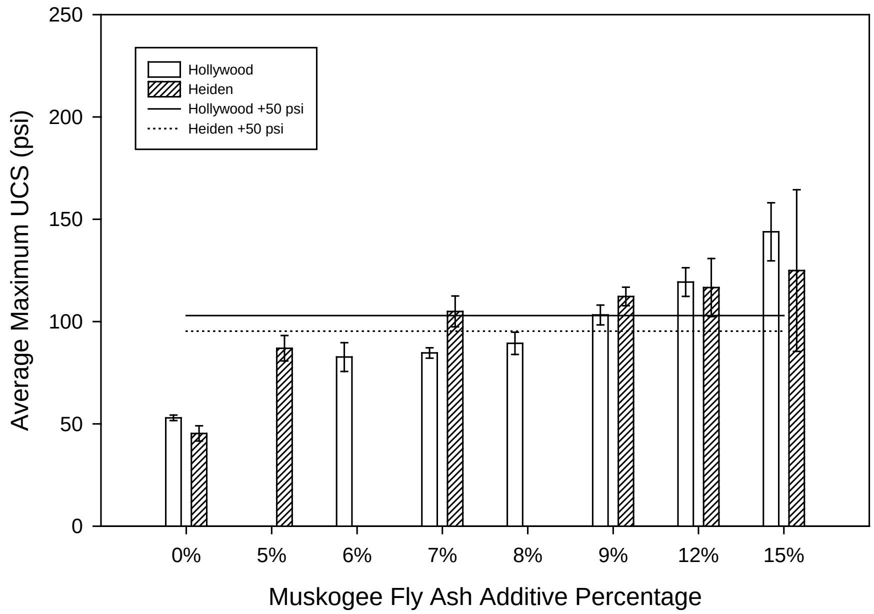


Figure 28: UCS Plots for A-7-6 Soils with Muskogee FA

All the mineralogical and physico-chemical tests were performed at the same additive amounts that were used in the UCS testing. The majority of the tests were performed at two curing times; 2-hour and 14 days. The 2-hour cured samples were prepared by measuring an amount of soil and the appropriate additive amount based on the dry weight of soil and mixing the two immediately and adding water as needed for the particular test. The 2-hour cure was used for each sample to ensure uniformity in the testing program. The 14-day cured samples were obtained by air-drying and crushing the 14-day cured UCS samples over a #40 sieve and performing the various tests on the crushed soil. The two curing times were chosen to see if any significant changes in the soil properties occurred between 2 hours and 14 days of curing. The following sections contain discussions on each of the different properties tested and their relation to the unconfined compression strengths.

The results shown are all plotted with respect to the ordinate axis (y) and the unconfined compression strength values are plotted with respect to the abscissa axis (x). The raw data values and the original plots of each property versus the specific additive percentages are shown in Appendix A: Atterberg Limits in Figure A.34 through Figure A.56 and Table A-10 through Table A-17, shrinkage results in Figure A.57 through Figure A.78 and Table A-18 through Table A-25 , pH and conductivity data in Figure A.79 through Figure A.98 and Table A-26 to Table A-28, cation exchange capacity results in Figure A.99 through Figure A.108 and Table A-29 to Table A-31, and specific surface area data in Figure A.109 through Figure A.138 and Table A-32 to Table A-39. In the following sections, each figure depicts A-4, A-6, and A-7-6 soils as three plots from top to bottom, respectively.

5.2 Atterberg Limit Results

It has already been shown with the UCS test results that Atterberg Limits alone do not explain the differences in strength gain of soils with identical AASHTO classifications. However, it is important to understand how these Atterberg Limits change with additive type and amount because Atterberg Limits will still play a role, along with other fundamental soil properties, in predicting the strength of stabilized soils.

Samples cured for 2-hours were prepared by taking air-dried soil and mixing the stabilizer directly and then mixing in water and waiting two hours for the samples to mellow before testing. Tests labeled “14-day cured” were performed using the UCT samples after testing that had cured for 14 days. After processing these dried UCT samples past a #40 sieve, water was added back to the soil and allowed to cure an additional two hours prior to testing the Atterberg Limits. The majority of samples were tested promptly after 14 days, but due to schedule issues, some testing was delayed up to two days. In these instances, water was added two hours prior to testing as with the other samples.

5.2.1 Summary of Atterberg Limits

In general, adding additives to the different soils caused reductions in the liquid limits, increases in the plastic limits, and reductions in the plasticity indices. The results can be viewed in Figure A.28 to Figure A.33. The additives caused approximately 5-10% changes in the three properties in the trends just mentioned. In terms of the soil groups, only the A-6 and A-7-6 groups can truly be compared as only one of the three A-4 soils (Stephenville) was consistently plastic and found to have any Atterberg Limits. The difference in curing time between 2-hours and 14 days did not change the general trends of the properties, but it did cause a slight reduction in the liquid limits and plasticity indices and a slight increase in the plastic limits. The only major difference between the 2-hour cured and 14-day cured results pertained to the Flower Pot soil when treated with fly ash. The 2-Hour plastic limit decreased as the strength increased, but the 14-day plastic limit values increased as the strength increased. A possible explanation could be the varying amount of gypsum (sulfate) pieces in the Flower Pot samples tested caused the plastic limit to behave differently.

In terms of change of Atterberg Limits with unconfined compression strength, there were relatively weak trends. These results can be viewed in Figures A.28-A.33. To see the results of the Atterberg Limits versus additive content for each soil, please see the following figures and tables in Appendix A: for the A-4 soils see Figure A.34 to Figure A.36 and Table A-10 to Table A-12, for the A-6 soils see Figure A.37 to Figure A.48 and Table A-13 to Table A-15, and for the A-7-6 soils see Figure A.49 to Figure A.56 and Table A-16 to Table A-17.

5.3 Shrinkage Results

The linear shrinkage and shrinkage limit values were easy to determine, therefore, were tested for each soil at each stabilization amount. Snethen et al. 1977 found that besides the liquid limit and plasticity index, shrinkage limit and linear shrinkage were significant indicator properties of potential swell in expansive soils. The testing of the shrinkage properties took place simultaneously with the Atterberg Limit tests. The soil for Atterberg Limit testing was mixed to a blow count of approximately 25 ± 1 blows and the soil was then placed in the linear shrinkage mold for testing. As such, the 2-hour and 14-day curing designations carry the same meaning here as with the Atterberg Limits.

For soils tested with CKD and fly ash, in the A-4 soil plot only a single point appears for each of the Minco and Stephenville soils and these points represent the raw soil shrinkage values. This is because these soils were tested at Oklahoma State University and shrinkage tests were not part of the testing program being conducted for this research project.

5.3.1 Linear Shrinkage Cured 2-Hours

5.3.1.1 Linear Shrinkage with CKD

All three soil groups showed correlations between the percentage of linear shrinkage and the unconfined compression strengths (Figure 29). In the A-4 soil group, only the Devol soil was tested for the linear shrinkage with CKD added. It had very small values for the linear shrinkage, but did show a slight decreasing trend. Both the A-6 and A-7-6 soils showed a consistent reduction in the linear shrinkage as the strength increased, with the A-6 soils showing an approximate reduction of 5% and the A-7-6 soils being reduced about 5-10%.

5.3.1.2 Linear Shrinkage with Fly Ash

Figure 30 shows results of linear shrinkage after 2-Hours curing time vs. the unconfined strength. The Devol (A-4) soil showed a decrease in shrinkage and strength when fly ash was added. The three A-6 soils did not show a change across the group, but each soil exhibited a decrease in the linear shrinkage as the strength increased. In contrast, the A-7-6 soils showed a consistent decrease in the shrinkage amount with increasing strength values.

5.3.1.3 Linear Shrinkage with Lime

In Figure 31, the linear shrinkage of the A-6 and A-7-6 soil groups decreased as the strength of the soil-additive mixtures increased.

In the A-6 soil group, the three soils decreased along a fairly uniform trend line, but the two A-7-6 soils did not share the same trend.

5.3.2 Shrinkage Limit Cured 2-Hours

5.3.2.1 Shrinkage Limit with CKD

In Figure 32, the Devol (A-4) soil did not show a measureable shrinkage limit once CKD was added. In both the A-6 and A-7-6 soil groups, however, the shrinkage limit increased as the strength increased, except for Flower Pot. The shrinkage limit of the Flower Pot soil did not change with the strength, but the Ashport-Grainola and Kirkland-Pawhuska (A-6) and the Hollywood and Heiden (A-7-6) soils showed a consistent increase with increasing strengths.

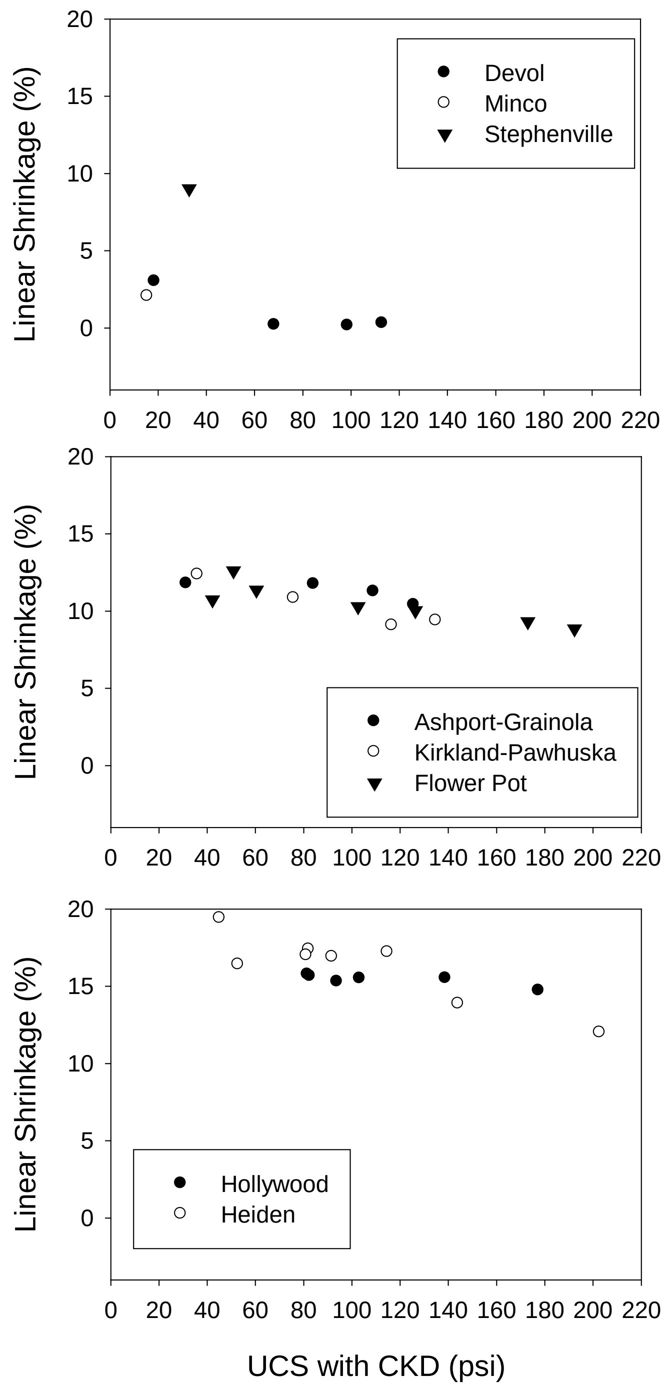


Figure 29 - Linear Shrinkage (2-Hour) with CKD for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

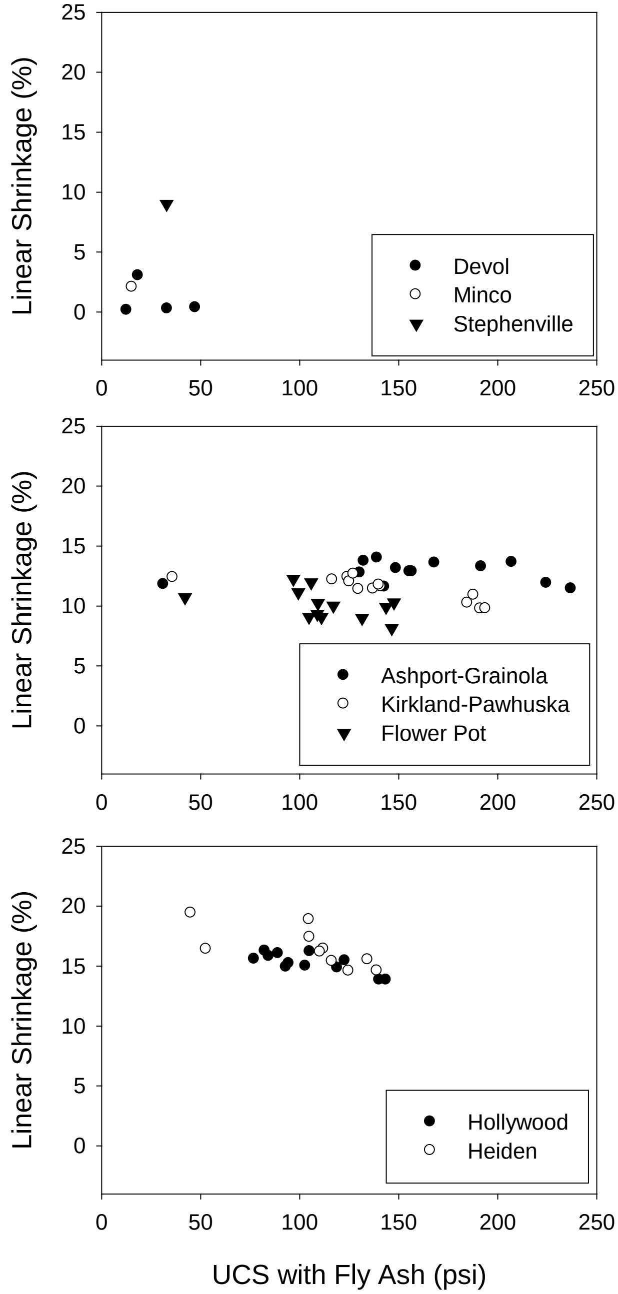


Figure 30 - Linear Shrinkage (2-Hour) with Fly Ash for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

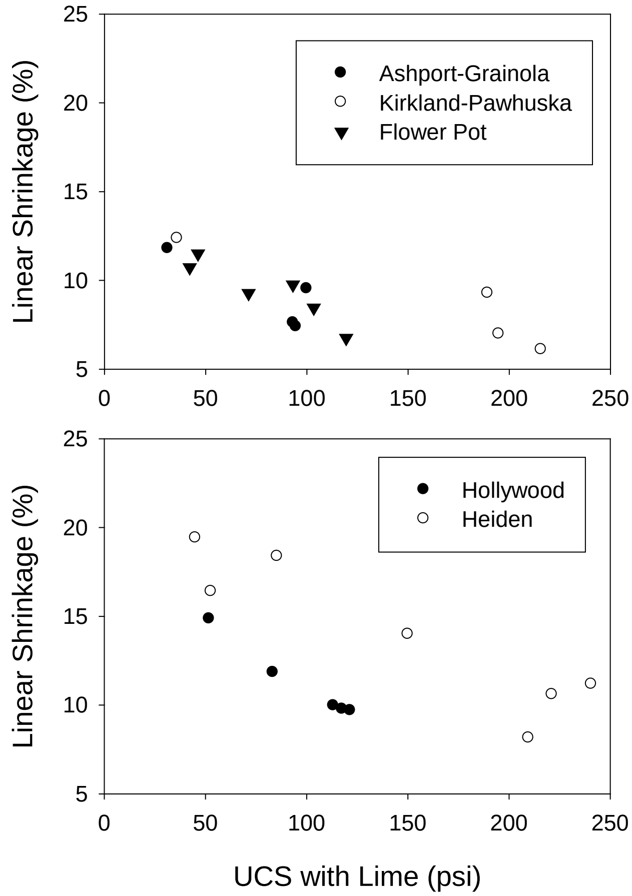


Figure 31- Linear Shrinkage (2-Hour) with Lime for A-6 (Top) and A-7-6 (Bottom) Soils

5.3.2.2 Shrinkage Limit with Fly Ash

Figure 33 shows the shrinkage limit of the three soil groups treated with fly ash plotted versus the unconfined compression strengths. The Devol soil again had no measureable shrinkage limit. The A-6 soils showed considerable scatter among the three tested soils, but the group overall showed a trend of the shrinkage limit increasing as the strength increased. In the A-7-6 group, the values from the two soils fell along the same trend line initially, but diverged at high strengths.

5.3.2.3 Shrinkage Limit with Lime

Figure 34 shows that the shrinkage limit increases with the unconfined compression strength when the soils were treated with lime as an additive. In the A-6 soil group, the shrinkage limit of the Ashport-Grainola and Flower Pot soils increased rapidly as the strength increased, but the Kirkland-Pawhuska soil did not show any trend. The two A-7-6 soils showed shrinkage limits that increased consistently along the same trend line.

5.3.3 Linear Shrinkage Cured 14 Days

5.3.3.1 Linear Shrinkage with CKD

As Figure 35 shows, the 14 days cured linear shrinkage of the three soil groups decreased slightly as the strength values increased. The Devol (A-4) soil had very small shrinkage values to begin with, but still decreased. The linear shrinkage of the A-6 soils fell along one trend line and decreased about 5% from the raw soil to the strongest soil mixture. In the A-7-6 soil group, the two soils also fell along a single trend line but the decrease was approximately 10%. In the A-7-6 soils plot, both soils showed vertically aligned points just after the raw soil. These points are those samples stabilized with 6% (top) and 7% CKD (bottom). The increased additive content caused the linear shrinkage to drop, even though the samples had very similar strengths.

5.3.3.2 Linear Shrinkage with Fly Ash

In Figure 36, the linear shrinkage of each soil decreased as the strength of the respective soil-additive mixtures increased. Both the A-6 and A-7-6 soil groups showed the linear shrinkage values consistently decreased along similar trend lines with the A-7-6 soils showing more shrinkage than the A-6 soils.

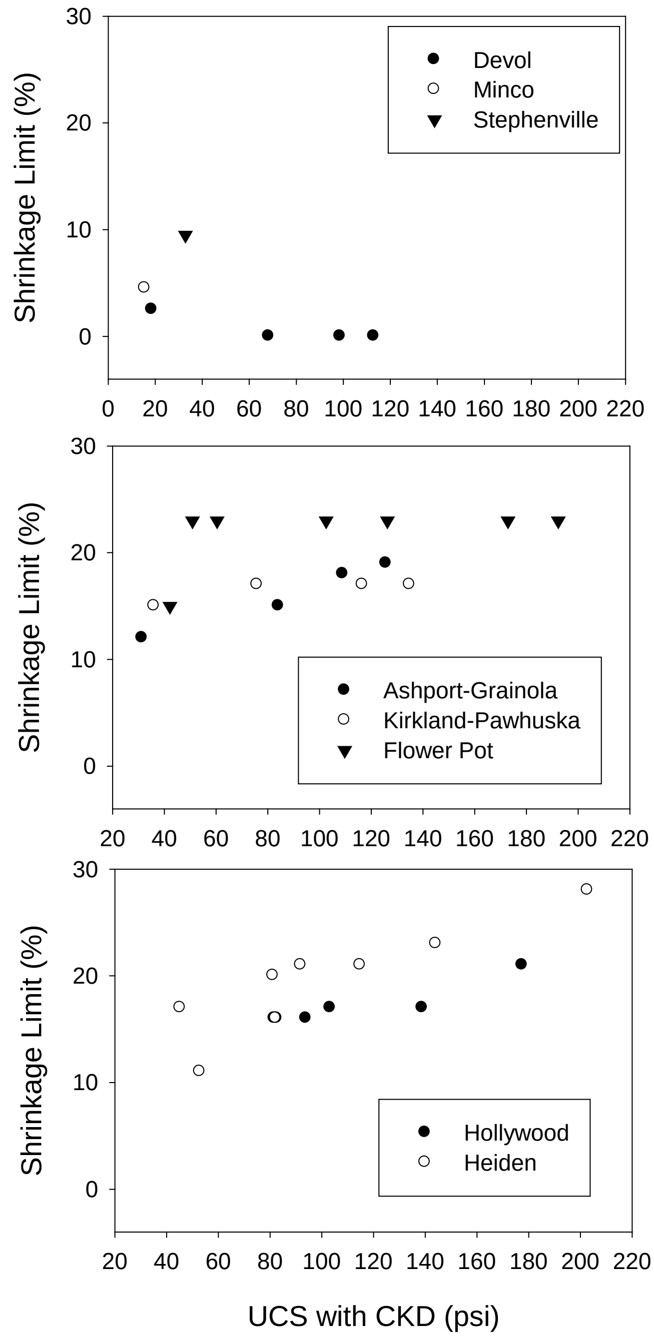


Figure 32 - Shrinkage Limit (2-Hour) with CKD for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

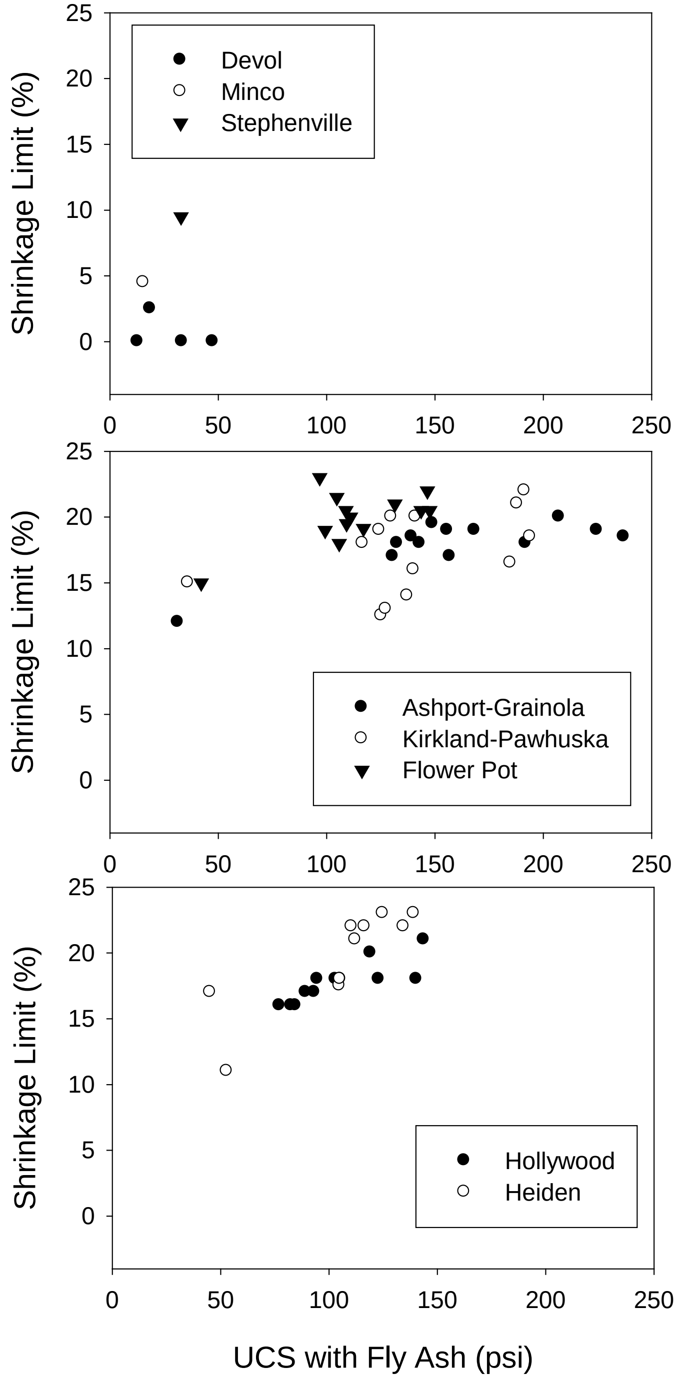


Figure 33- Shrinkage Limit (2-Hour) with Fly Ash for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

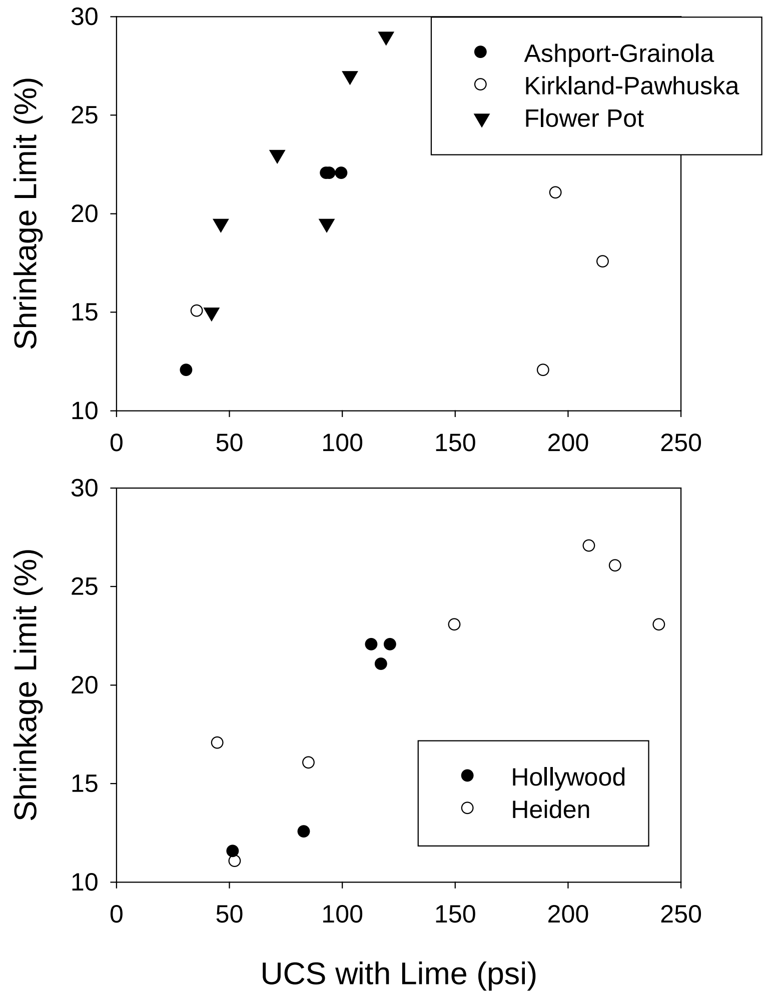


Figure 34- Shrinkage Limit (2-Hour) with Lime for A-6 (Top) and A-7-6 (Bottom) Soils

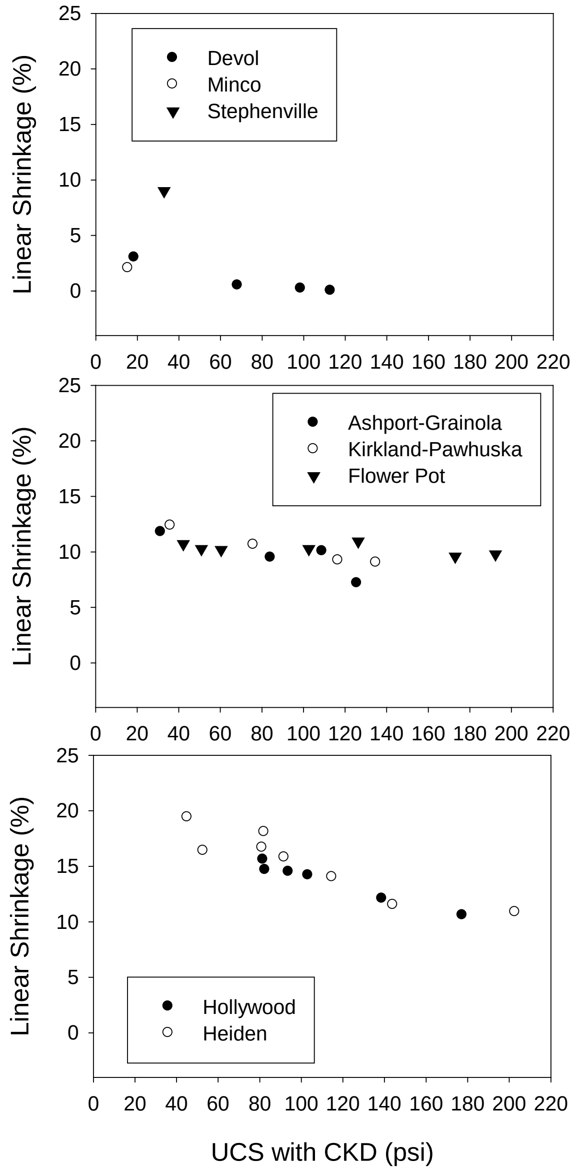


Figure 35 - Linear Shrinkage (14-day) with CKD for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

5.3.3.3 Linear Shrinkage with Lime

Figure 37 shows the changes in the linear shrinkage with the soil strength. In both plots, the linear shrinkage decreased as the strength increased. The Flower Pot and Kirkland-Pawhuska (A-6) soils fell along a constant trend line, but the Ashport-Grainola soil did not follow this trend and had much lower shrinkage values. The Heiden and

Hollywood (A-7-6) soils both decreased consistently, but seemed to have parallel trend lines. While the two A-7-6 soils show steadily decreasing linear shrinkages, the curves "bend" back to the left because the soils reached peak strengths before the final tested additive percentage and the strengths dropped after the peak.

5.3.4 Shrinkage Limit Cured 14 Days

5.3.4.1 Shrinkage Limit with CKD

The shrinkage limit generally increases as the strength of the soil-additive mixtures increase (Figure 38). The A-6 soils showed the most response of the three soil groups, with all three soils having similar shrinkage limit trends. The two A-7-6 soils increased, as well, but the data points were scattered and do not fit along any noticeable trend line.

5.3.4.2 Shrinkage Limit with Fly Ash

Figure 39 shows that the shrinkage limits of all three soil groups increased as the strength increased. The shrinkage limits of the three A-6 soils increased at three different rates, instead of a consistent response as seen with CKD stabilization. The A-7-6 soils did show a fairly uniform response between the two soils, with some scatter occurring at high strength values.

5.3.4.3 Shrinkage Limit with Lime

Figure 40 shows the trends of the 14 days cured shrinkage limit vs. the unconfined compression strength after 14 days of curing. In the plot of the three A-6 soils, the Ashport-Grainola and the Kirkland-Pawhuska soils appear to lie along one trend line, but the Flower Pot soil shrinkage limit increased at a faster rate and along a different trend line. The two A-7-6 soils showed considerable scatter in the data but showed a general increase in the shrinkage limit as the strength increased.

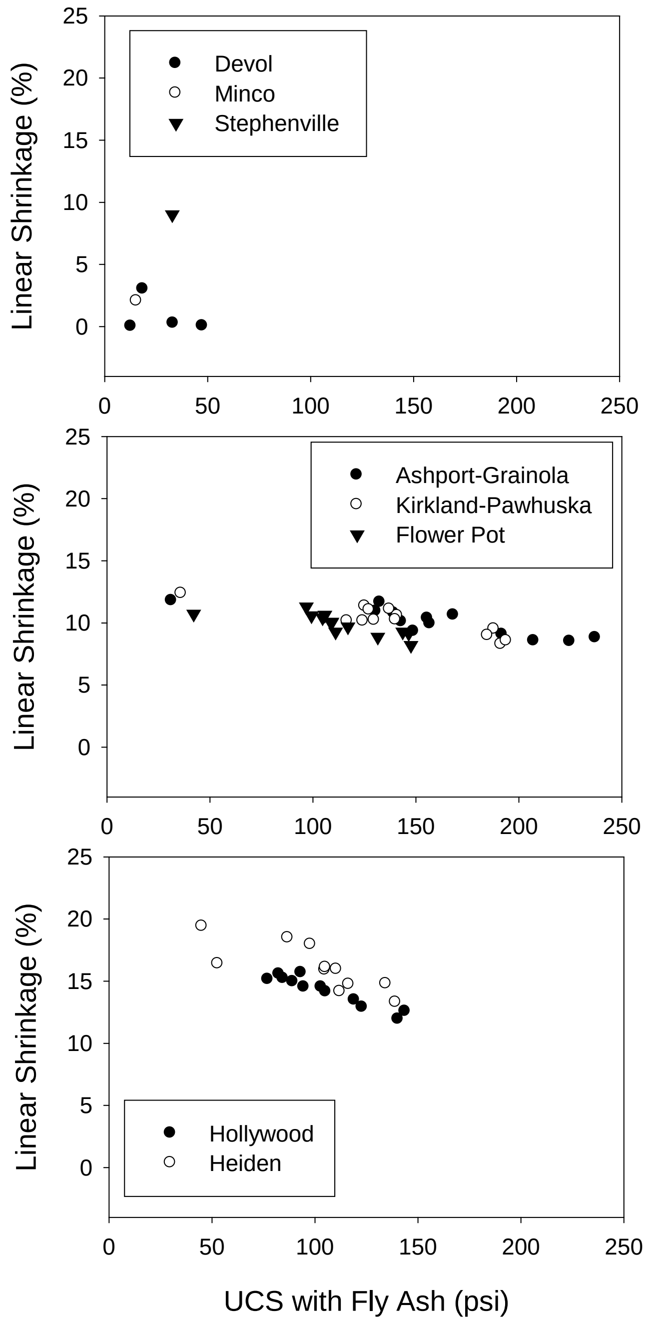


Figure 36 - Linear Shrinkage (14-day) with Fly Ash for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

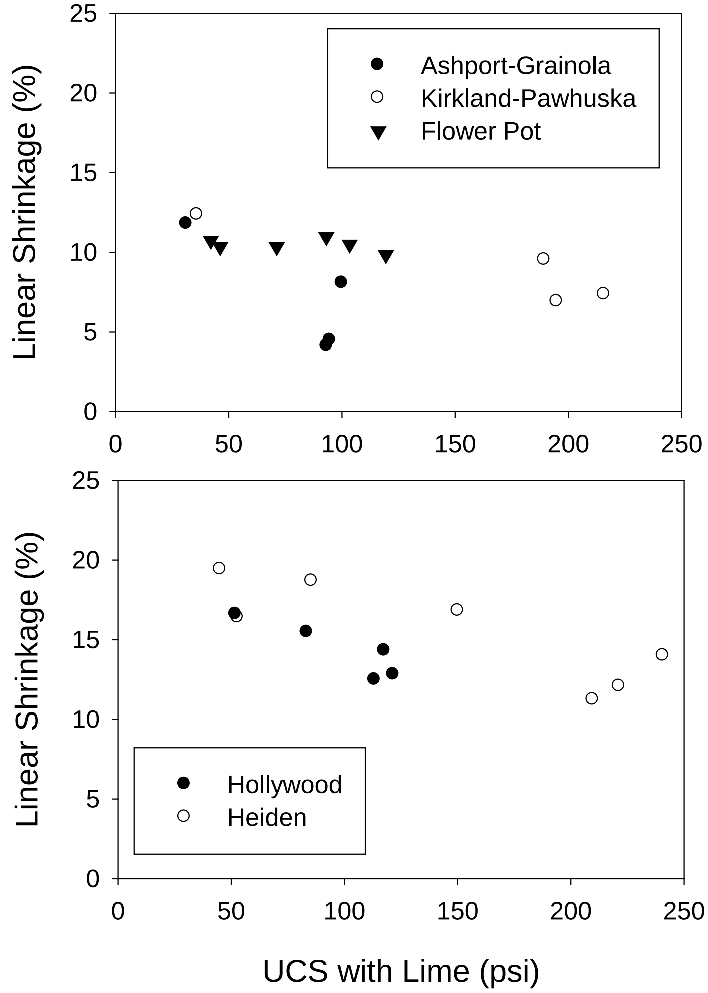


Figure 37 - Linear Shrinkage (14-day) with Lime for A-6 (Top) and A-7-6 (Bottom) Soils

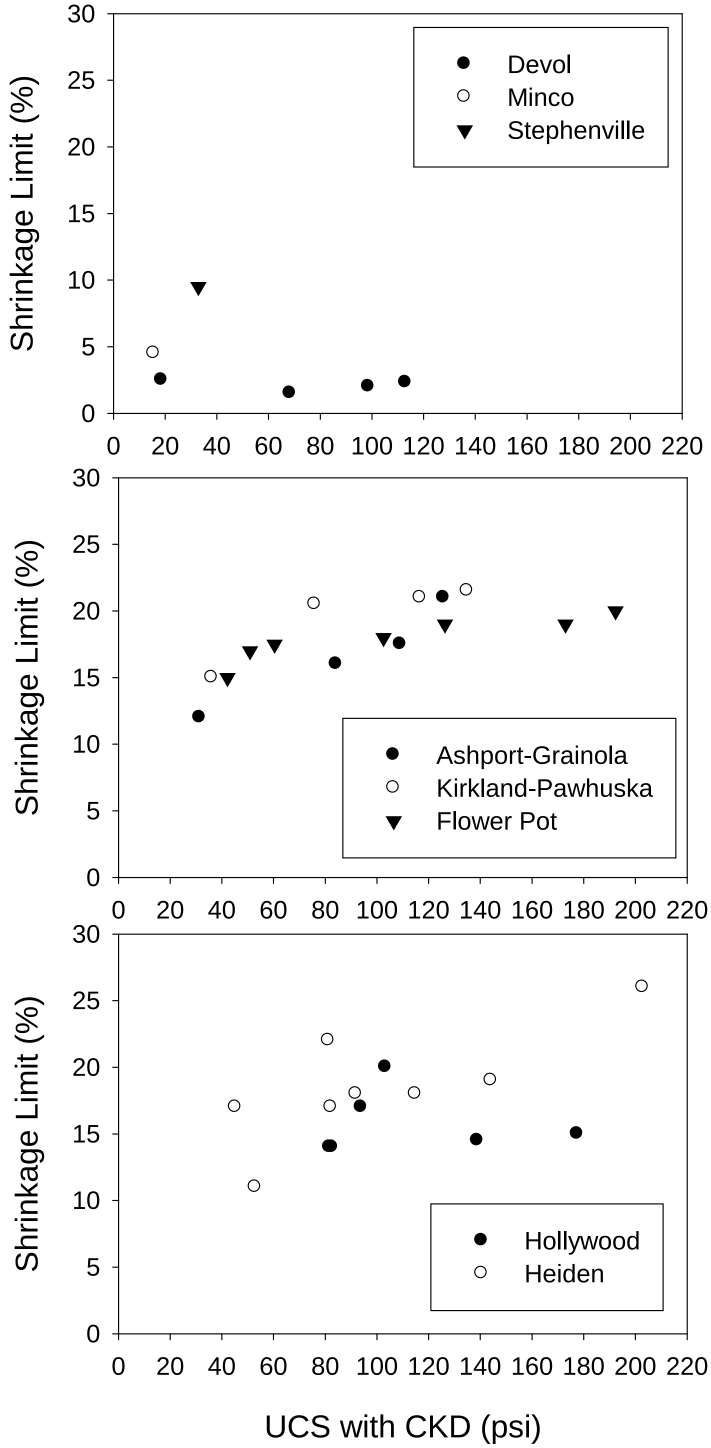


Figure 38 - Shrinkage Limit (14-day) with CKD for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

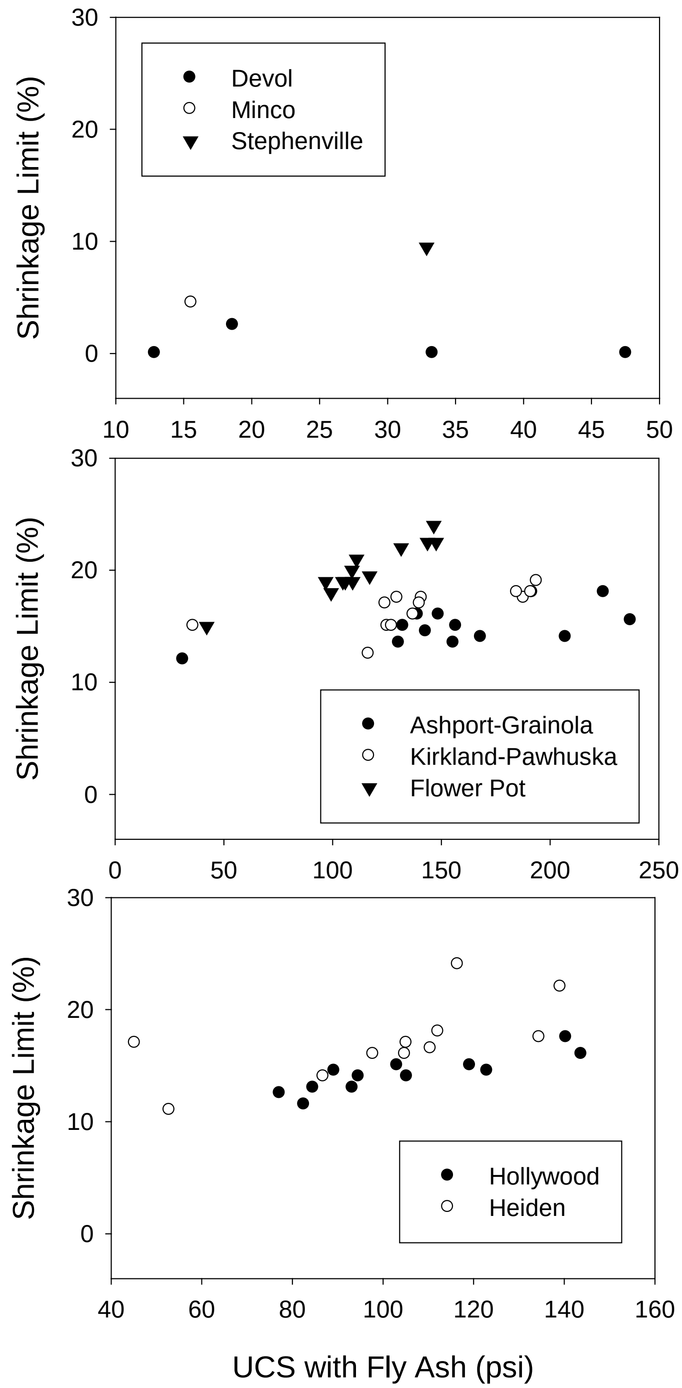


Figure 39 - Shrinkage Limit (14-day) with Fly Ash for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

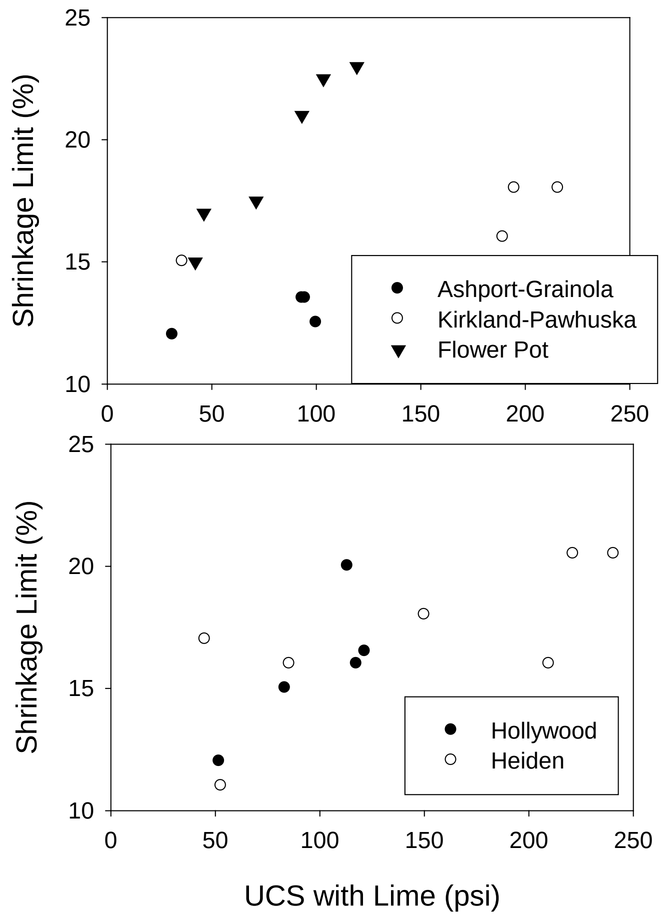


Figure 40 - Shrinkage Limit (14-day) with Lime for A-6 (Top) and A-7-6 (Bottom) Soils

5.3.5 Summary of Shrinkage

Adding the different chemical stabilizers to the test soils caused the linear shrinkage to decrease and the shrinkage limit to increase. From the 2-Hour to the 14-day tests, the linear shrinkage was found to be approximately 2-3% lower and the shrinkage limit was typically 0-5% lower after 14 days of curing time. Lime was generally the most effective stabilizer in reducing the amount of shrinkage each soil experienced. Only the Devol soil was tested for the shrinkage properties from the A-4 group, so group comparisons were not made. The linear shrinkage curves from both 2-Hour and 14-day curing times were the most consistent combined trends with CKD for the A-6 and A-7-6 soils, followed next by the fly ash trend. The lime results were rather scattered and did not show good combined trends. Also, the shrinkage limit results did not show good combined trends with any soils or additives.

Overall, the results and trends from the linear shrinkage tests were promising in terms of strength predictions. If an increase in strength of 50 psi (345 kPa) is needed to achieve adequate stabilization, a designer could look at these trends and define a decrease in the linear shrinkage needed to reach that strength increase. Based on the results detailed in this section and shown in Table 10, the reduction in the linear shrinkage is approximately 1-4% to achieve a strength increase of 50 psi (345 kPa). The reduction in linear shrinkage shown in the table is the maximum needed for all the soils tested.

Table 10 - Table of Linear Shrinkage Decreases for 50 psi (345 kPa) Strength Gain

	A-6 Soils		
Curing Time	CKD	Fly Ash	Lime
2 hour	3%	2%	4%
14 days	3%	3%	2%

	A-7-6 Soils		
Curing Time	CKD	Fly Ash	Lime
2 hour	3%	3%	4%
14 days	4%	4%	3%

A graphical example of this is shown in Figure 41. With an increase in 50 psi in UCS for the A-6 soils (top) stabilized with CKD, the average decrease in LS is about 1%, with a range from 1 to 3% for the individual soils. For the A-7-6 soils, a decrease in LS of about 1.5% provides an increase in 50 psi. Of course, additional soils, outside of this study, should be used as a verification of this method, but if strength increases can be predicted by decreases in LS, then typically, in 1 day, appropriate stabilization type and quantity could be verified.

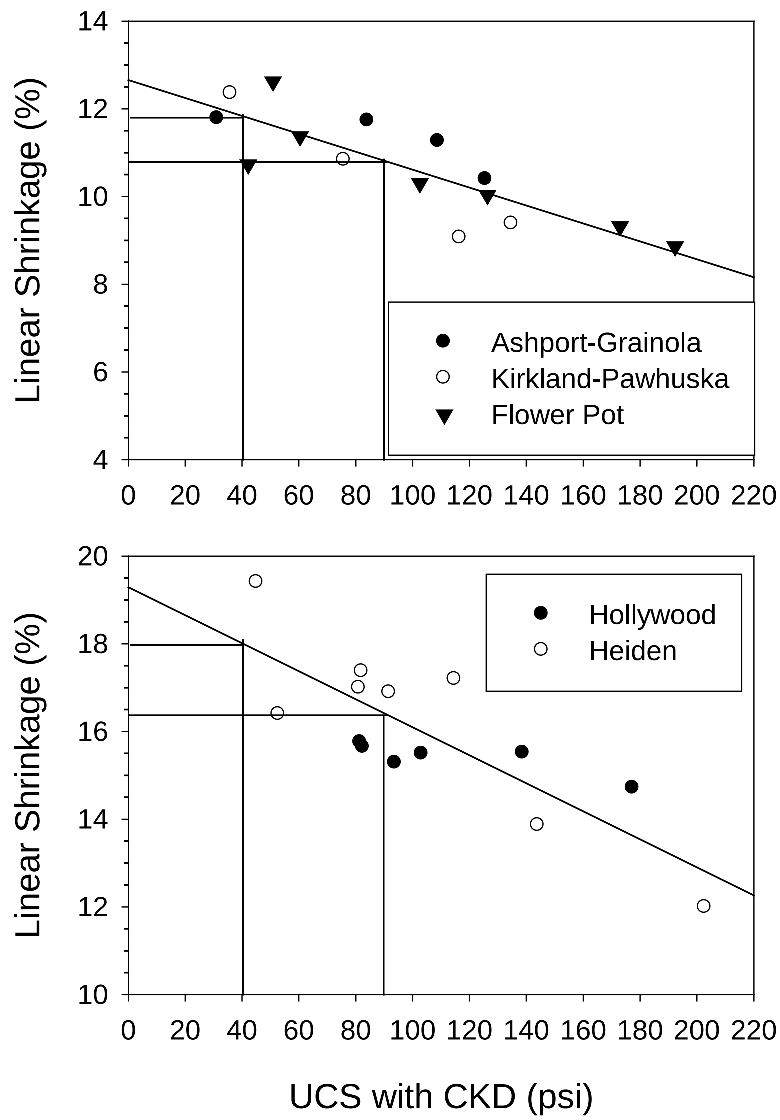


Figure 41 Quantifying Decrease in 2-hour Linear Shrinkage with an increase in 50 psi UCS.

To see the results of each shrinkage test plotted versus the additive content, please reference in Appendix A: Figure A.57 to Figure A.58 and Table A-18 to Table A-20 for the A-4 soils, Figure A.59 to Figure A.70 and Table A-21 to Table A-23 for the A-6 soils, and Figure A.71 to Figure A.78 and Table A-24 to Table A-25 for the A-7-6 soils.

5.4 pH Results

5.4.1 Introduction to pH Testing

As mentioned in the literature review, soil pH tests for estimating additive percentage is currently used only for lime treatments as ASTM standard (ASTM D 6276). The standard states that once the soil-additive solution pH reaches 12.4, the pH of lime, the mixture is calcium saturated. Unfortunately, no such standard exists for stabilization with cement kiln dust or fly ash. Research has been conducted on these additives to see if a similar threshold exists, but as these stabilizers are industrial byproducts, it is difficult to determine a consistent pH threshold level. One study was conducted by Miller and Azad (2000). They determined the pH of CKD was approximately 12.3 and their soil-additive mixture reached this pH at 15% CKD, which also corresponded to the additive percentage at which the soil was adequately stabilized. In this study, all soils were tested with each stabilizer to determine if similar trends exist across a wider soil database. The raw soils were mixed with the appropriate amount of stabilizer and water and tested at the 2-hour mark.

5.4.2 pH with CKD

All three soil groups showed two part correlations between the strength and the pH, as seen in Figure 42. All eight soils showed an initial jump in the pH to the first soil-additive mixture. Each soil reached a plateau in the pH value at approximately 12.2 when plotted versus the available strength data.

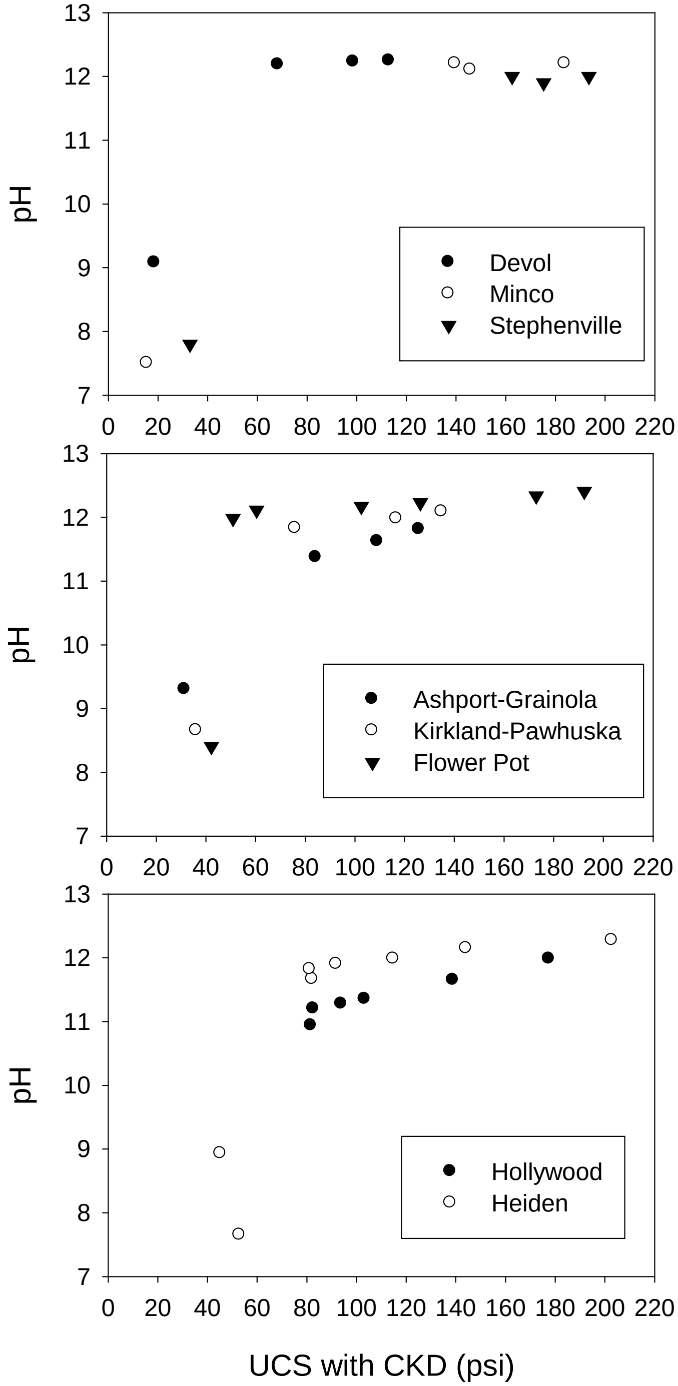


Figure 42 - pH Results with CKD for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

5.4.3 pH with Fly Ash

In Figure 43, the pH response of the test soils was much more varied with fly ash than with CKD. The A-4 soils seemed to have a two part response in the pH with a maximum value between 11.2 and 11.5. The three A-6 soils showed three different trend lines, with the Flower Pot reaching the highest pH after starting at the lowest pH and the Ashport-Grainola soil had the lowest stabilized pH after starting at the highest raw soil pH. The two A-7-6 soils had a similar pH response and fell nearly along a single trend line.

5.4.4 pH with Lime

Figure 44 shows the pH test results with lime as the stabilizing chemical. Both soil groups show two-part trends in the pH response of the different soils with lime as the stabilizing additive. The soils reached a plateau in the pH values at approximately 12.4, the pH of lime, and the response with lime was much steeper than those from either CKD or fly ash. In the A-7-6 soil group, the Hollywood soil pH increased faster than that of the Heiden soil.

5.4.5 Summary of pH

Each soil group reacted slightly differently with the addition of each stabilizer, but in general, the A-7-6 soils showed the most rapid increase in the pH to the maximum value. When treated with the same additive, CKD for example, even the different soils within a single group reacted differently. The same was true in the fly ash section as there were clear differences between the Red Rock and Muskogee fly ash stabilized soils and the pH values with fly ash never leveled, as can be seen in Figures A.79-A.94. In fact, only the soils treated with lime reacted the same way. Aside from lime stabilization, there is no consistent trend within a particular soil and additive type, as seen in Figure 45. For example, the A-6 soils stabilized with fly ash have a pH difference of nearly 1.0 for the same additive percentage and never reach a consistent maximum value, as can be seen with lime. This would make it difficult to rely on the pH response to determine the appropriate modification point, although the trends are consistent.

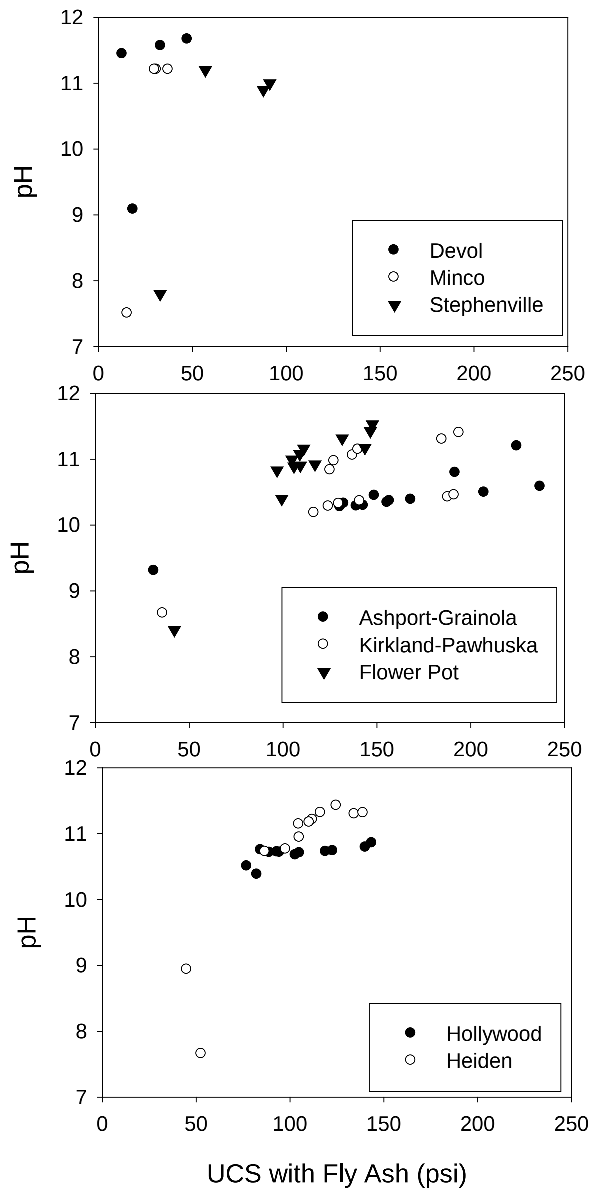


Figure 43 - pH Results with Fly Ash for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

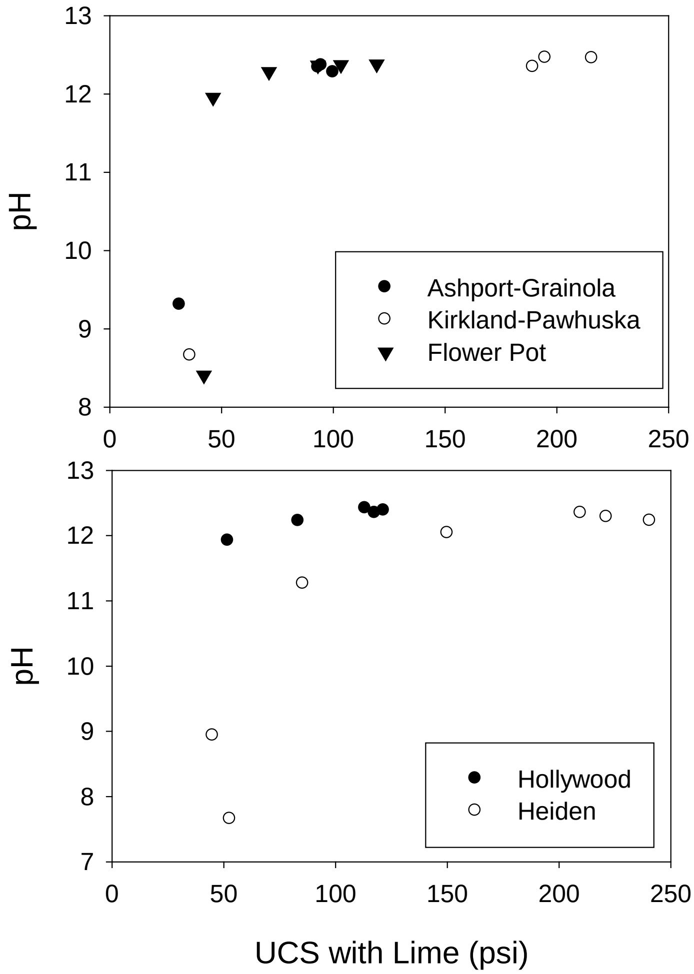


Figure 44 - pH Results with Lime for A-6 (Top) and A-7-6 (Bottom) Soils

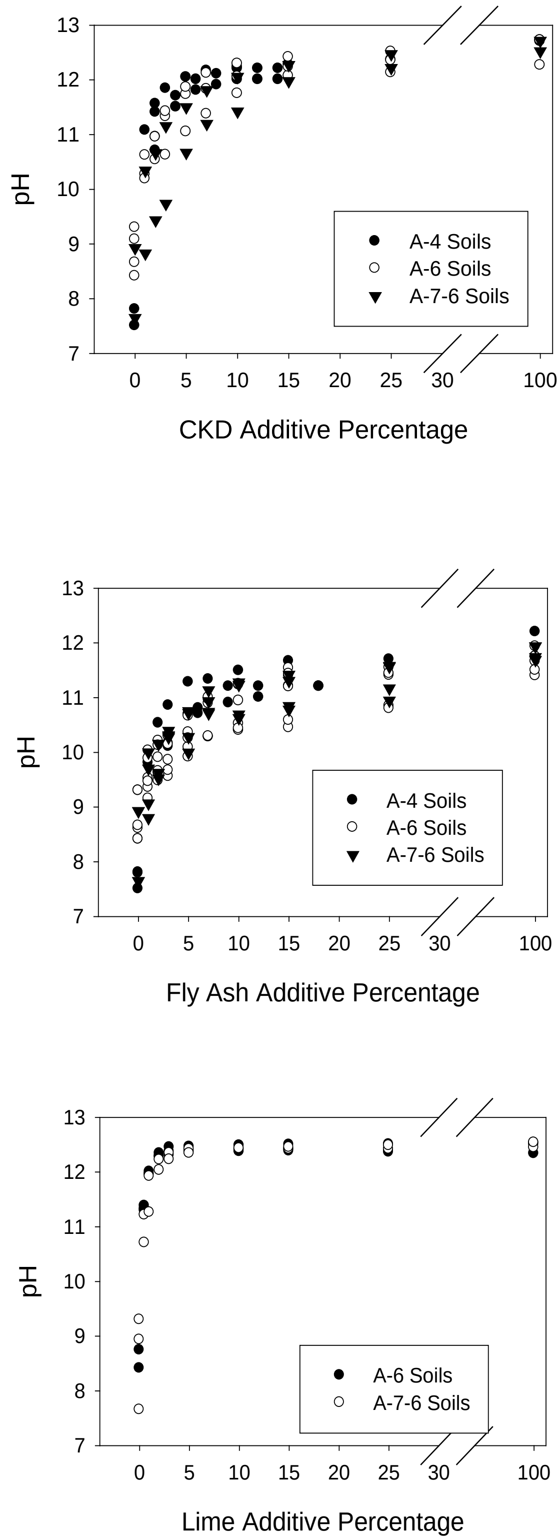


Figure 45 - Combined pH Curves for Different Additives

Please see the following figures and tables in Appendix A for the plots of pH versus the additive percentage and the actual pH values: Figure A.79 to Figure A.80 and Table A-26 for the A-4 soils, Figure A.83 to Figure A.86 and Table A-27 for the A-6 soils, and Figure A.91 to Figure A.94 and Table A-28 for the A-7-6 soils.

5.5 Conductivity Results

5.5.1 Introduction to Conductivity Testing

Unlike the Atterberg Limits or the shrinkage properties, it was unknown whether or not the electrical conductivity of the soil-additive mixtures would be relevant to predicting the strength gain of stabilized soils. The conductivity was tested with a digital measuring device very similar to the one used for determining the pH. The same samples used for the pH tests were reused for the conductivity tests as the digital meters did not alter the soils. Due to the ease of testing the conductivity, and to determine if the conductivity would show a reasonable trend with strength gain, it was included in the parameter database. Just like the pH tests, the conductivity tests were performed on 2-Hour cured samples.

5.5.2 Conductivity with CKD

In Figure 46, the A-7-6 soils showed the strongest linear correlation between the conductivity and the unconfined compression strength. The values from the two soils fell closely along one trend line. The A-6 soils also showed a solid linear correlation, with the Ashport-Grainola and Kirkland-Pawhuska soils having a near-identical response and the Flower Pot soil having a higher conductivity. The trend line from the three A-4 soils moved in the opposite direction as the two other soil groups. The correlation was also not as strong as the Devol soil conductivity actually increased while the general group results trended downward with increasing strengths.

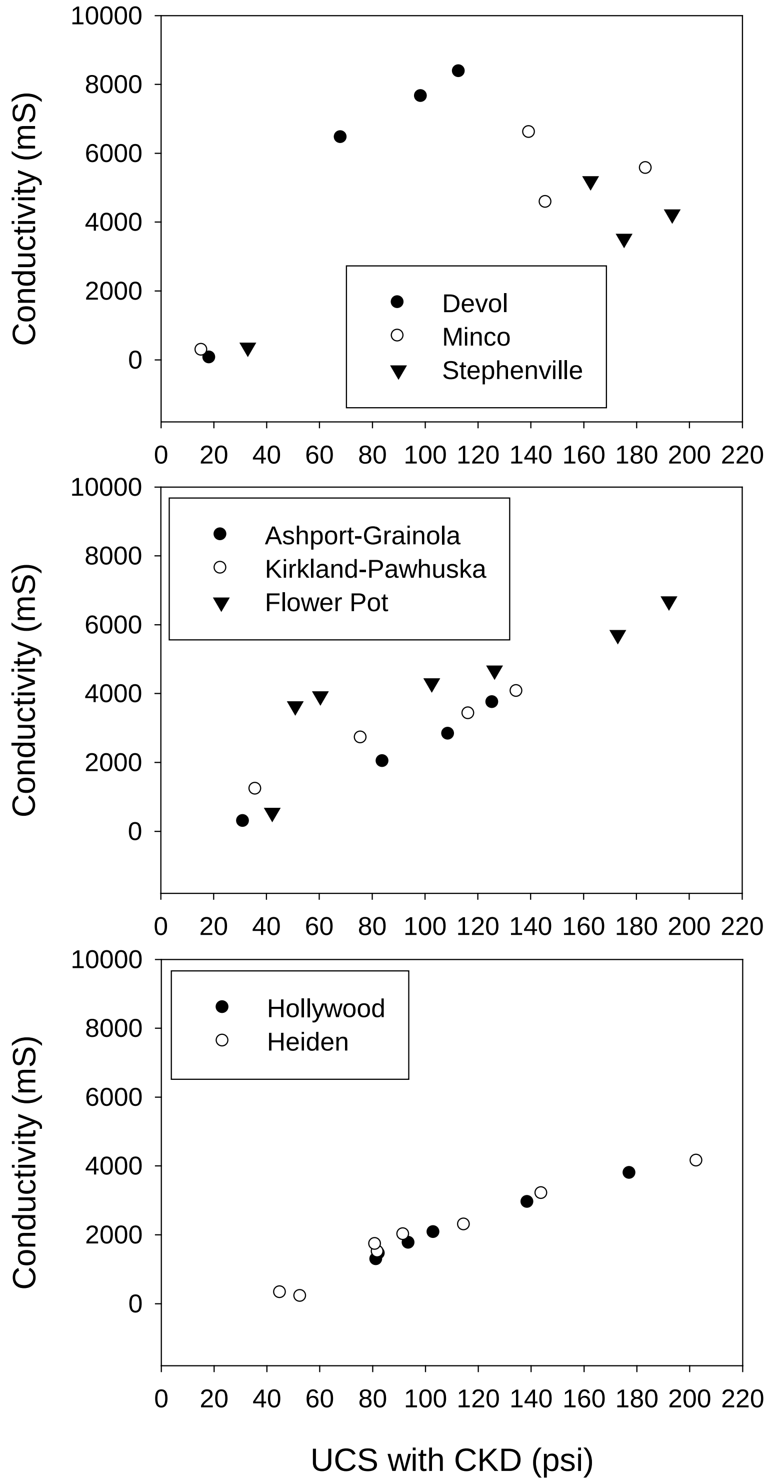


Figure 46 - Conductivity with CKD for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

5.5.3 Conductivity with Fly Ash

As Figure 47 shows, the A-7-6 soil group again showed the most consistent conductivity response. Both soils increased along one trend line as the strength increased. The A-6 soils also showed increases in the conductivity individually, but did not share a common group response. Each soil increased along its own parallel trend line with the Flower Pot soil having the highest conductivity and the Ashport-Grainola soil having the lowest conductivity. As opposed to the conductivity with CKD, the A-4 soils showed an increasing trend in the conductivity with fly ash as the unconfined compression strength increased. The plot contained considerable scatter in the data as the values from the three soils did not fall along a common trend line.

5.5.4 Conductivity with Lime

The plots in Figure 48 show the conductivity responses of the five soils in the A-6 and A-7-6 soil groups. All five soils had linear increases in the conductivity of the soil-additive mixtures, but neither group showed a uniform group response. The A-6 soils had the highest conductivity values, but each soil conductivity increased at a different rate. In the A-7-6 soil group, the conductivities of the two soils increased seemingly in parallel.

5.5.5 Summary of Conductivity

The A-4 soils showed considerable scatter when treated with both CKD and fly ash. However, when the A-6 and A-7-6 soils were treated with fly ash, both groups showed fairly consistent trends. That carried over to the fly ash stabilized samples for the two A-7-6 soils, and to the lime stabilized samples at a lesser degree. The conductivities of the three A-6 soils when treated with fly ash were quite different, though. Each soil was essentially its own trend parallel to the other soils. When treated with lime, the A-6 soils did not even show a general trend and were quite scattered instead.

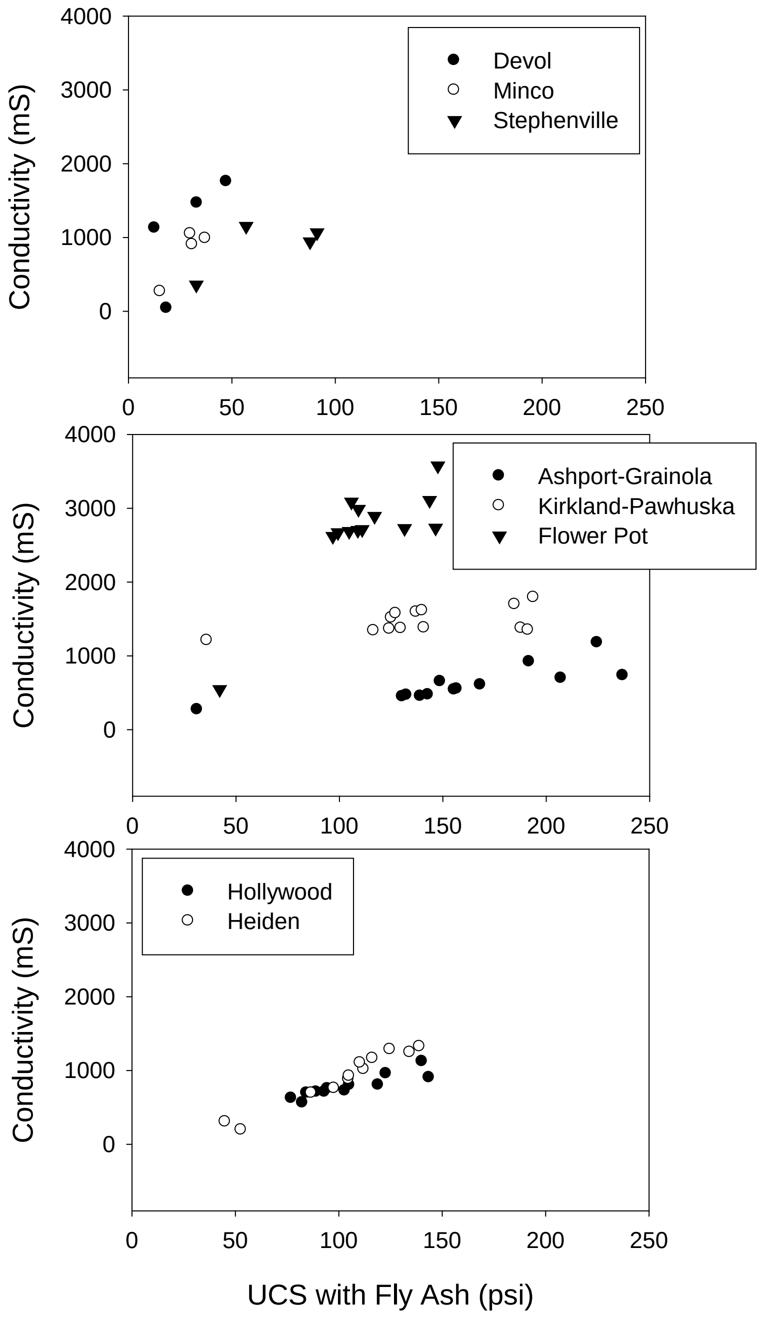


Figure 47 - Conductivity with Fly Ash for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

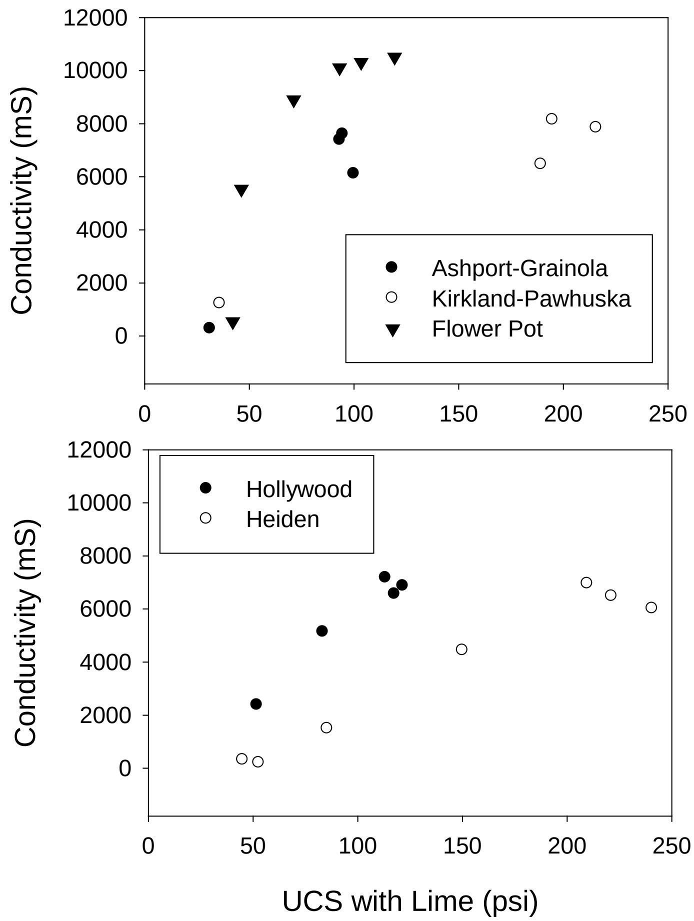


Figure 48 - Conductivity with Lime for A-6 (Left) and A-7-6 (Right) Soils

The actual results and the plots of the conductivity versus the additive percentage for each soil group are contained in Appendix A in: Figure A.81 to Figure A.82 and Table A-26 for the A-4 soils. Figure A.87 to Figure A.90 and Table A-27 for the A-6 soils and Figure A.95 to Figure A.98 and Table A-28 for the A-7-6 soils.

5.6 Cation Exchange Capacity Results

5.6.1 Introduction to Cation Exchange Capacity Testing

Unlike the other tests discussed in this chapter, the cation exchange capacity was the only one that required samples to be sent to an external testing facility. That facility was

MDS Harris Laboratory located in Lincoln, Nebraska. As the samples had to be shipped to the laboratory, the naming conventions used thus far (2-Hour and 14-day cured samples) do not apply to this section. The samples were prepared over the course of several days and shipped to the laboratory where the samples were tested over the course of several days up to two weeks and the results were returned via email. Therefore, the results labeled “uncured” are those that were prepared at 2-hours of curing time by adding the required amount of each additive to a standard amount of soil, mixing with water, then drying for shipment to the laboratory, and those labeled as “cured” are those samples that were shipped to the laboratory after testing the UCS and crushing the UCS samples at 14 days of curing time. The actual curing times of the samples are unknown, but likely range from one to six weeks based on delays at the laboratory.

5.6.2 Uncured CEC

5.6.2.1 CEC with CKD

Figure 49 shows the cation exchange capacity values for the three soil groups. Each soil group had a different general response. In the A-4 group, the Devol soil CEC increased with strength, but the Stephenville and Minco soils did not have noticeable trends. The Ashport-Grainola and Kirkland-Pawhuska soils in the A-6 group increased at similar rates, but the Flower Pot soil had an initial jump in the CEC from the raw soil and then remained nearly constant thereafter. In the A-7-6 soil group, both soils’ CEC values increased rapidly at low strengths but then remained constant at higher strengths.

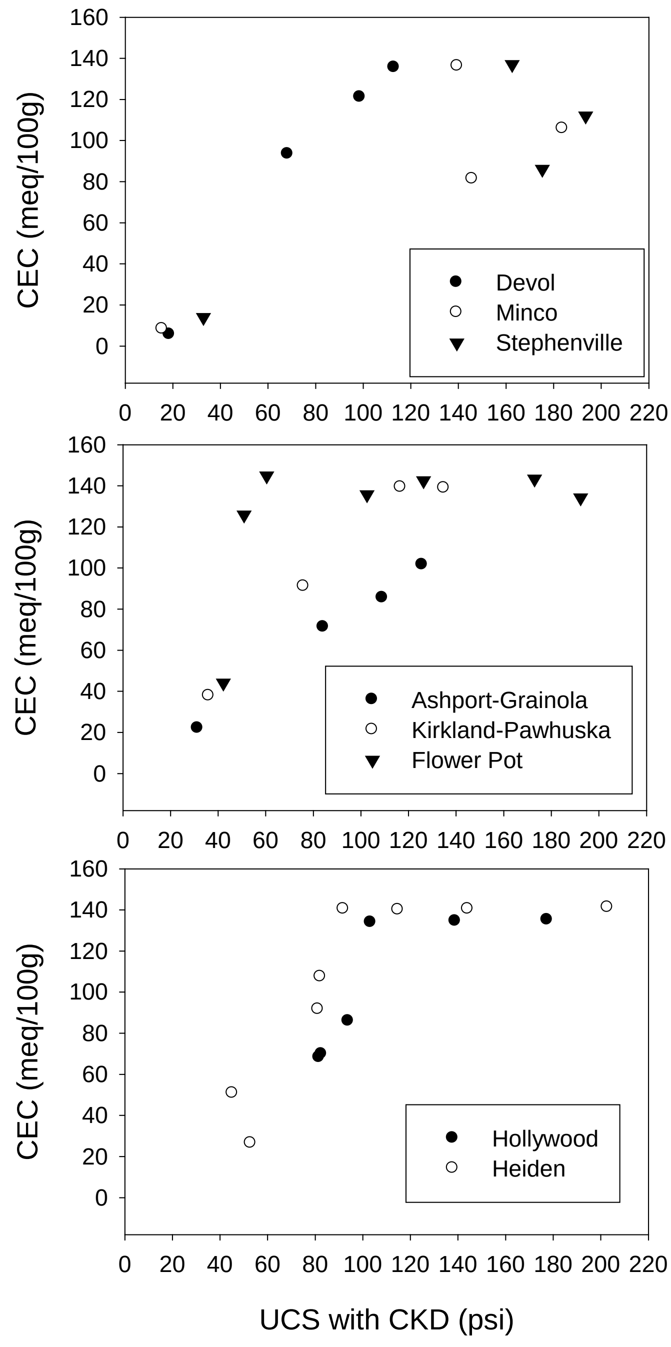


Figure 49 - CEC (Uncured) with CKD for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

5.6.2.2 CEC with Fly Ash

All eight soils have CEC values that increased as their respective unconfined compression strengths increased (Figure 50). In the A-4 soil group, the CEC values at low strengths were relatively scattered but became more consistent at higher strengths. The CEC of each of the three A-6 soils increased consistently, but along parallel trend lines for each soil, not a single response as a group. The same held true for the two A-7-6 soils, as both the Hollywood and Heiden soil CEC values increased with increasing strengths, but in parallel instead of together.

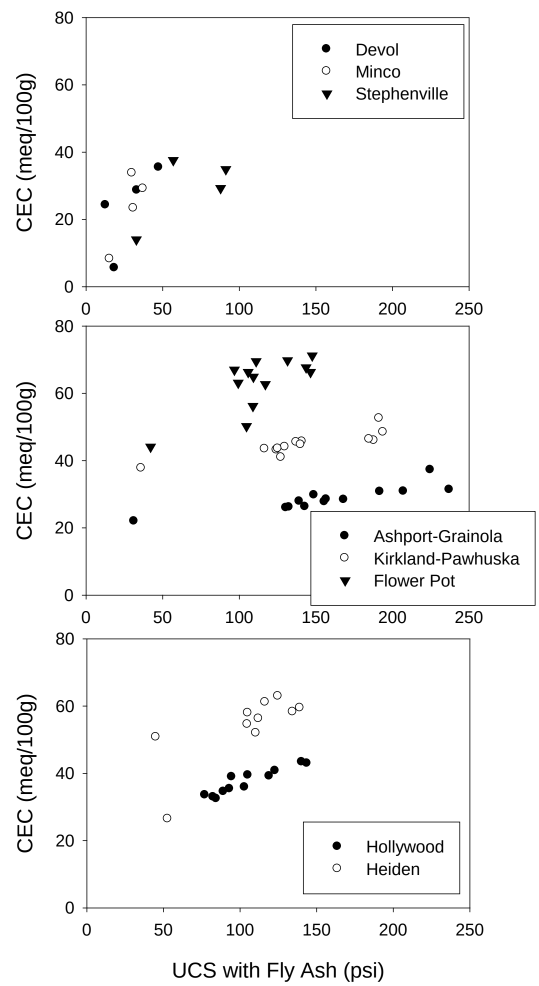


Figure 50 - CEC (Uncured) with Fly Ash for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

5.6.2.3 CEC with Lime

Figure 51 shows the results of cation exchange capacity tests performed on the five soils treated with lime from this study.

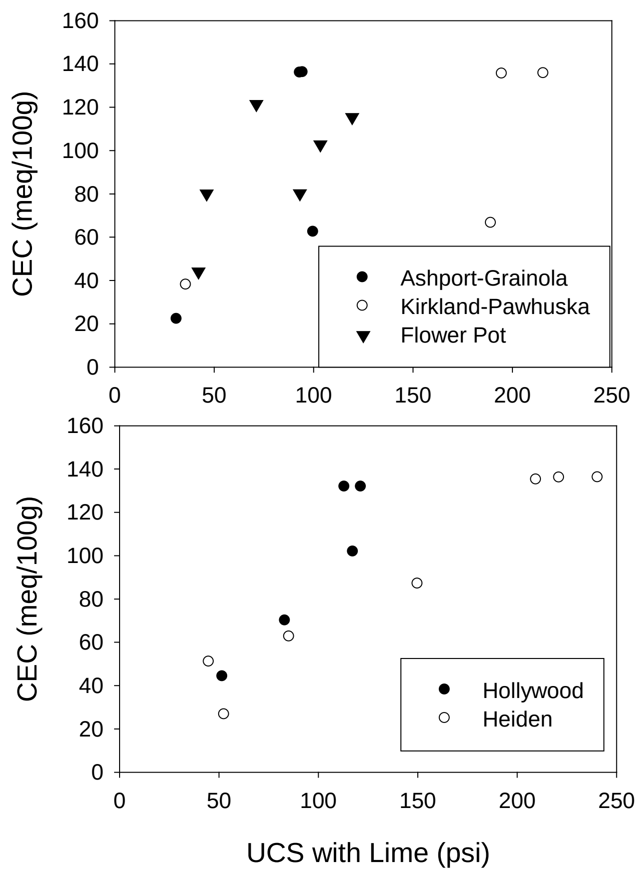


Figure 51 - CEC (Uncured) with Lime for A-6 (Top) and A-7-6 (Bottom) Soils

The three A-6 soils had significant scatter within the data, with all three soils having different CEC responses. The A-7-6 soils showed more consistent data, as the CEC values of both soils increased linearly at low strengths and the Hollywood soil CEC values deviated from the trend line at higher Hollywood soil strengths.

5.6.3 Cured CEC

5.6.3.1 CEC with CKD

Figure 52 contains the results of CEC tests performed after allowing the soil-additive mixtures to cure for at least 14 days. Only the Devol soil was tested after curing from the three A-4 soils, but it showed an increasing trend in the CEC as the strength increased. The data from the three A-6 soils mostly fell along a similar, increasing trend line. The CEC of the A-7-6 soils increased as well, but the two soils showed parallel trends. The Hollywood soil increased consistently, and the Heiden soil CEC values were higher and more scattered.

5.6.3.2 CEC with Fly Ash

As seen in Figure 53, when treated with fly ash, each soil in the three groups reacted differently. The Devol (A-4) soil CEC values increased after the initial strength decrease from the raw soil. In the A-6 soil group, each soil showed increases in the CEC values with increasing strengths, but the values from the three soils did not fall along a single group trend line. The same held true for the two A-7-6 soils as they both had increasing CEC values but parallel trends.

5.6.3.3 CEC with Lime

Figure 54 shows the results of CEC tests performed on A-6 and A-7-6 soils after allowing the soil-additive mixtures to cure. In the A-6 soil group, only the Kirkland-Pawhuska soil showed a consistent trend. The data from the Flower Pot and Ashport-Grainola soils were very scattered and did not show noticeable trends. However, the CEC values from the A-7-6 soils increased along a common trend line.

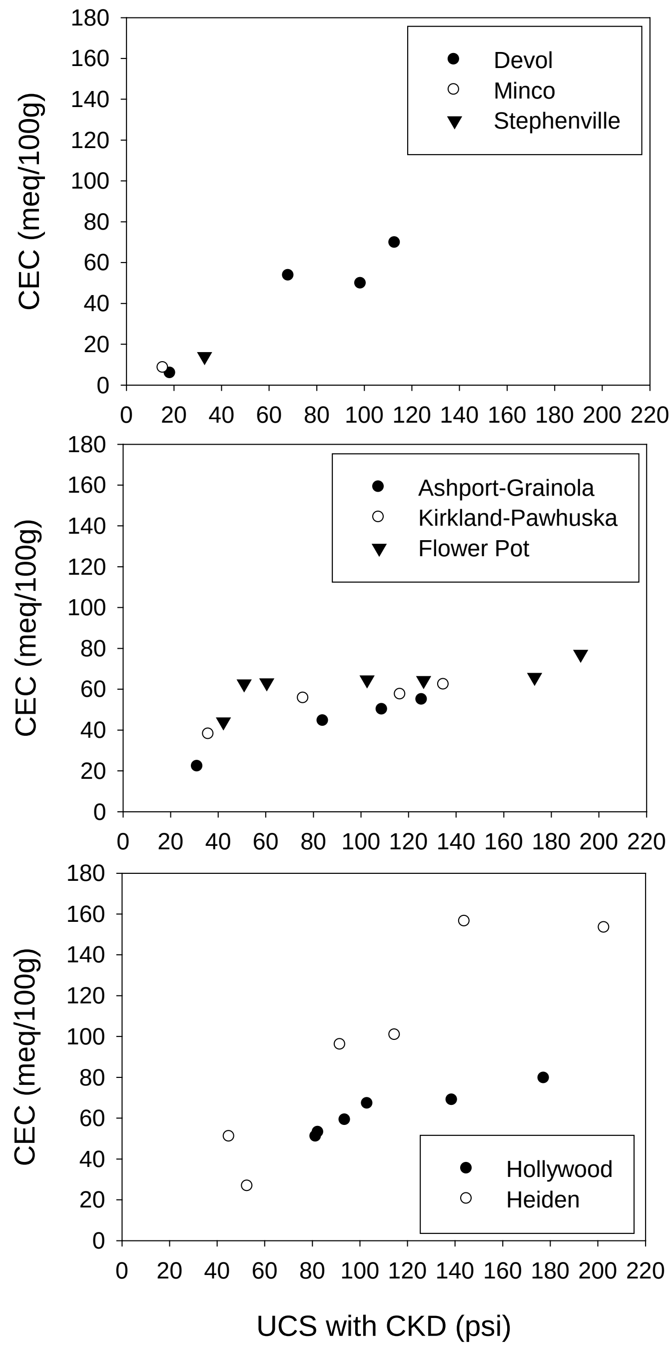


Figure 52 - CEC (Cured) with CKD for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

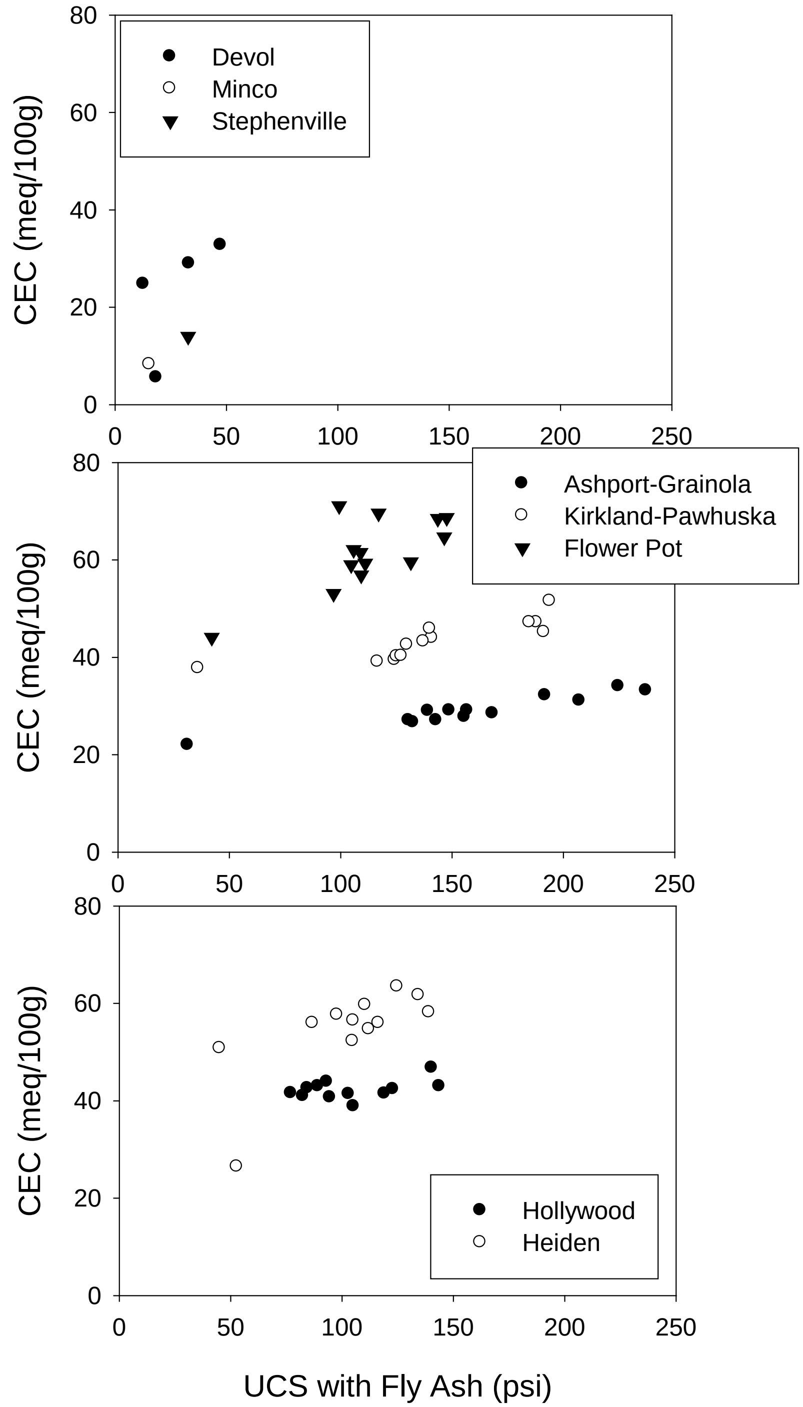


Figure 53 - CEC (Cured) with Fly Ash for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

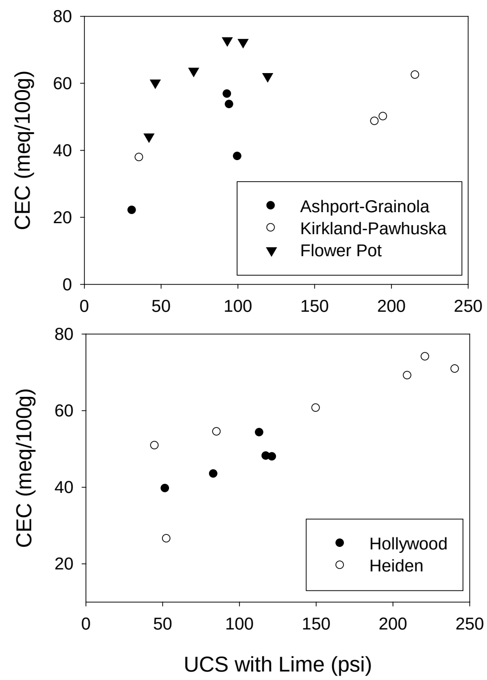


Figure 54 - CEC (Cured) with Lime for A-6 (Top) and A-7-6 (Bottom) Soils

5.6.4 Summary of CEC

When stabilized with fly ash, none of the test soils showed any appreciable differences between the uncured (2-hour mix) and the cured (14-day UCS) samples. However, there were noticeable differences in the soils stabilized with CKD and lime. In each soil treated with either CKD or lime, the cured CEC values were approximately half of the values of the uncured samples treated at the same percentage. The reactivity of CKD and lime are much higher due to the presence of higher amounts of calcium oxide (lime) in CKD and lime than in the two fly ash samples used here, but the cause of the CEC reduction is unknown. One potential explanation could be that the Ca^{+2} ions are initially reactive, but that reactivity (and the CEC) drops after curing because the Ca^{+2} ions have replaced all the lower valence cations by that point. The actual results for each soil are plotted versus the additive content in Appendix A in the following figures and tables: Figure A.99 and A.100 and Table A-29 for the A-4 soils, Figure A.101 to

Figure A.104 and Table A-30 for the A-6 soils, and Figure A.105 to Figure A.108 and Table A-31 for the A-7-6 soils.

5.7 Specific Surface Area Results

As discussed in Chapter 3, the specific surface area testing plan was split into testing the total and external specific surface areas of a single sample. The internal specific surface area was the difference between the two. On the whole, these tests followed the same 2-Hour and 14-day curing time regimen. The 2-Hour total specific surface area samples were mixed with water, cured for 2 hours, and then placed in a 110°C oven to dry at least 16 hours prior to testing. The results for the total specific surface area are discussed in this chapter, and the results of the total, external and internal SSA are shown in Appendix A, Tables A-32 through A-39.

5.7.1 Total Specific Surface Area Cured 2-hours

5.7.1.1 Total SSA with CKD

As Figure 55 shows, only the A-7-6 soils showed consistent trends when treated with CKD, albeit in parallel lines instead of a single group line. The difference in SSA between two soils classified with similar Atterberg Limits (Heiden PI = 44 and Hollywood PI = 34) is important to note and helps explain the differences in behavior when stabilized with a particular type and amount of stabilizer. The SSA of the A-7-6 soils each decreased slightly as the strength increased. The data from the A-6 soils was quite inconsistent, and the three A-4 soils each reacted differently. The Devol soil SSA values decreased, the Minco values decreased initially and then increased, and the Stephenville SSA values were relatively constant as the strength increased.

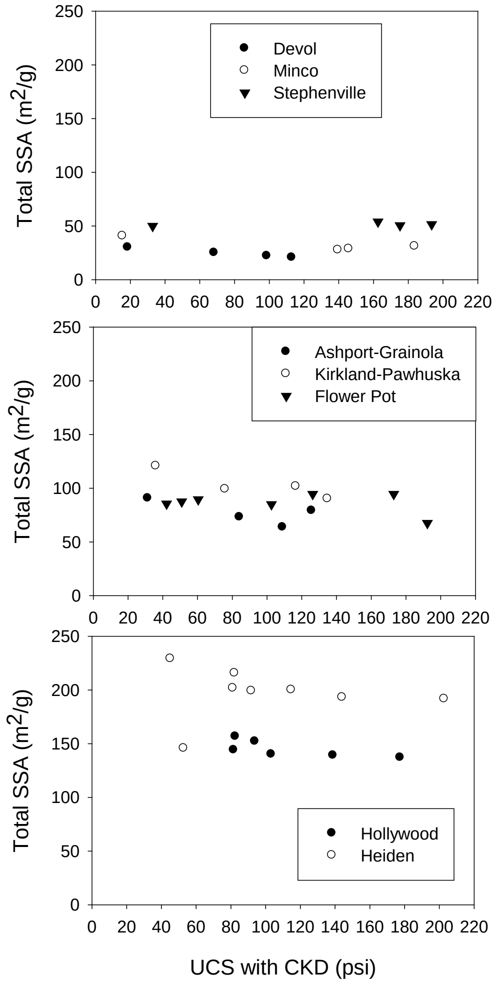


Figure 55 - Total SSA (2-Hour) with CKD for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

5.7.1.2 Total SSA with Fly Ash

Figure 56 contains the results of the total specific surface area tests performed on the eight study soils. The SSA of each A-4 soil remained fairly constant as the strength increased. The data in the A-6 soils plot shows generally constant trends in the SSA values with increasing unconfined strengths, but the combined data set is quite scattered. In the A-7-6 soils, the SSA values of the two soils fell slightly with increasing strengths, albeit at different rates. The Heiden soil SSA was initially higher and fell at a faster rate than the Hollywood soil, which only decreased slightly.

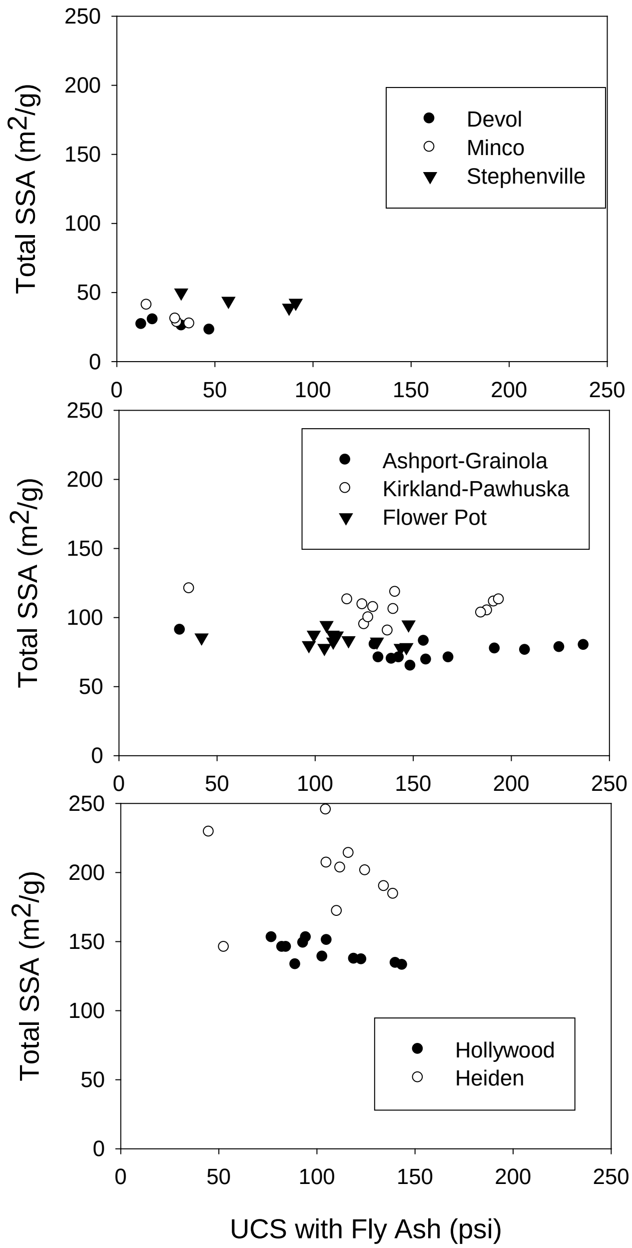


Figure 56 - Total SSA (2-Hour) with Fly Ash for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

5.7.1.3 Total SSA with Lime

Figure 57 shows two different trends. In the A-6 soils, the SSA does not change significantly globally, despite the scatter in the individual soils. In the A-7-6 soils, a different trend appeared. The Hollywood A-7-6 soil remained constant, but the Heiden soil SSA decreased initially and then increased as the strength increased.

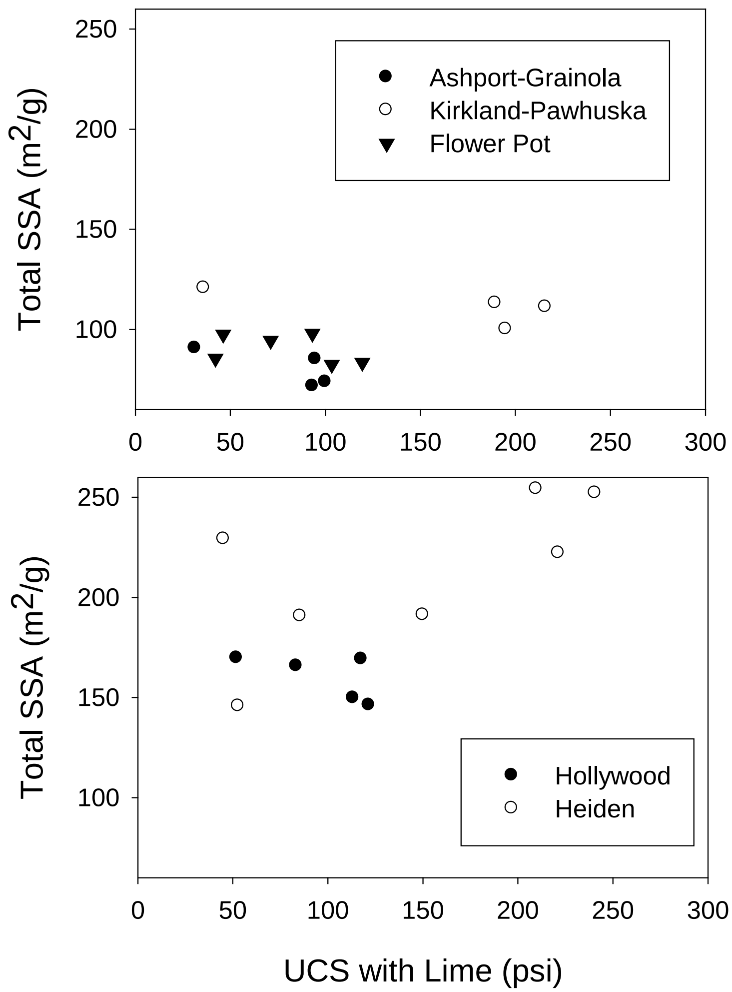


Figure 57 - Total SSA (2-Hour) with Lime for A-6 (Top) and A-7-6 (Bottom) Soils

5.7.2 Total Specific Surface Area Cured 14 Days

5.7.2.1 Total SSA with CKD

Figure 58 shows decreasing total specific surface area values with increasing unconfined compressive strengths. Only the Devol soil was tested in the A-4 group and it showed a trend line. The A-6 soils contained more variability, but generally also had decreasing total specific surface area values. However, the different soil values did not fall closely along a single trend line. In the A-7-6 soil group, each soil experienced decreasing surface area values as the strength increased, but again the soils decreased in parallel instead of along a single group trend line.

5.7.2.2 Total SSA with Fly Ash

Figure 59 shows that as the unconfined strength rises, the total specific surface area of each soil-additive mixture slightly decreases. The total surface area of the Devol soil rose initially and then did not change much. The three A-6 soils showed slightly decreasing surface areas with increasing strength, with the Ashport-Grainola and Flower Pot soils falling along a common trend line and the Kirkland-Pawhuska soil having values slightly above this line. The surface areas of the two A-7-6 soils were somewhat scattered, but both generally had lower total SSA values at higher strengths than at lower strengths.

5.7.2.3 Total SSA with Lime

Figure 60 illustrates how the total specific surface area of a soil is affected by lime stabilization and generally decreases as the unconfined compression strength increases.

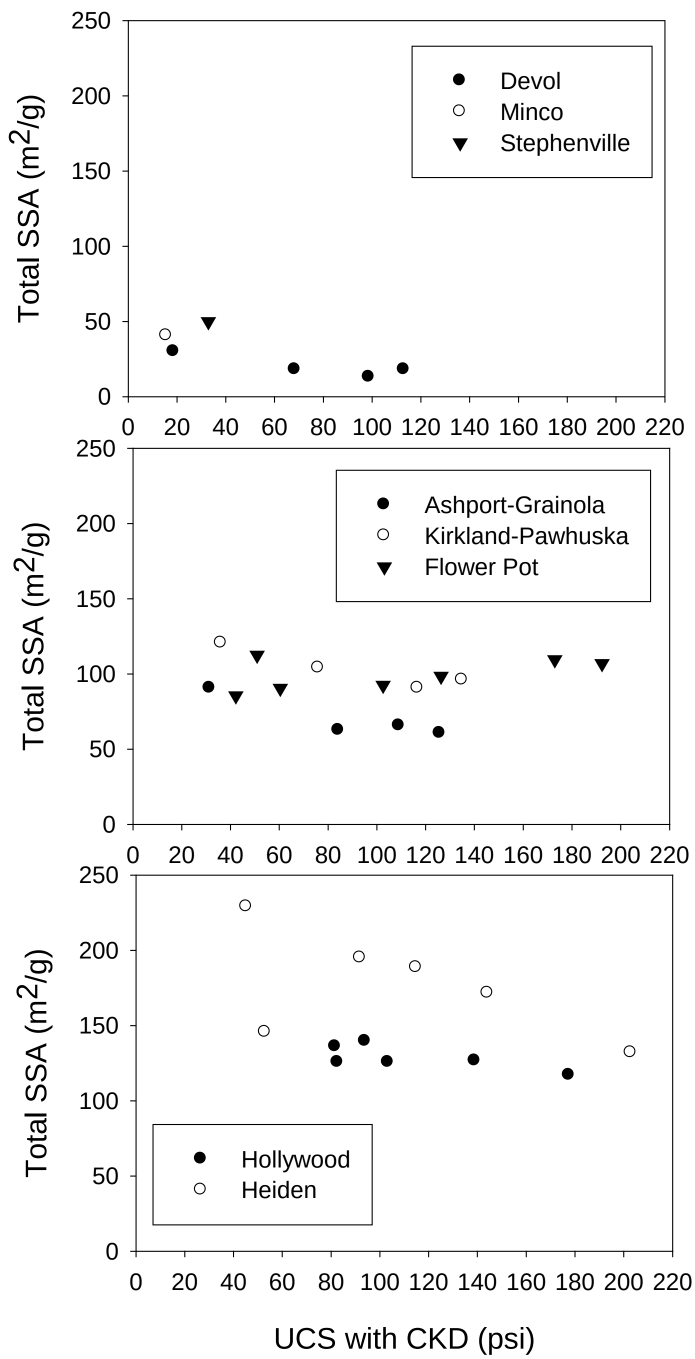


Figure 58 - Total SSA (14-day) with CKD for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

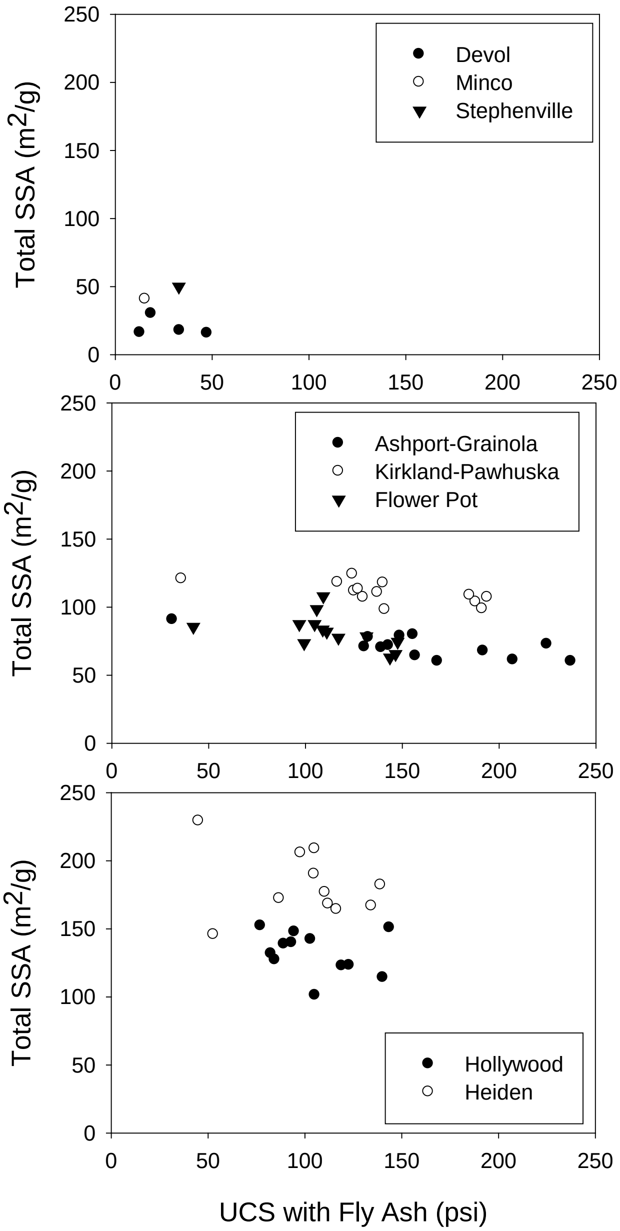


Figure 59 - Total SSA (14-day) with Fly Ash for A-4 (Top), A-6 (Center), and A-7-6 (Bottom) Soils

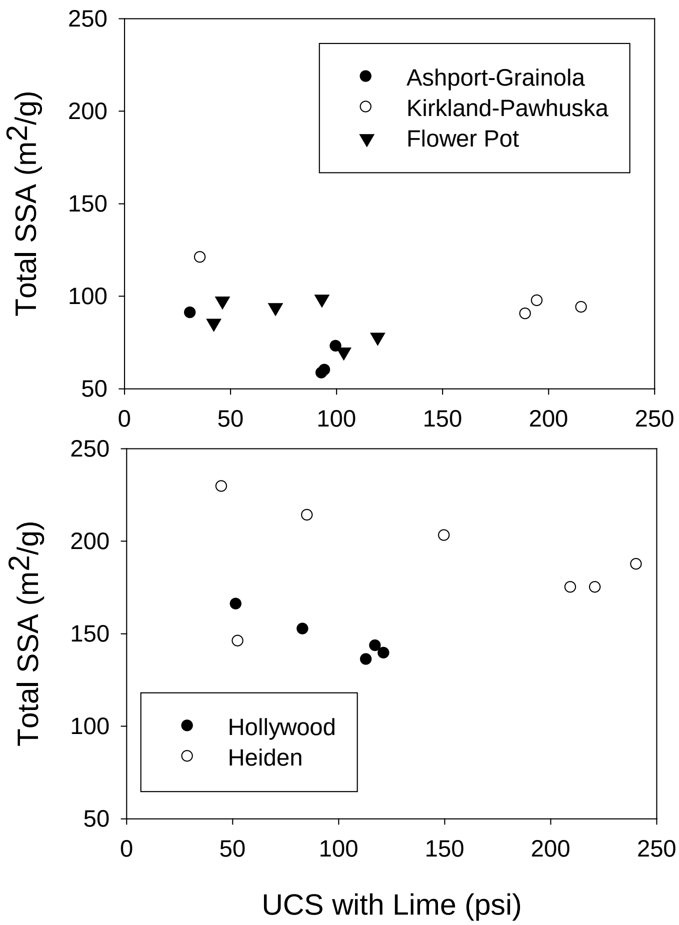


Figure 60 - Total SSA (14-day) with Lime for A-6 (Top) and A-7-6 (Bottom) Soils

In the A-6 soil group, the Kirkland-Pawhuska and the Flower Pot soils had similar total surface area responses, but the Ashport-Grainola surface area values were lower. In the A-7-6 soil group, the total specific surface areas of both the Hollywood and Heiden soils decreased, but in parallel and not along a common trend line.

5.7.3 Summary of Specific Surface Area

After comparing the results from the 2-hour cured and 14 days cured specific surface area tests, there were few differences between the two values for a given soil and additive combination. The SSA of each soil generally decreased as the strength increased (additive content increased) and the majority of the soils showed generally lower 14-day cured SSA values that ranged from approximately 5 to 20 m^2/g less than the 2-Hour cured samples. However, the SSA values for the Heiden (A-7-6) soil showed changes ranging for 0 up to nearly 100 m^2/g. To see the actual data values and the plots of the specific surface areas vs. the additive percentage, please refer to the following figures in Appendix A: Figure A.109 through Figure A.114 and Table A-32 to Table A-34 for the A-4 soils, Figure A.115 through Figure A.126 and Table A-35 to Table A-37 for the A-6 soils and Figure A.127 to Figure A.138 and Table A-38 to Table A-39 for the A-7-6 soils.

5.8 Statistical Analysis

Statistical analyses were performed on the data collected from the different tests conducted during the course of this study. The goal of the statistical analyses was to determine correlations among the different soils of a given AASHTO classification with a specific additive, such as the three A-6 soils with lime as the stabilizer. While initially, it was the intent to predict the unconfined compression strength using various soil parameters, it became clear that numerous soil parameters would have to be measured to determine the UCS adequately. While this approach very accurately predicted the UCS, unless all the soil parameters were already in a database, this would not be a practical approach. These models can be furnished upon request. Therefore, a model was created in an attempt to predict the optimum additive percentage, at which a particular soil first reaches the 50 psi (345 kPa) strength gain over the raw soil strength, using only a few commonly measured properties of the different raw soils. This is a very practical approach to determining the optimum additive percentage of any soil and can be used to check the OHDL-50 table. Multiple scenarios were tested involving different combinations of parameters to find the best predictions. However, only one model will be presented: a model using the Atterberg Limits, average pH, and the clay size fraction of each soil. This model was chosen because it provided an accurate optimum additive percentage prediction based on the measured values and contained easy-to-test parameters.

Various abbreviations for the tested parameters will be used: A description of each of these abbreviations follows.

UCS = Unconfined compression strength (psi)

UCS^+ = Raw soil UCS + 50 psi (345 kPa) minimum strength gain (psi)

Constant = Intercept of the linear model as it crosses the UCS axis

% = Additive percentage (2% = 2)

$LL_o =$ Liquid limit, cured 2-hours (%)

$PL_o =$ Plastic limit, cured 2-hours (%)

pH_{avg} = Average pH at a specific additive percentage

Adjusted R^2 = Adjusted coefficient of determination

SE = Standard error of the estimate (psi)

N = Number of data points analyzed in the model

Op% = Optimum additive percentage (%)

Clay = Clay size fraction (%)

The results of the statistical analyses performed using the Atterberg Limits, the average pH, and the clay fraction are shown in Equations [5], [6], and [7], which were used to calculate the points shown in Figure 61.

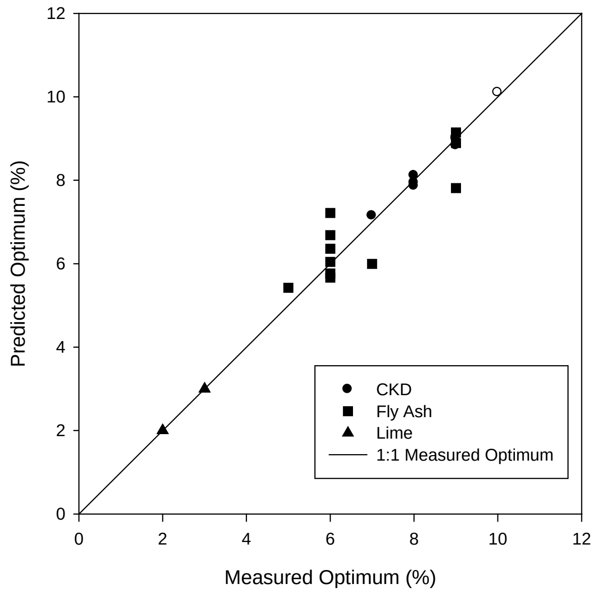


Figure 61- Atterberg Limits, Average pH, and Clay Fraction Model for Raw Soils

$$Op\%_{CKD} = 0.03(UCS^{+}) - 0.057(Clay) + 0.02(LL_0) - 0.198(PL_0) + 1.132(pH_{avg}) - 17.538 \qquad [5]$$

Adjusted R^2 = 0.944, SE = 0.220 %, and N = 8.

$$Op\%_{FA} = 0.066(UCS^{+}) - 0.211(LL_0) + 0.301(PL_0) - 0.106(Clay) + 3.165(pH_{avg}) - 57.43 \qquad [6]$$

Adjusted R^2 = 0.549, SE = 0.988 %, and N = 13.

$$Op\%_{Lime} = 0.00047(UCS^{+}) + 0.02(Clay) + 1.419(pH_{avg}) + 0.01(PI_0) - 15.403 \qquad [7]$$

Adjusted R^2 = 1.0, SE = 0 %, and N = 5.

The addition of the clay fraction percentage and the average pH to the Atterberg Limits model greatly improved the basic model predictions. The CKD stabilization model became nearly an exact match to the measured optimum percentages, and the lime stabilization model was an exact statistical match to the optimum percentages. The fly ash model also improved from the basic Atterberg Limits model, but not to the same degree as the CKD and lime models. The biggest problem with these models is the constant term at the end of each equation is extremely large and introduces an indirect source of error into each model. However, only having to measure the UCS, clay fraction, pH and PI of the raw soil is relatively easy in predicting the amount of optimum additive content to gain that necessary 50 psi strength increase and can be a valuable tool, in addition to the OHD L-50 table, in determining if a particular soil will be adequately stabilized.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The overall goal of this research project was to assist the state in validating and improving the recommendations of OHD L-50 “Soil Stabilization Mix Design Procedure.” The research focused on AASHTO Soil Group Classifications falling under the fine-grained soil category (e.g., A-4 to A-7). This goal was achieved through specific objectives, which were to:

A. Identify and investigate the variations in soil characteristics of Oklahoma Soils within specified AASHTO Soil Group Classifications,

B. Evaluate OHD L-50 for the test soils and test additives identified,

C. Thoroughly characterize the test soils identified to determine mineralogical, physical, chemical, and engineering index properties to ascertain any behavioral differences.

D. Refine and optimize the recommendations in OHD L-50 by examining potentially useful and quick methods for selecting additive contents.

To accomplish these objectives, eight common fine-grained soils (classified as either A-4, A-6, or A-7-6 soils by the AASHTO classification system) were sampled from across the state of Oklahoma, tested with four different chemical additives (Hydrated Lime, CKD and 2 sources of Class C Fly Ash) in varying amounts. These raw and stabilized soils were then subjected to various soil property tests to assess the degree of stabilization achieved using the recommended ODOT additive quantities and also to determine why the soils that were classified similarly behaved differently in some cases.

Each soil was thoroughly characterized and the soil properties used to determine the effects of these different properties on predictions of the stabilized soil strength.

Based on the results of the research work conducted, the following conclusions may be made:

1. In general, the use of the Atterberg Limits alone does not provide an accurate prediction of the stabilized strength. However, model predictions were considerably more accurate when the soils were divided according to the AASHTO classification, which supports the use of OHD L-50 as a stabilization guide.
2. The pH response of soils treated with CKD and fly ash is similar to that of the lime response, but the pH curves with fly ash seldom reached a constant value. However, they reached a constant rate of change, which can be used to estimate optimal conditions in a similar fashion as lime.
3. The bar linear shrinkage test provides valuable data for predicting stabilized soil strengths. As noted in Table 10, a specific decrease in the value of the linear shrinkage could be used to indicate the optimum additive percentage to achieve adequate stabilization. For example, if an A-6 soil treated with 8% CKD shows a linear shrinkage decrease of 3% from the raw soil linear shrinkage, then that soil should be adequately stabilized.
4. It is possible to use only parameters from raw soils to predict the optimum additive percentages. The full models were typically the most accurate, but the models using only the Atterberg Limits, clay fraction, and average pH were effective at making estimates. These models are promising because being able to estimate optimum additive percentage while only testing a raw soil would save considerable time and effort.

5. Based on the results of this laboratory study, both A-6 soils and A-7-6 soils gained the recommended 50 psi strength after stabilization, with less fly ash, cement kiln dust and hydrated lime than is currently indicated in the 2009 OHD L-50 Table. The amount of stabilizer necessary to gain that 50 psi strength increase, as found in this research project, are presented next to the existing recommendations in OHD L-50 (Table 11). The first number listed is the existing recommendation, while numbers in **bold** are supported by the data of this research. For both the A-7-6 and the A-6 soils, stabilized with FA and CKD (A-7-6, FA and CKD and A-6, CKD, only) there were no recommendations listed in the 2009 OHD L-50 table, and in this laboratory study, it was found that in each of those three particular combinations, 9% stabilizer was adequate to increase the strength 50 psi over the raw soil strength.

Table 11: Comparison of Existing OHDL-50 Stabilization Recommendations and Data Found in this Study.

ADDITIVE (Expressed as a percentage added on dry over basis)	SOIL GROUP CLASSIFICATION – AASHTO M145		
	A-4	A-6	A-7-6
FLY ASH	14*	14–$**6%**	****9%**
CEMENT KILN DUST (Other Type Plants)	12–$**10%**	****9%**	****9%**
HYDRATED LIME*		4–$**4%**	5-$**3%**

* Existing recommendation in OHDL-50. Stabilization, as defined by an increase in strength of 50 psi above the soil's raw strength, was not seen in 2 of the 3 A-4 soils tested with FA in this study. In fact, even when the percentage of FA was increased to 15%, the strength of the two soils did not increase.

$ Stabilizer amount that achieved 50 psi increase in strength above the raw soil in this study.

** New addition to this table. No previous recommendations for these soil or stabilization categories were given in OHD L-50.

6.2 Recommendations

It is recognized that the additive content at which a strength gain of 50 psi occurs in this laboratory study is lower than is currently recommended. Laboratory mixing and sample preparation were carefully controlled, and in the field, non-homogenous spreading and mixing of stabilizer in the subgrade is a reality, as is loss due to various reasons, therefore necessitating extra stabilizer to ensure an adequate strength gain. It was also shown in Snethen et al. (2008) that field mixed samples had 50-90% less strength than laboratory mixed samples. This could be the result of numerous factors including insufficient field mixing, lower percentage of additive in field mixed samples (this is an unknown), and losses in strength due to delays in compaction of field mixed samples. In addition, when X-ray Fluorescence (XRF) was used to determine the stabilizer amount in the field, for CKD and FA sites, the XRF always showed lower percentages in the field. The results of the XRF will be discussed in more detail in Volume II. Therefore, it is not recommended to use lower values in the field. It is, however, recommended to use CKD and FA to stabilize A-6 and A-7-6 soils. While this laboratory study shows that 9% of these additives increase the strength of the soil by 50 psi, it may be prudent to raise these levels to the same amount that is listed for the other soil and additive combinations to account for additive losses and strength reductions occurring in the field (e.g. 14% FA for A-7-6 soils, 12% CKD for A-6 and 12% CKD for A-7-6). This would be similar to the current standard practice of increasing additive percentages from laboratory mix design results, performed in accordance with OHDL-50 recommendations using the ASTM D4609 procedure, to field application.

It is also recommended that a note be added to the existing OHDL-50 table that gives the option to further test A-6 and A-7-6 soils in linear shrinkage. A raw soil test and a test with the recommended additive (2-hour cure) could be run and if there is an adequate reduction in linear shrinkage (see Table 8), then the required 50 psi strength increase can be verified. If an adequate reduction in linear shrinkage is not seen, then this soil should be investigated further. In addition, the model predictions generated in this study that use the Atterberg Limits, clay fraction and pH to estimate optimum additive content, can be used as another way of verifying adequate stabilization.

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APPENDIX

LIST OF TABLES

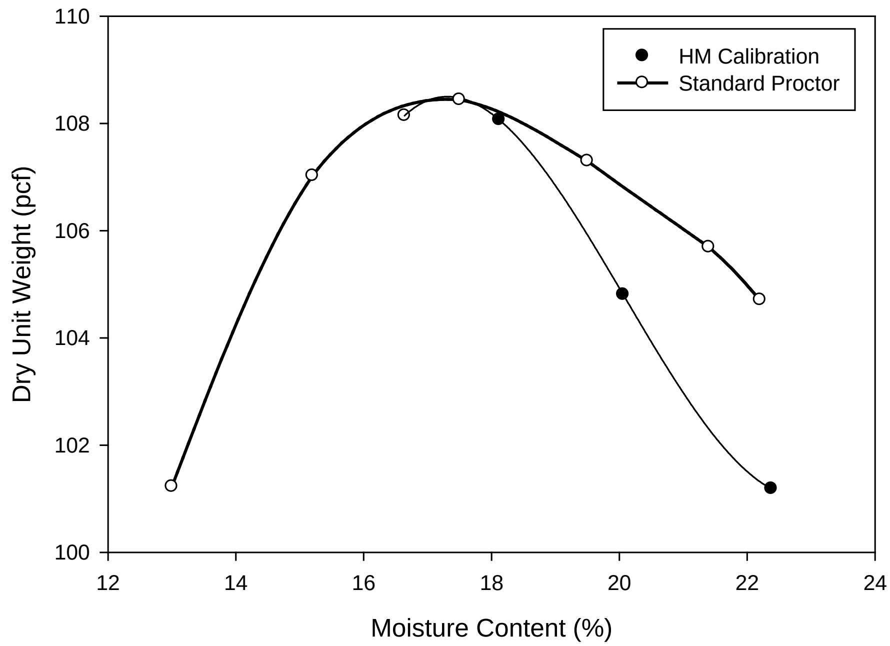

Figure A.1: Kirkland-Pawhuska (A-6) HM Calibration Curve Raw Soil (10 blows/layer)

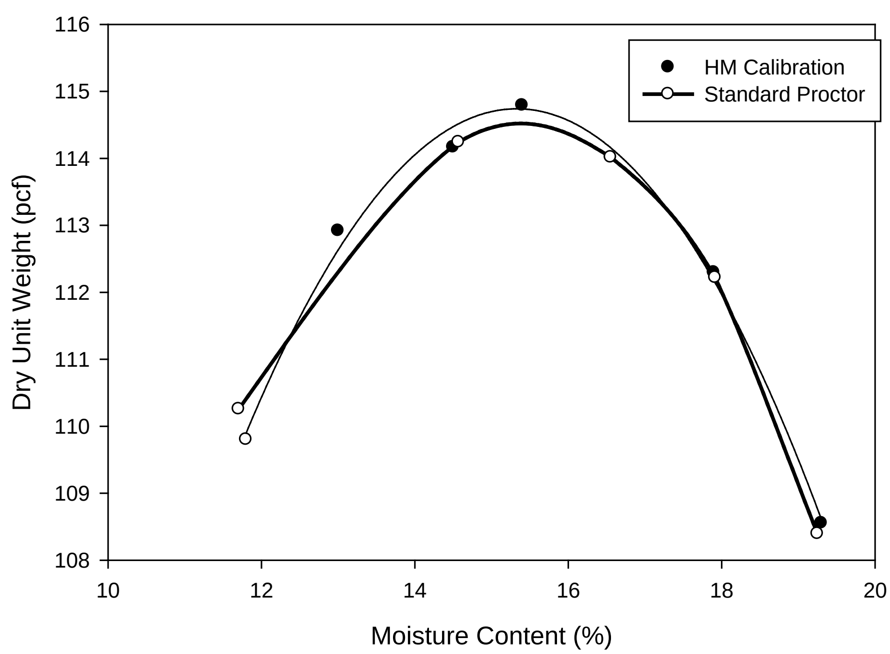

Figure A.2: Ashport-Grainola (A-6) HM Calibration Curve Raw Soil (10 blows/layer)

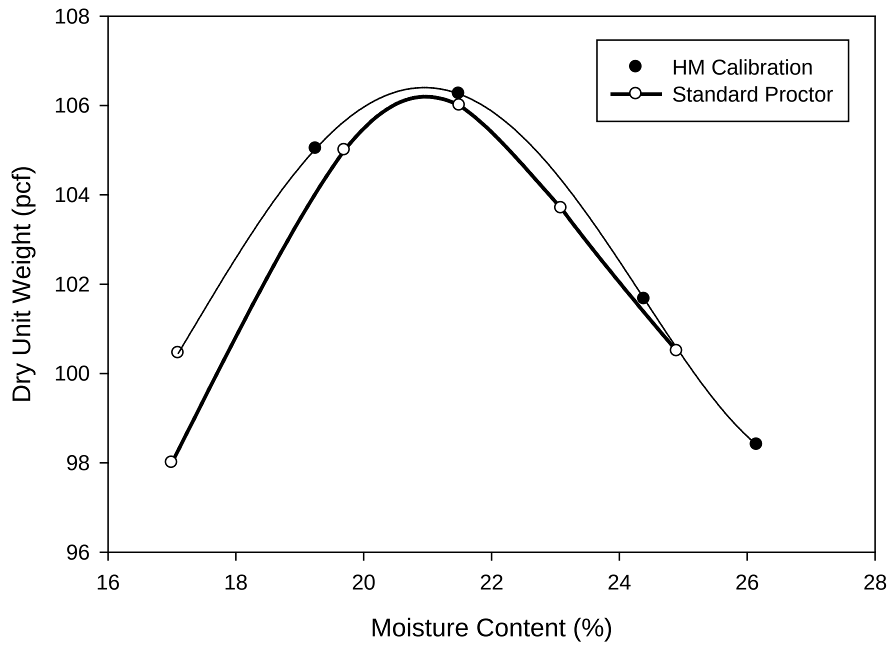

Figure A.3: Flowerpot (A-6) HM Calibration Curve Raw Soil (10 blows/layer)

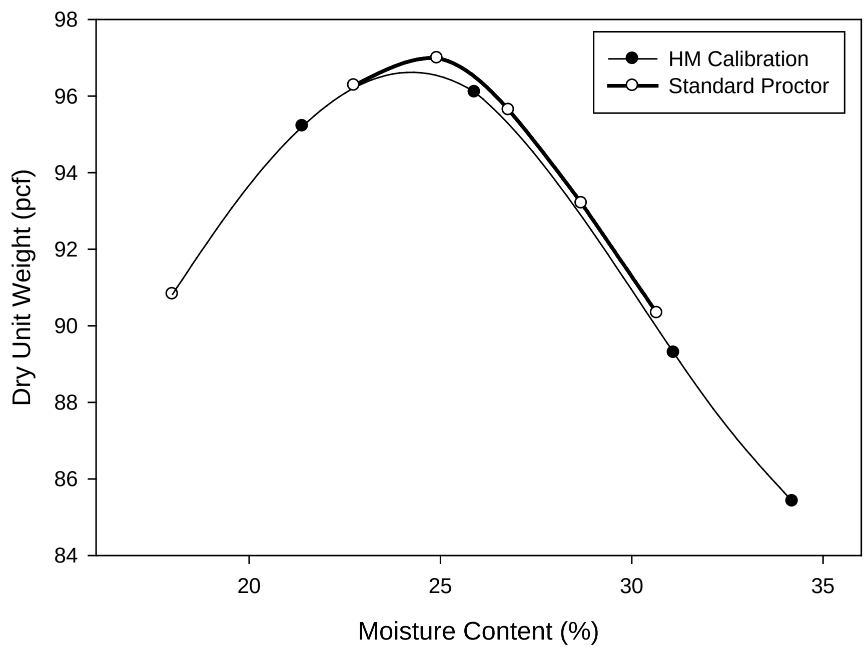

Figure A.4: Heiden (A-7-6) HM Calibration Curve Raw Soil (6 blows/layer)

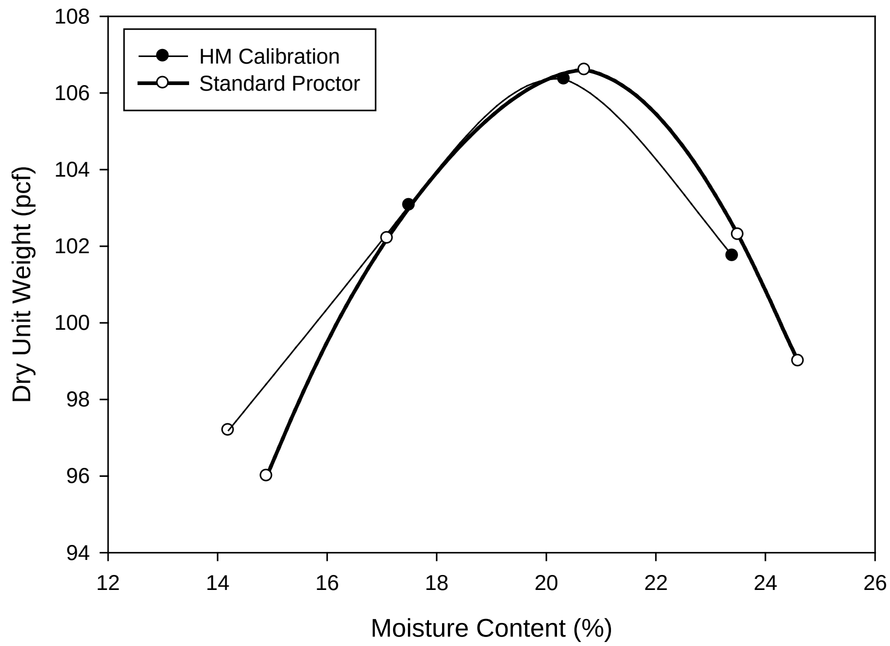

Figure A.5: Hollywood (A-7-6) HM Calibration Curve Raw Soil (5 blows/layer)

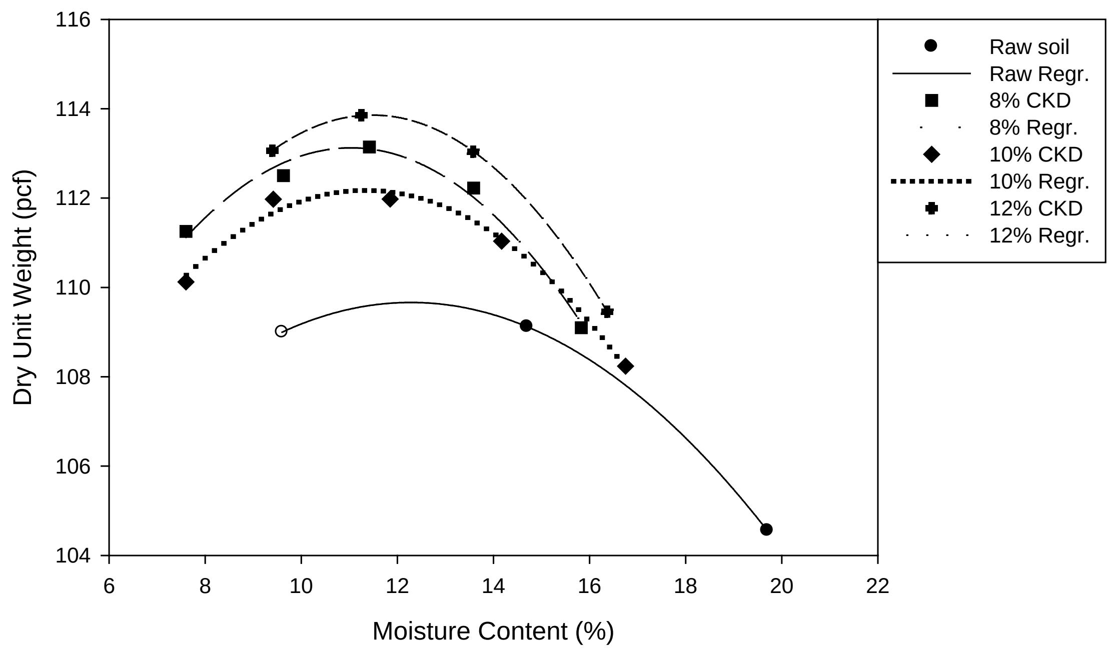

Figure A.6: Devol (A-4) OMC Curves with CKD

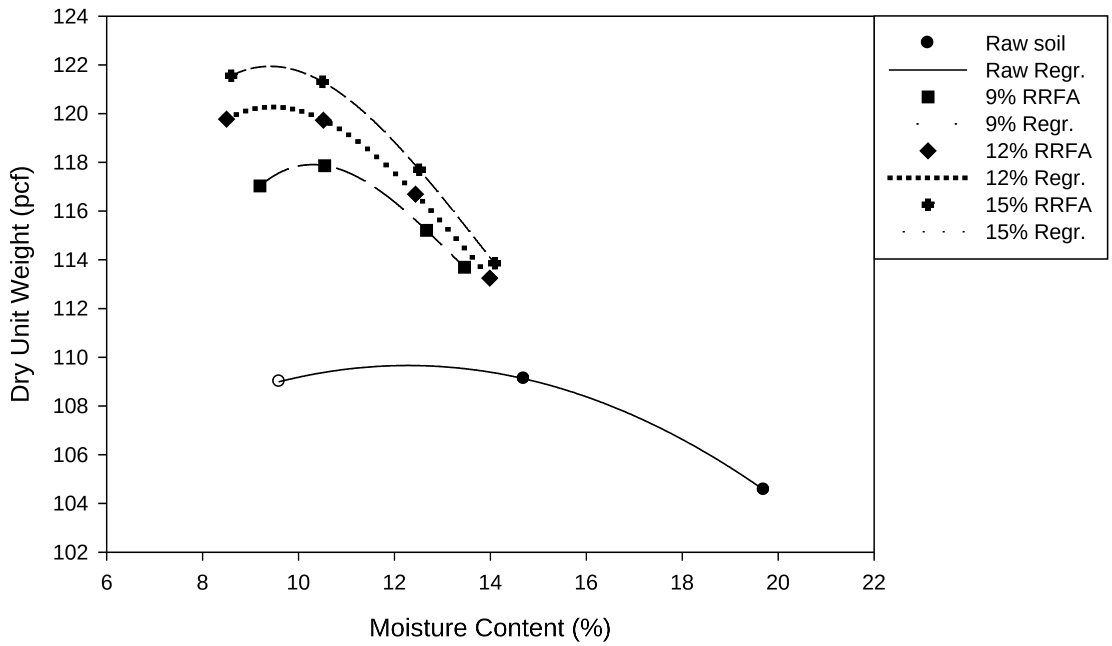

Figure A.7: Devol (A-4) OMC Curves with Red Rock Fly Ash

Table A.1 Devol (A-4) OMC and Dry Unit Weight Values from Standard Proctor Tests

Additive Type	Additive Percentage	OMC (%)	Dry Unit Weight (pcf)
Raw soil	0%	12.30	108.61
CKD	8%	11.00	112.08
	10%	10.50	111.20
	12%	11.40	112.77
Red Rock Fly Ash	9%	10.30	116.80
	12%	9.50	119.13
	15%	9.40	120.77

Table A.2: Minco (A-4) OMC and Dry Unit Weight Values from Standard Proctor Tests

Additive Type	Additive Percentage	OMC (%)	Dry Unit Weight (pcf)
Raw soil	0%	13.30	111.20
CKD	8%	-	
	10%	15.10	106.85
	12%	-	
Red Rock Fly Ash	9%	-	
	12%	12.50	112.58
	15%	-	-

Table A.3: Stephenville (A-4) OMC and Dry Unit Weight Values from Standard Proctor Tests

Additive Type	Additive Percentage	OMC (%)	Dry Unit Weight (pcf)
Raw soil	0%	13.60	115.10
CKD	8%	-	
	10%	14.60	113.15
	12%	-	
Red Rock Fly Ash	9%	-	
	12%	12.40	116.99
	15%	-	-

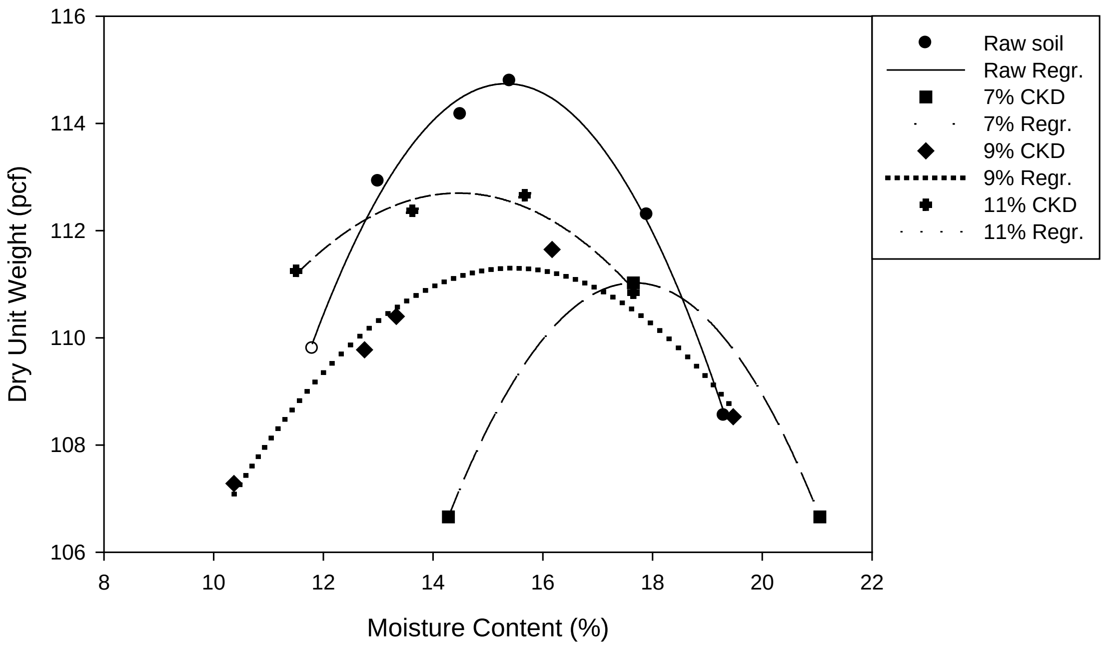

Figure A.8: Ashport-Grainola (A-6) OMC Curves with CKD

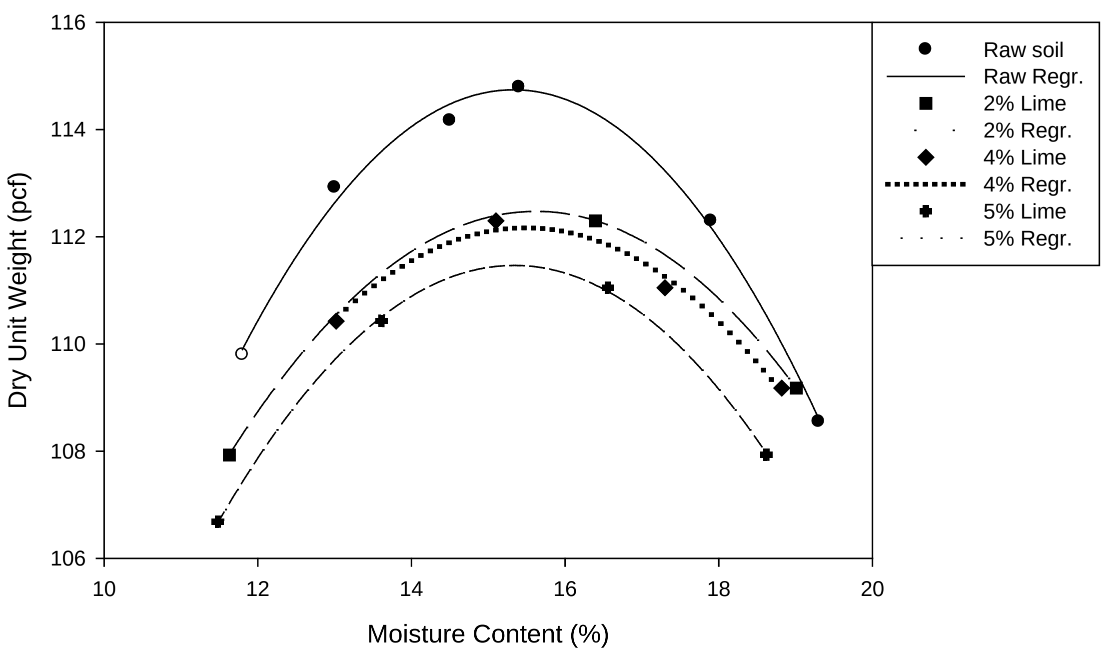

Figure A.9: Ashport-Grainola (A-6) OMC Curves with Lime

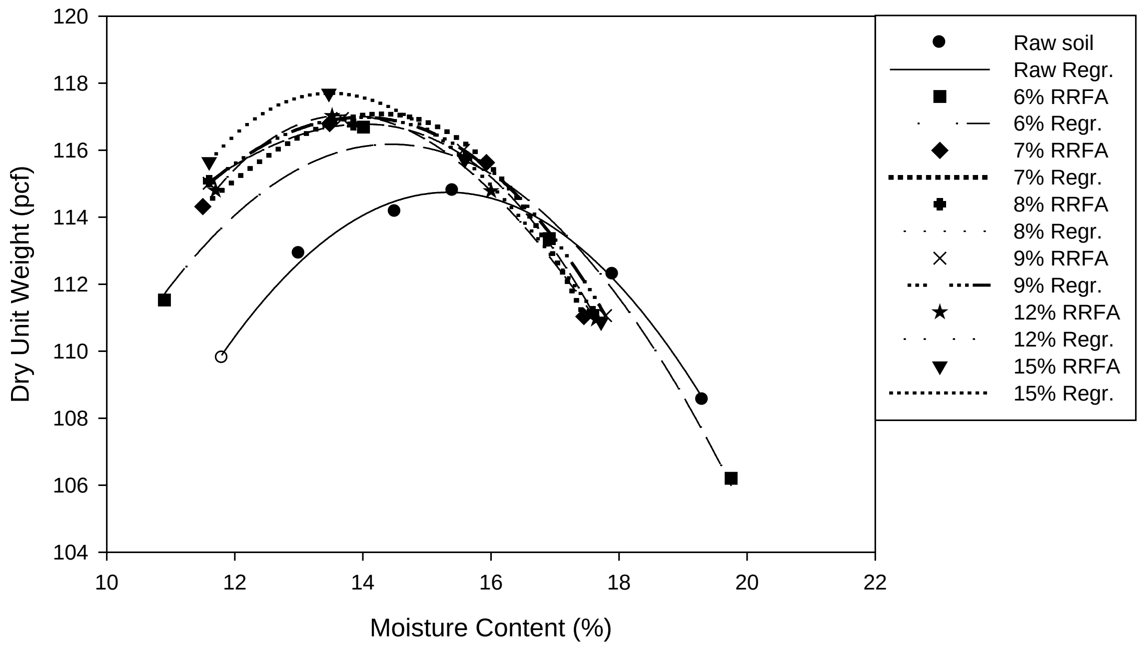

Figure A.10: Ashport-Grainola (A-6) OMC Curves with Red Rock FA

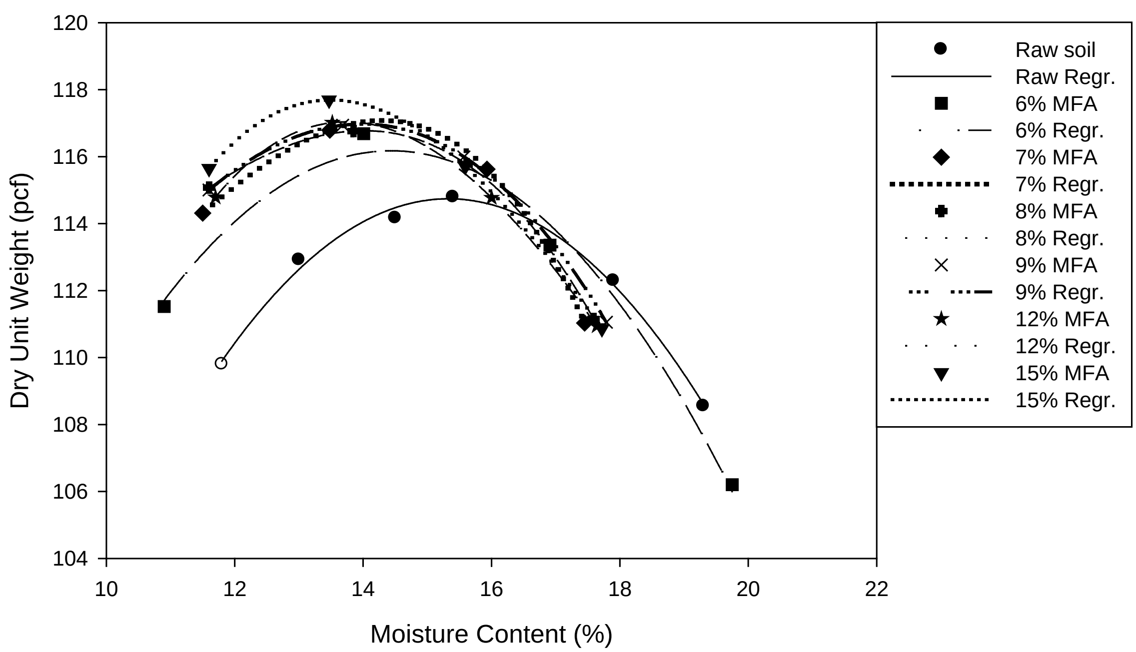

Figure A.11: Ashport-Grainola (A-6) OMC Curves with Muskogee FA

Table A-4: Ashport-Grainola (A-6) OMC and Dry Unit Weight Values

Additive Type	Additive Content	OMC (%)	Dry Unit Weight (pcf)
Raw soil	0%	15.54	113.27
Lime	2%	15.25	111.57
	4%	15.10	110.88
	5%	15.50	109.81
CKD	7%	16.30	109.12
	9%	15.50	110.57
	11%	15.10	111.70
Red Rock Fly Ash	6%	14.00	115.61
	7%	14.30	115.98
	8%	14.00	115.67
	9%	14.30	115.98
	12%	13.70	115.92
	15%	13.50	116.55
Muskogee Fly Ash	6%	14.00	115.61
	7%	14.30	115.98
	8%	14.00	115.67
	9%	14.30	115.98
	12%	13.70	115.92
	15%	13.50	116.55

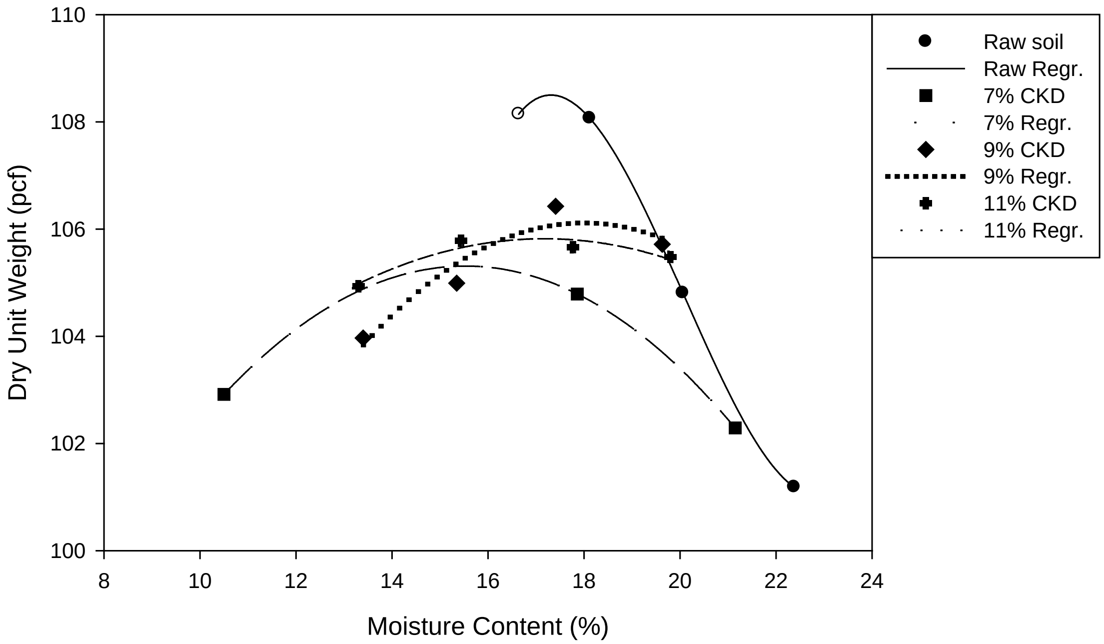

Figure A.12: Kirkland-Pawhuska (A-6) OMC Curves with CKD

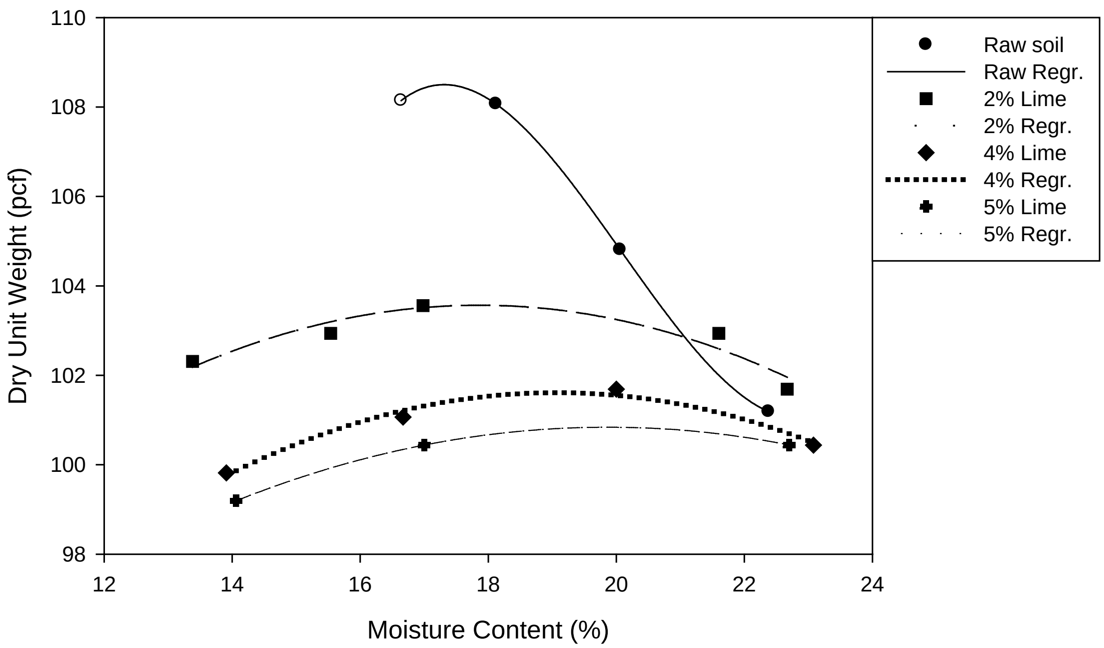

Figure A.13: Kirkland-Pawhuska (A-6) OMC Curves with Lime

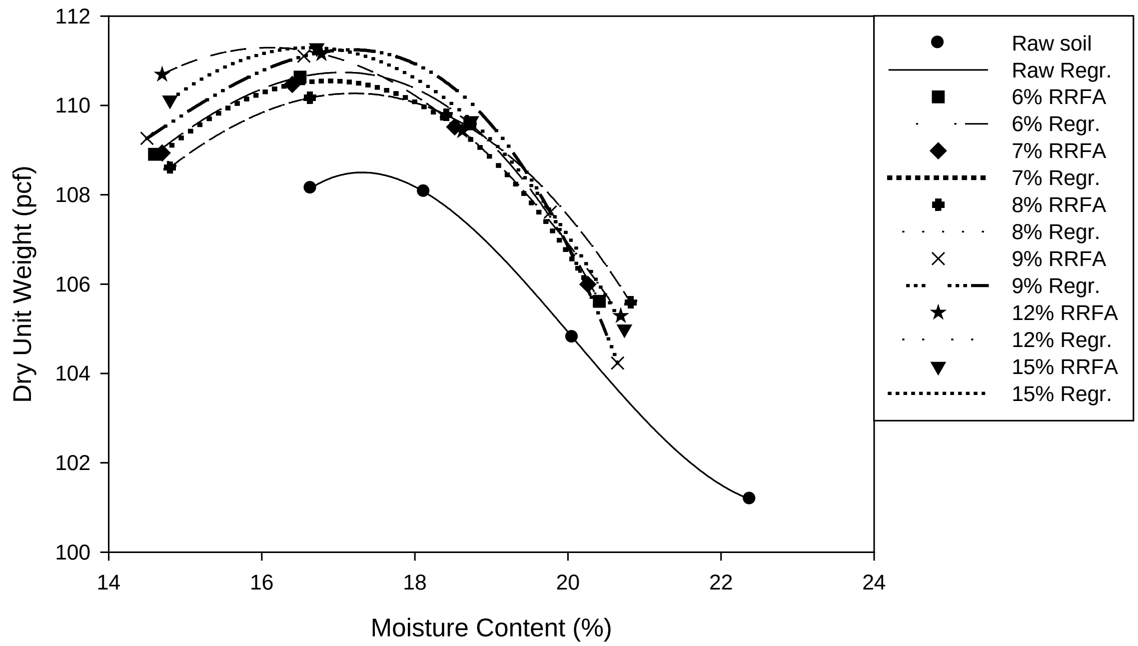

Figure A.14: Kirkland-Pawhuska (A-6) OMC Curves with Red Rock FA

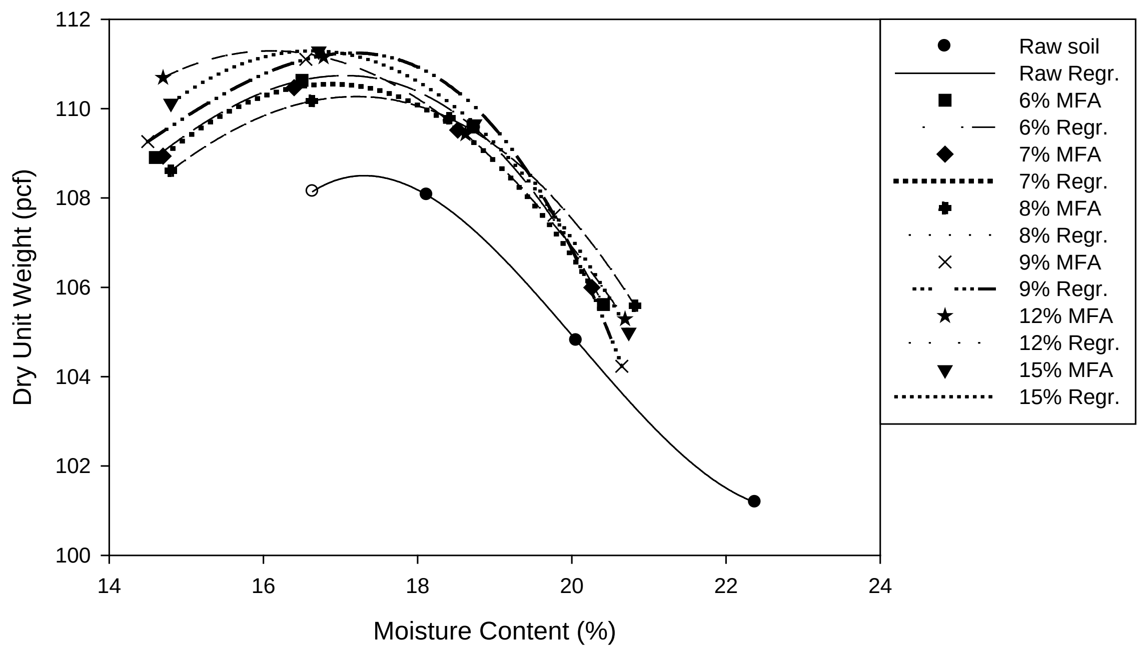

Figure A.15: Kirkland-Pawhuska (A-6) OMC Curves with Muskogee FA

Table A-5: Kirkland-Pawhuska (A-6) OMC and Dry Unit Weight Values

Additive Type	Additive Content	OMC (%)	Dry Unit Weight (pcf)
Raw soil	0%	17.30	107.48
Lime	2%	17.90	102.82
	4%	17.50	100.93
	5%	20.00	100.67
CKD	7%	16.00	102.88
	9%	18.10	105.59
	11%	17.20	104.83
Red Rock Fly Ash	6%	16.90	109.62
	7%	16.90	109.49
	8%	17.20	109.24
	9%	17.20	110.19
	12%	16.10	110.25
	15%	16.60	110.25
Muskogee Fly Ash	6%	16.90	109.62
	7%	16.90	109.49
	8%	17.20	109.24
	9%	17.20	110.19
	12%	16.10	110.25
	15%	16.60	110.25

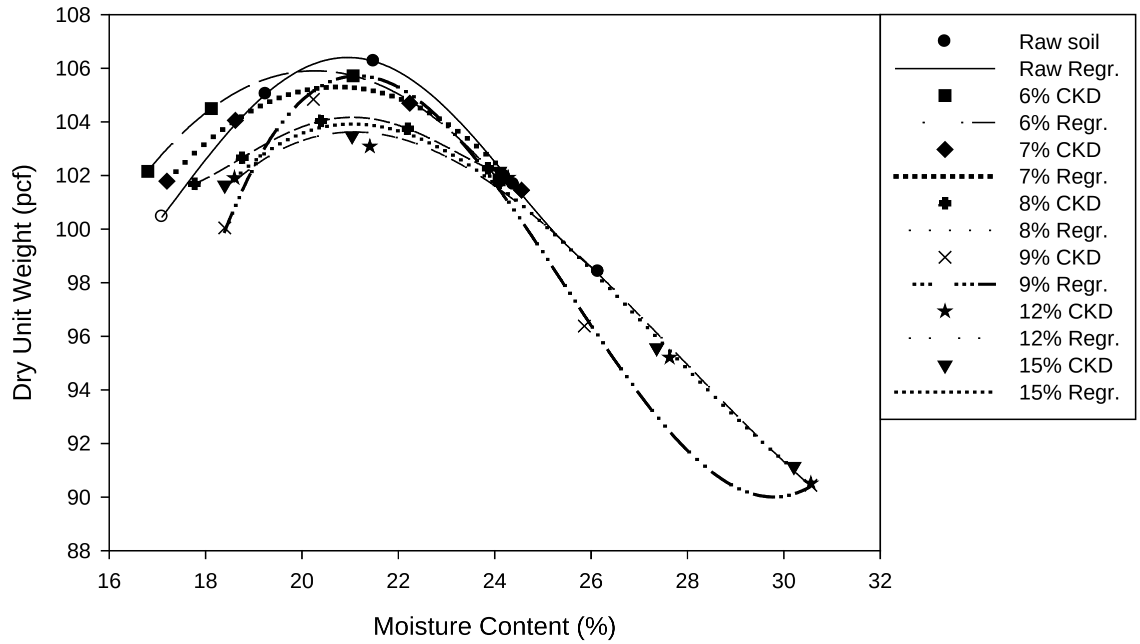

Figure A.16: Flower Pot (A-6) OMC Curves with CKD

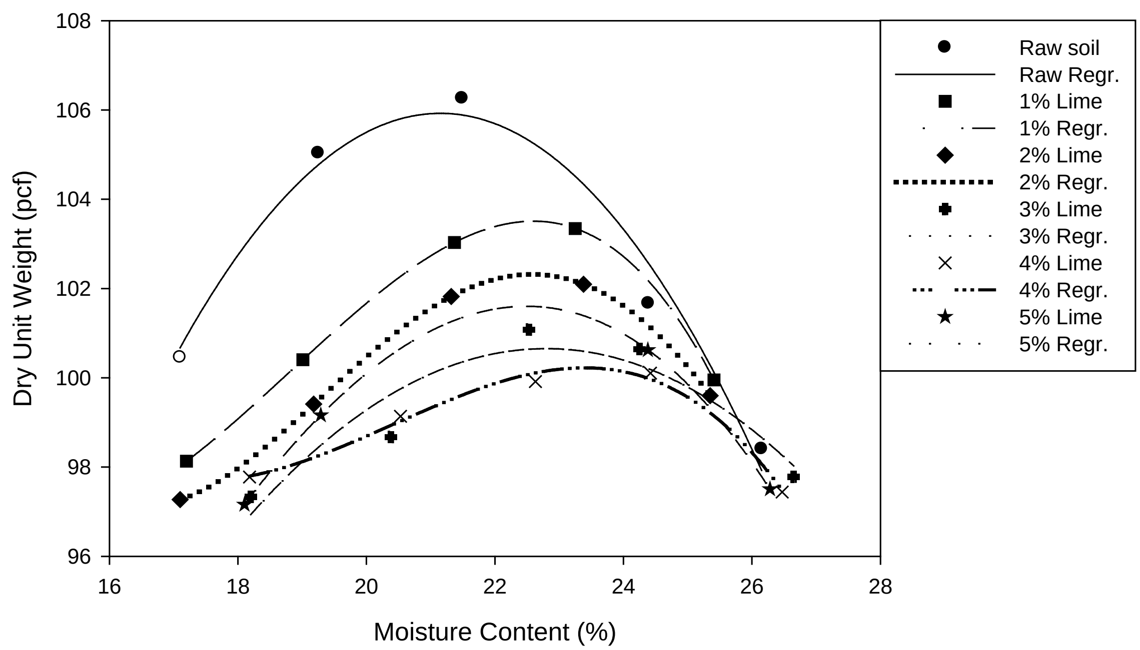

Figure A.17: Flower Pot (A-6) OMC Curves with Lime

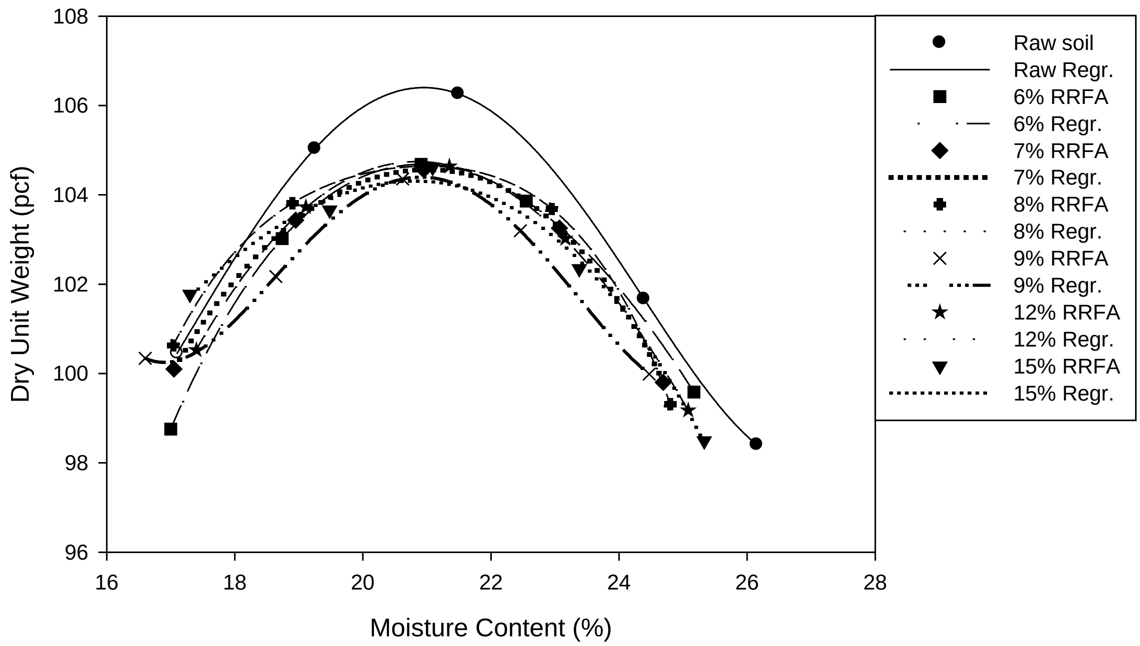

Figure A.18: Flower Pot (A-6) OMC Curves with Red Rock FA

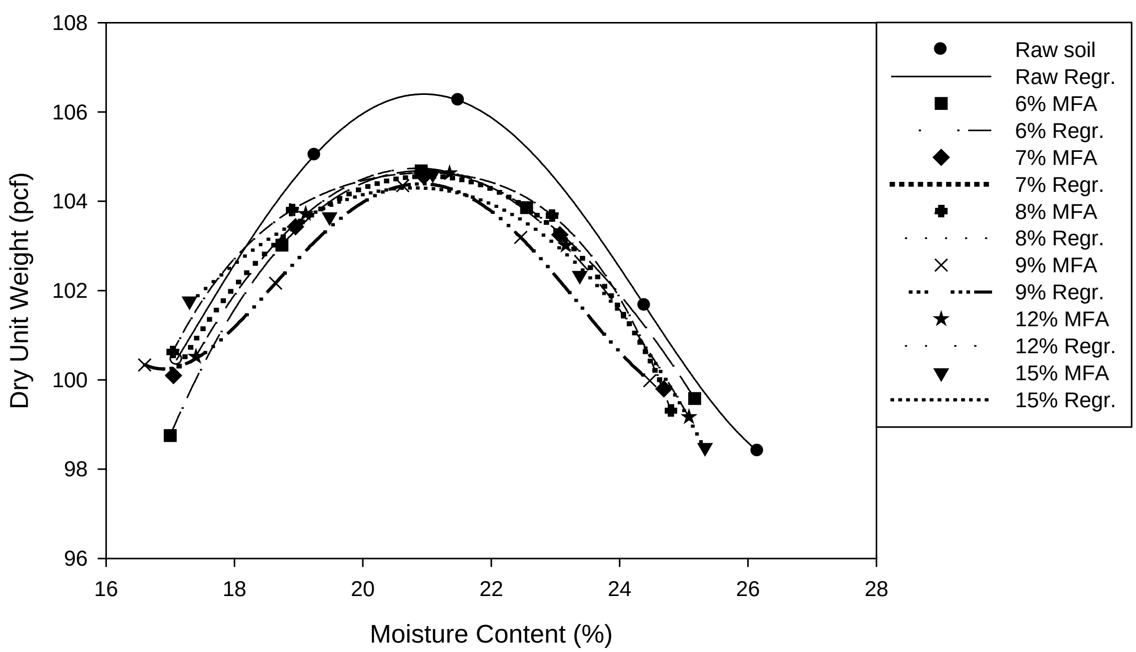

Figure A.19: Flower Pot (A-6) OMC Curves with Muskogee FA

Table A-6: Flower Pot (A-6) OMC and Dry Unit Weight Values

Additive Type	Additive Content	OMC (%)	Dry Unit Weight (pcf)
Raw soil	0%	20.90	105.40
Lime	1%	22.60	102.50
	2%	22.60	101.37
	3%	23.10	99.73
	4%	23.90	99.10
	5%	22.50	100.67
CKD	6%	20.30	104.90
	7%	20.70	104.33
	8%	21.10	103.38
	9%	21.40	104.71
	12%	21.80	102.12
	15%	21.60	102.56
Red Rock Fly Ash	6%	20.90	103.70
	7%	21.00	103.64
	8%	21.00	103.70
	9%	21.10	103.51
	12%	20.80	103.76
	15%	21.30	103.64
Muskogee Fly Ash	6%	20.90	103.70
	7%	21.00	103.64
	8%	21.00	103.70
	9%	21.10	103.51
	12%	20.80	103.76
	15%	21.30	103.64

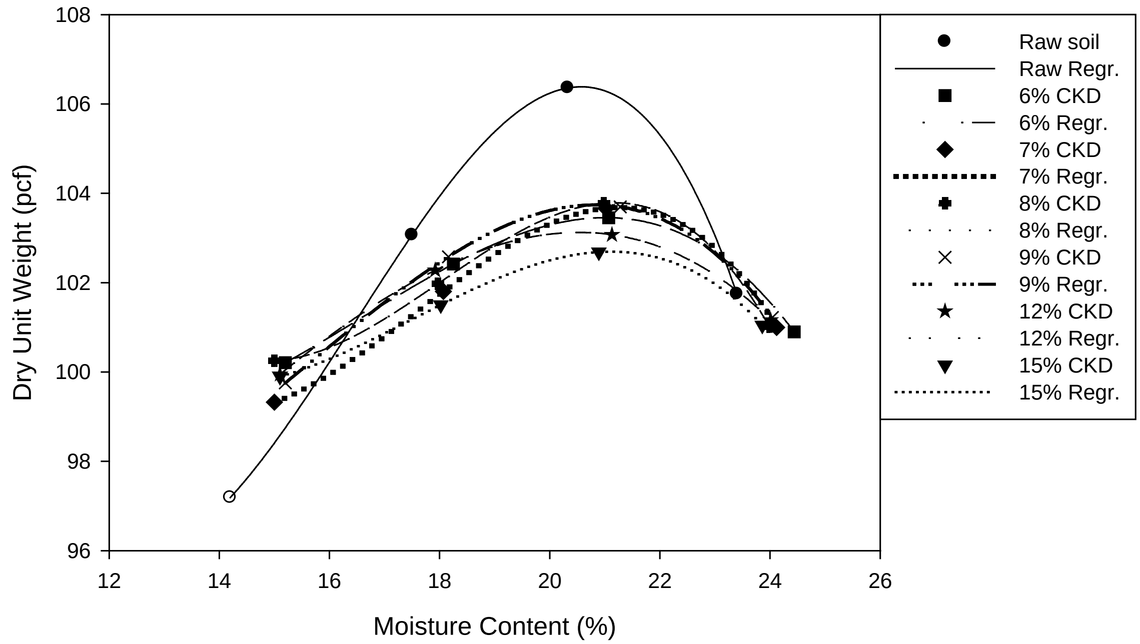

Figure A.20: Hollywood (A-7-6) OMC Curves with CKD

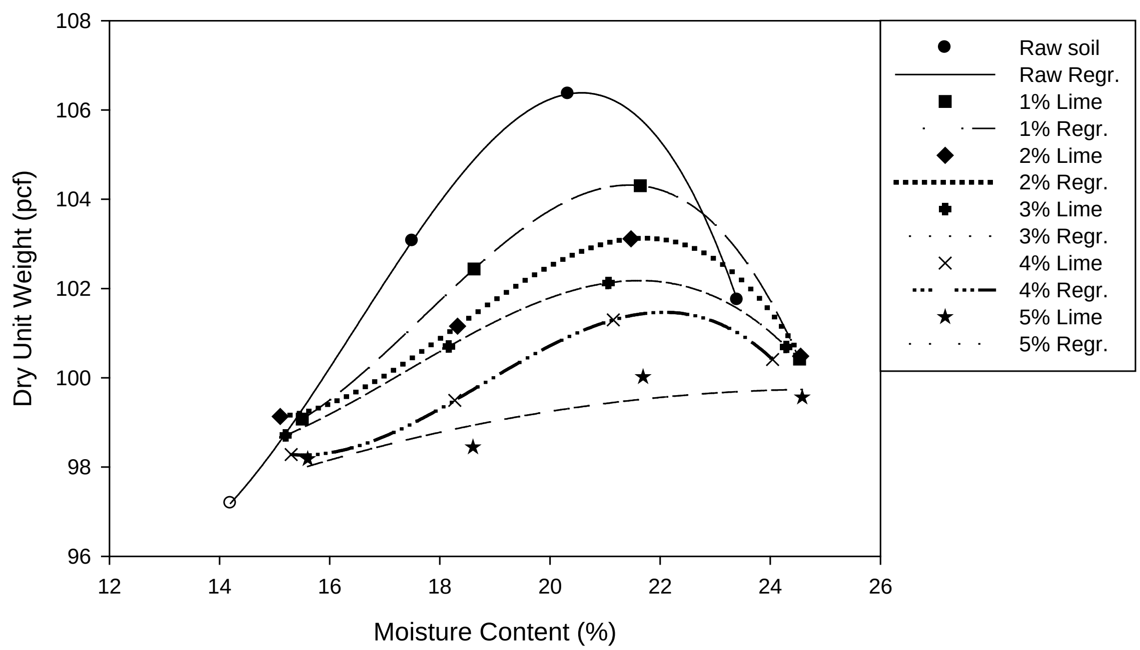

Figure A.21: Hollywood (A-7-6) OMC Curves with Lime

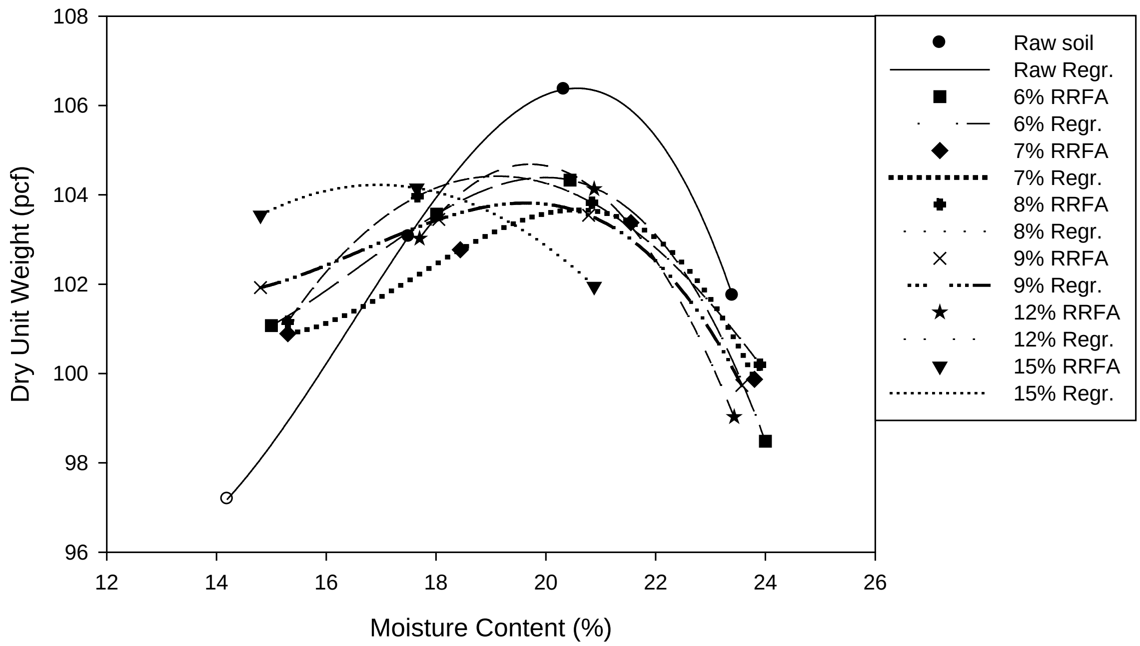

Figure A.22: Hollywood (A-7-6) OMC Curves with Red Rock FA

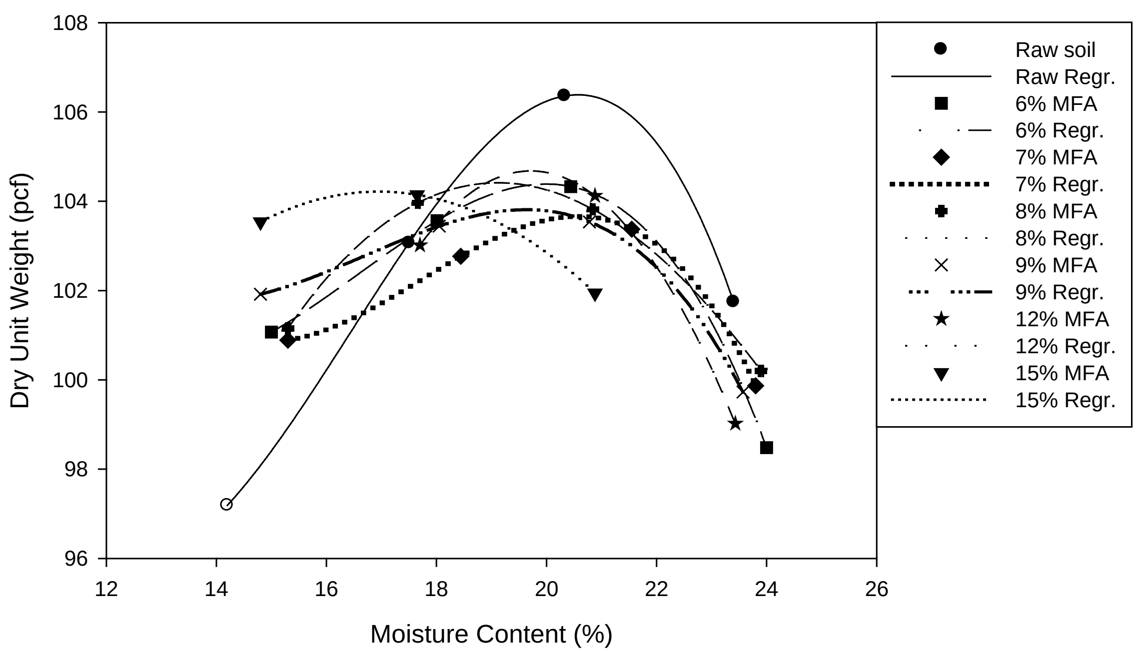

Figure A.23: Hollywood (A-7-6) OMC Curves with Muskogee FA

Table A-7: Hollywood (A-7-6) OMC and Dry Unit Weight Values

Additive Type	Additive Content	OMC (%)	Dry Unit Weight (pcf)
Raw soil	0%	20.60	105.40
Lime	1%	21.40	103.32
	2%	21.70	102.12
	3%	21.60	101.18
	4%	22.10	100.49
	5%	22.40	99.16
CKD	6%	21.00	102.50
	7%	21.30	102.69
	8%	21.20	102.82
	9%	20.80	102.75
	12%	20.50	102.12
	15%	21.10	101.68
Red Rock Fly Ash	6%	20.00	103.38
	7%	20.60	102.69
	8%	19.10	103.45
	9%	19.60	102.82
	12%	19.70	103.70
	15%	17.00	103.26
Muskogee Fly Ash	6%	20.00	103.38
	7%	20.60	102.69
	8%	19.10	103.45
	9%	19.60	102.82
	12%	19.70	103.70
	15%	17.00	103.26

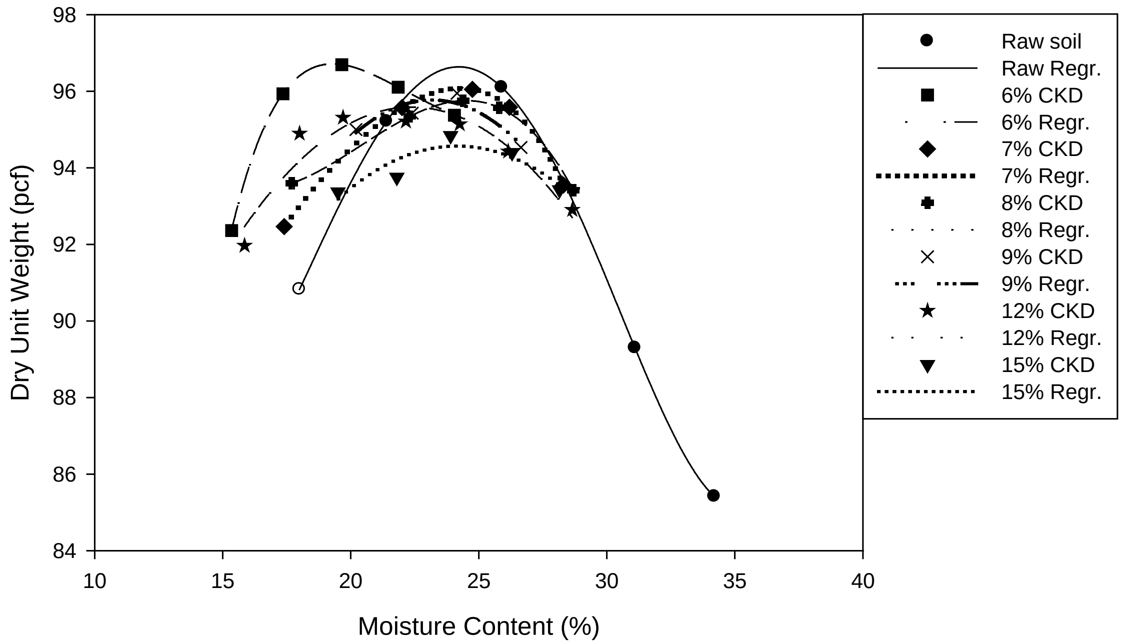

Figure A.24: Heiden (A-7-6) OMC Curves with CKD

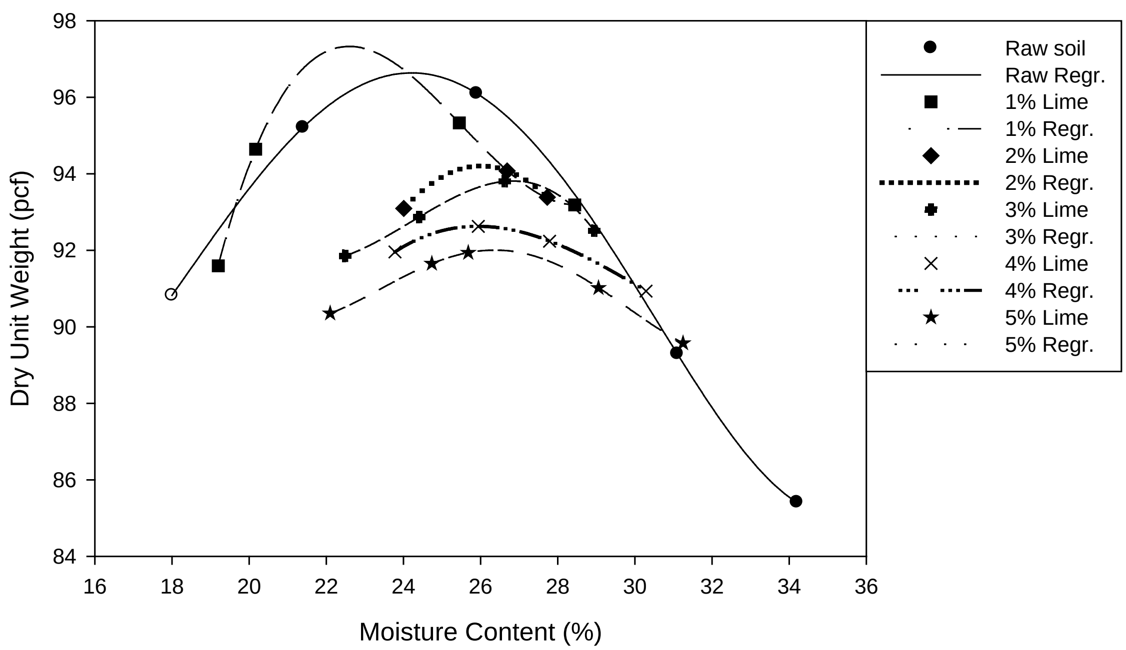

Figure A.25: Heiden (A-7-6) OMC Curves with Lime

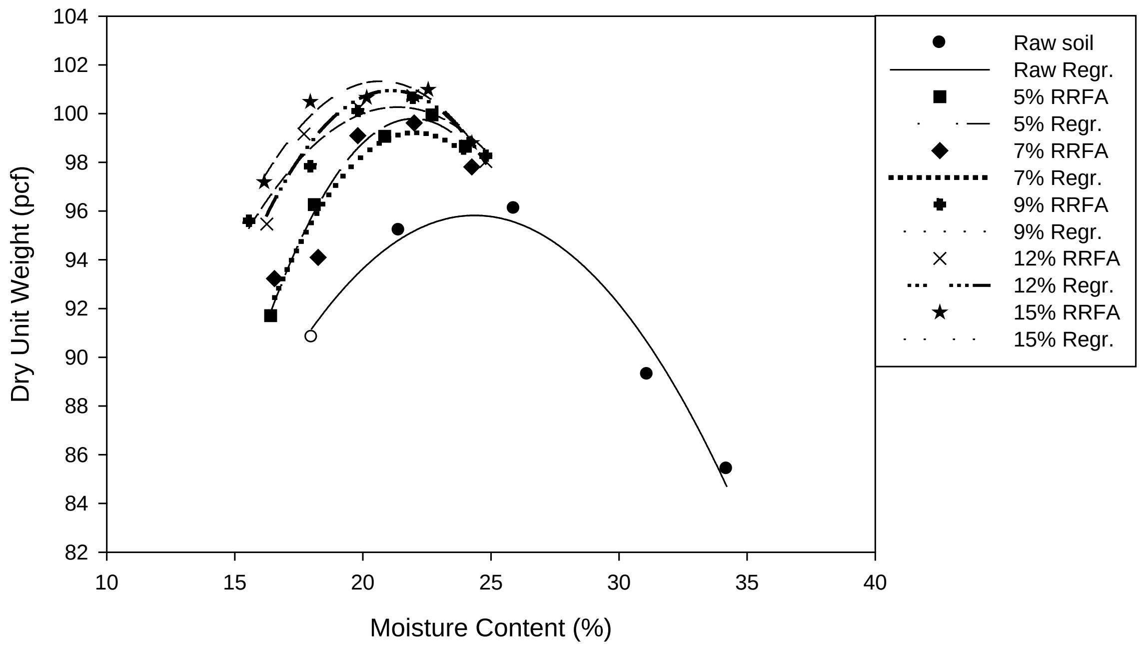

Figure A.26: Heiden (A-7-6) OMC Curves with Red Rock FA

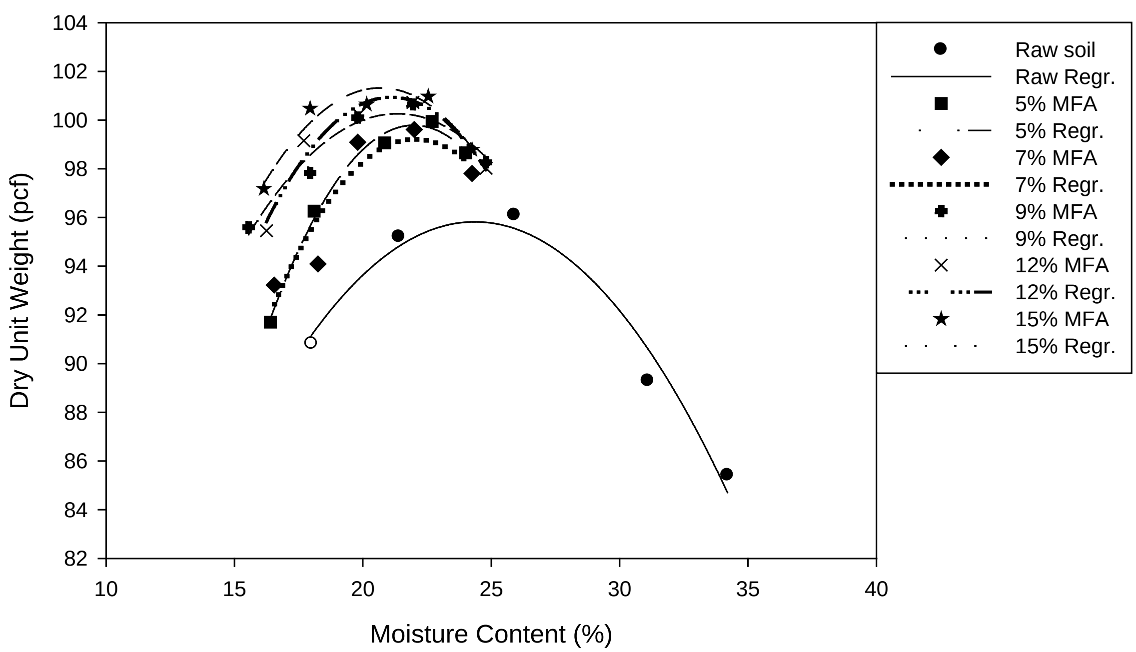

Figure A.27: Heiden (A-7-6) OMC Curves with Muskogee FA

Table A-8: Heiden (A-7-6) OMC and Dry Unit Weight Values

Additive Type	Additive Content	OMC (%)	Dry Unit Weight (pcf)
Raw soil	0%	24.20	97.65
Lime	1%	22.60	96.39
	2%	26.00	93.30
	3%	26.80	92.93
	4%	25.90	91.79
	5%	26.30	91.10
CKD	6%	19.60	95.82
	7%	24.20	95.19
	8%	24.50	94.88
	9%	24.20	95.07
	12%	20.50	94.44
	15%	24.00	94.00
Red Rock Fly Ash	5%	22.00	98.85
	6%	-	-
	7%	22.00	98.28
	8%	-	-
	9%	21.50	99.35
	12%	21.00	100.04
	15%	20.50	100.42
Muskogee Fly Ash	5%	22.00	98.85
	6%	-	-
	7%	22.00	98.28
	8%	-	-
	9%	24.20	97.65
	12%	22.60	96.39
	15%	26.00	93.30

Table A-9: UCS Values for All Soils

14 Days Cured Average Maximum Unconfined Compression Strength (psi)									
		A-4 Soils			A-6 Soils			A-7-6 Soils	
Additive Type	Additive Content	Devol	Minco	Stephenville	Ashport-Grainola	Kirkland-Pawhuska	Flower Pot	Hollywood	Heiden
Raw soil	0%	18.7	15.6	32.9	31.4	36.1	42.2	52.9	45.3
Lime	1%						46.2	52.1	85.6
	2%				100.1	189.5	71.2	83.6	150.2
	3%						93.1	117.8	240.8
	4%				93.4	215.9	103.4	121.8	221.5
	5%				94.9	195.0	119.5	113.5	209.8
CKD	6%						50.9	81.7	82.3
	7%				84.2	76.0	60.4	82.6	81.3
	8%	68.3	145.9	175.3			102.6	94.0	91.9
	9%				109.1	116.7	126.3	103.4	114.9
	10%	98.7	183.8	193.5					
	11%				125.8	134.9			
	12%	113.1	139.6	162.6			173.0	138.9	144.2
	15%						192.4	177.6	202.8
Red Rock Fly Ash	5%								97.9
	6%				132.7	116.8	99.4	77.3	
	7%				139.4	124.5	105.9	93.4	105.3
	8%				157.0	130.0	109.2	94.7	
	9%	12.9	31.1	87.8	148.9	141.2	117.0	105.4	110.6
	12%	33.3	37.4	91.2	192.0	188.1	143.6	123.1	134.6
	15%	47.6	30.2	57.0	224.8	191.5	147.6	140.5	139.2
Muskogee Fly Ash	5%								86.9
	6%				130.7	125.3	96.8	82.6	
	7%				143.1	127.5	104.8	84.7	104.9
	8%				155.8	137.4	109.0	89.3	
	9%				168.4	140.2	111.0	103.2	45.3
	12%				207.4	184.9	131.6	119.3	85.6
	15%				237.2	194.1	146.5	143.8	150.2

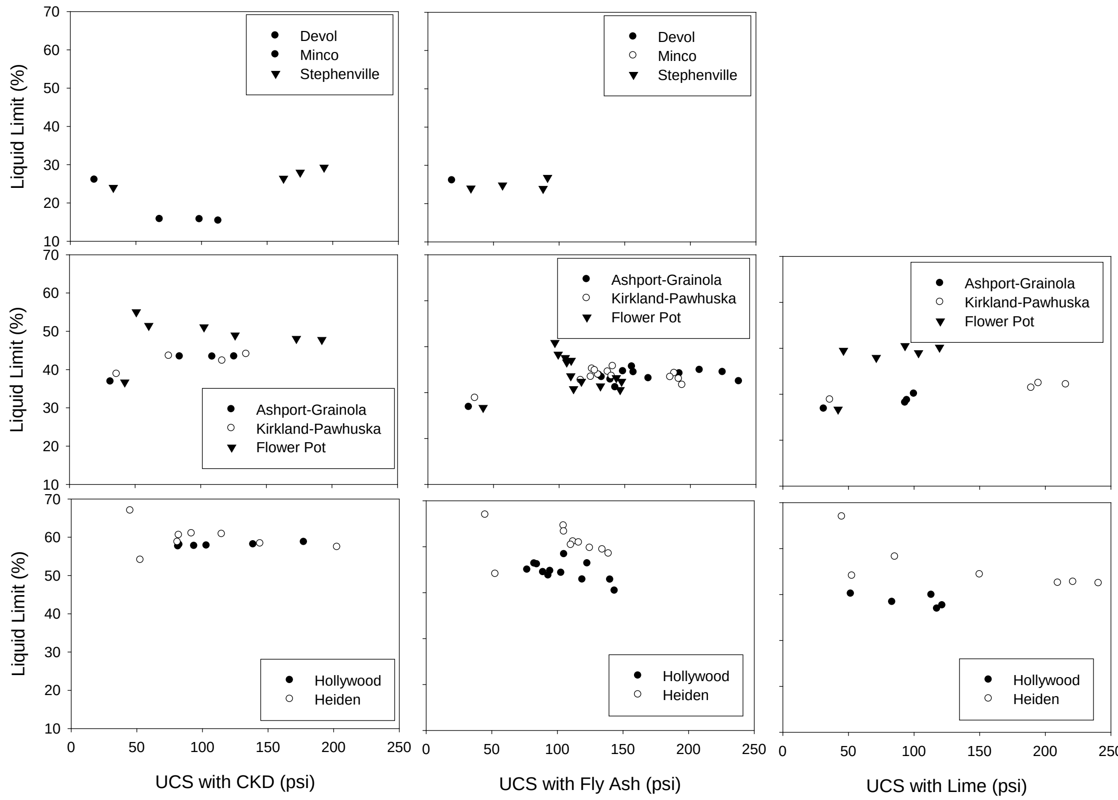

Figure A.28 - Liquid Limits (2-Hours) with CKD (Left), Fly Ash (Center), and Lime (Right) Soils

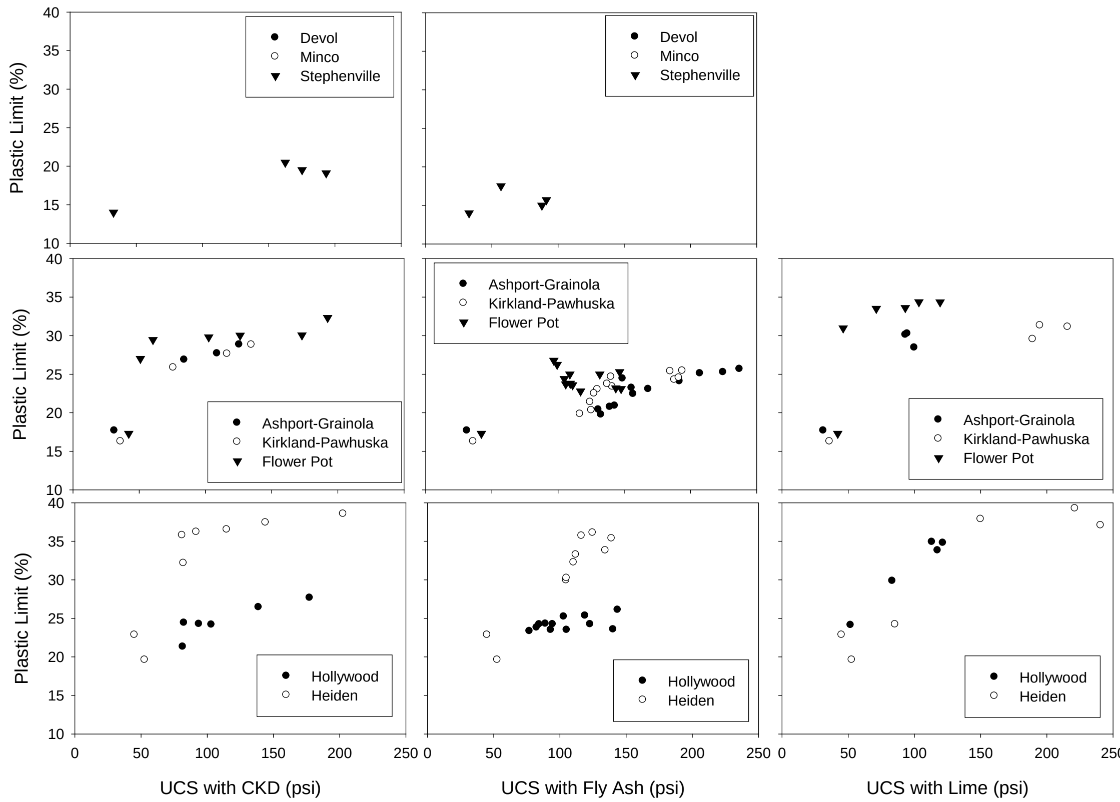

Figure A.29 – Plastic Limits (2-Hour) with CKD (Left), Fly Ash (Center), and Lime (Right) Soils

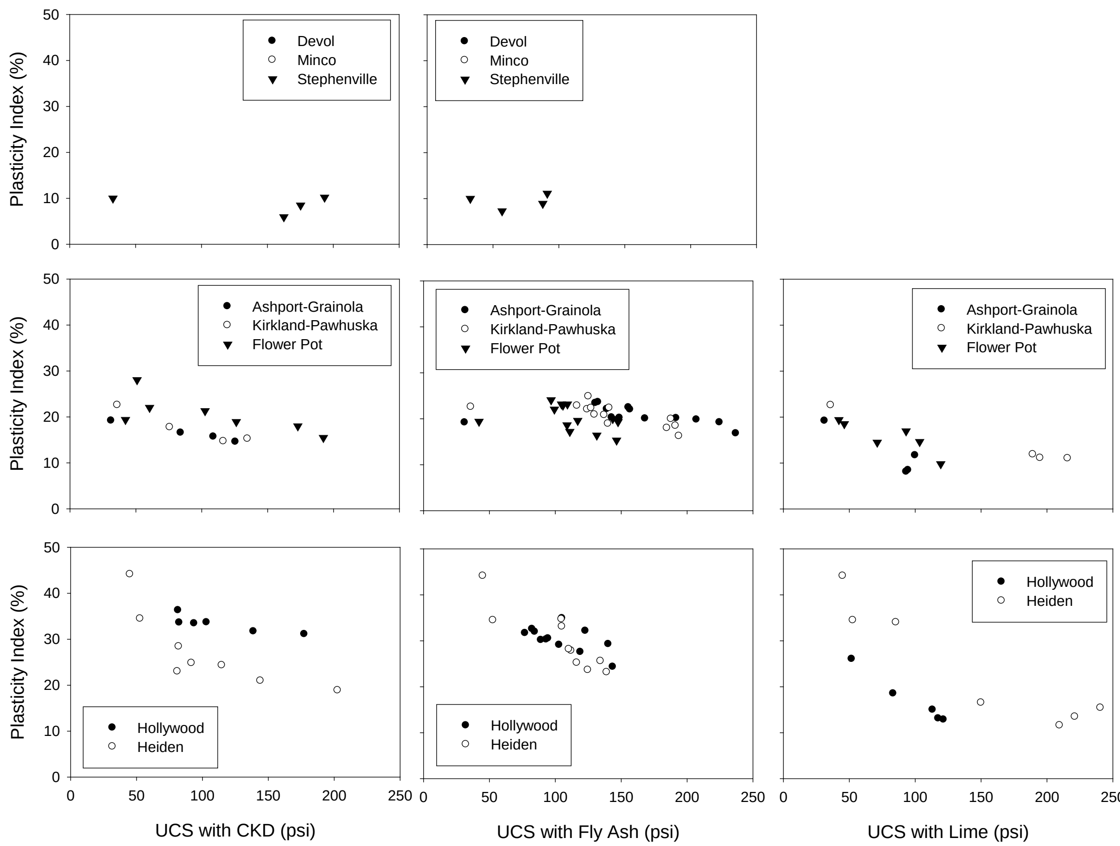

Figure A.30 – Plasticity Index (2-Hour) with CKD (Left), Fly Ash (Center), and Lime (Right) Soils

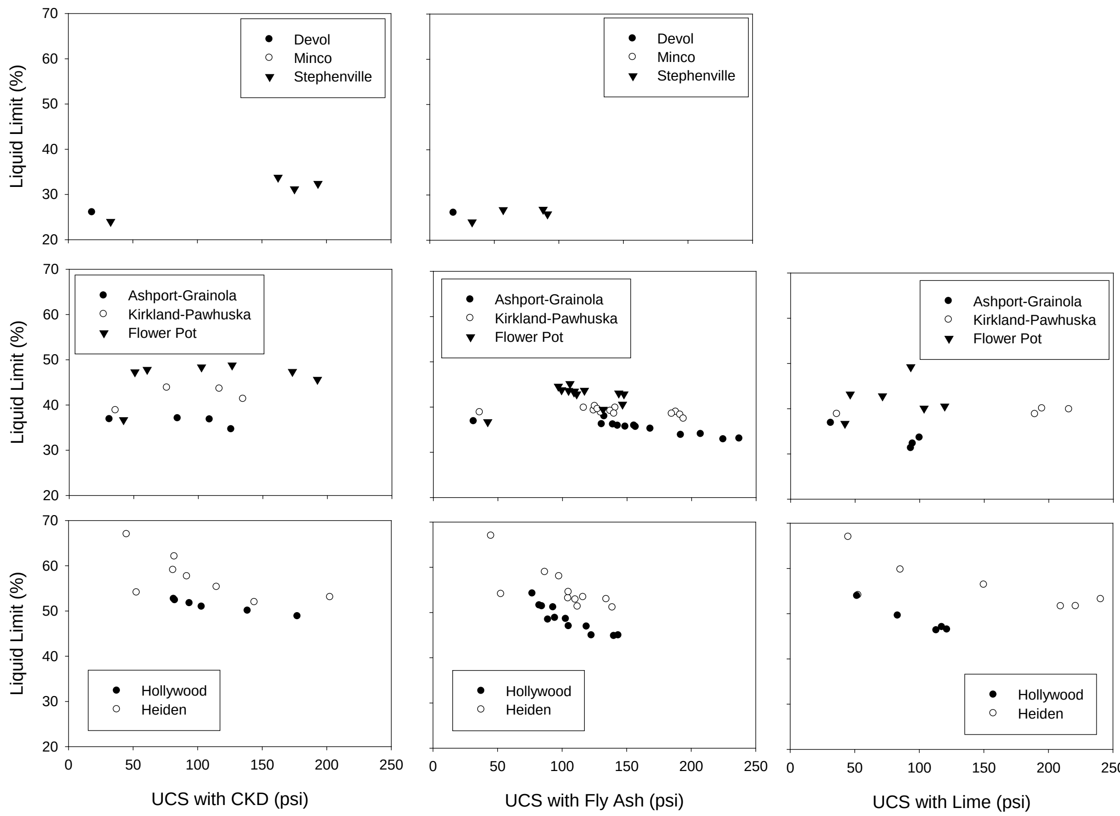

Figure A.31 - Liquid Limits (14 Day) with CKD (Left), Fly Ash (Center), and Lime (Right) Soils

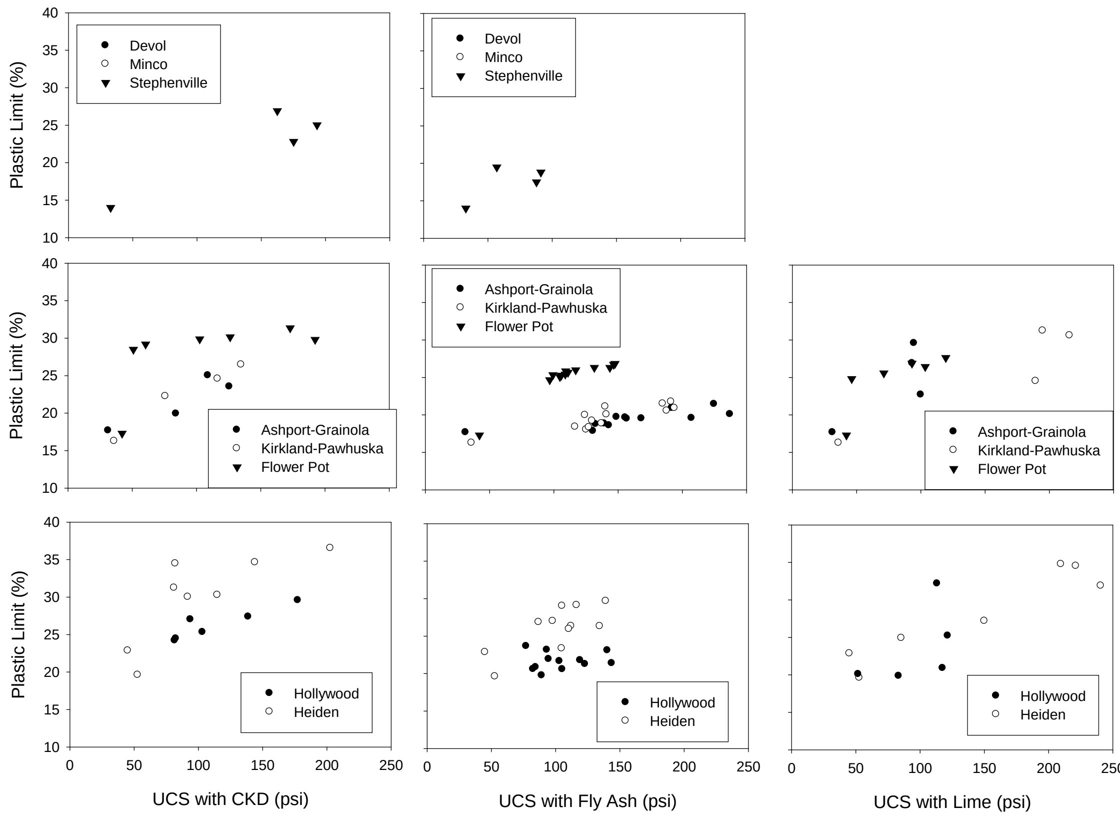

Figure A.32 – Plastic Limits (14 Day) with CKD (Left), Fly Ash (Center), and Lime (Right) Soils

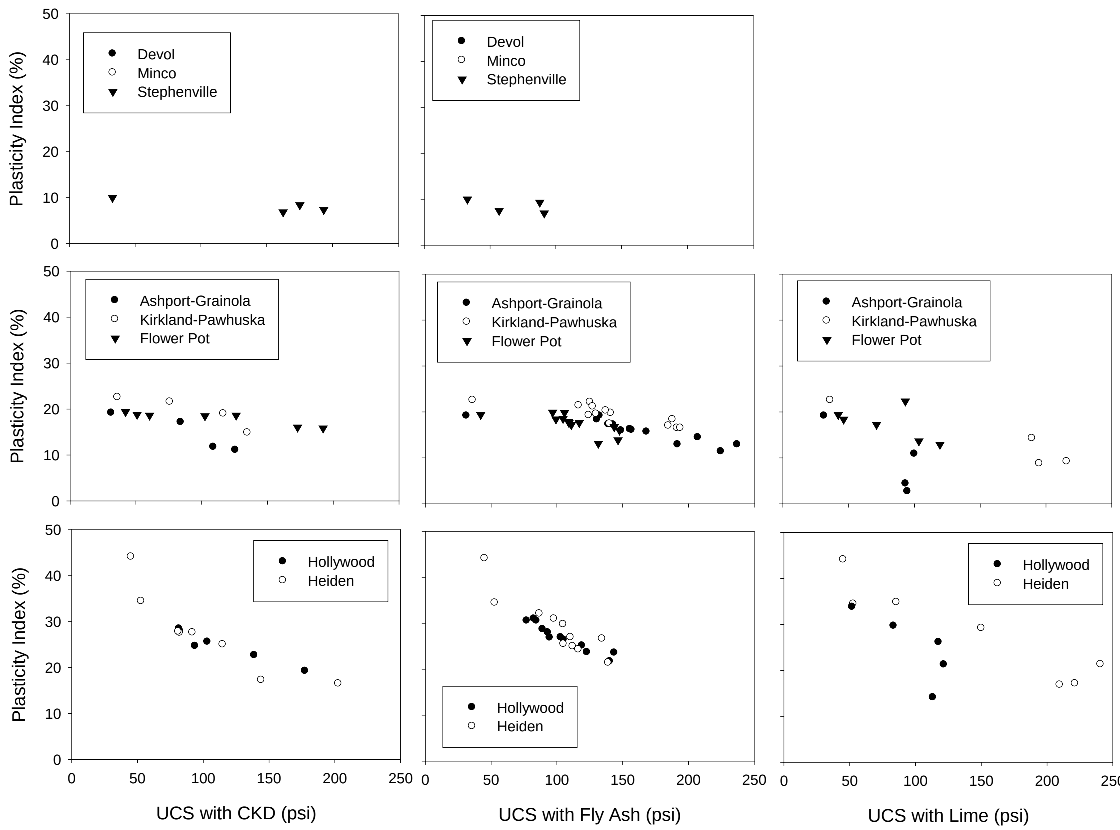

Figure A.33 – Plasticity Index (14 Day) with CKD (Left), Fly Ash (Center), and Lime (Right) Soils

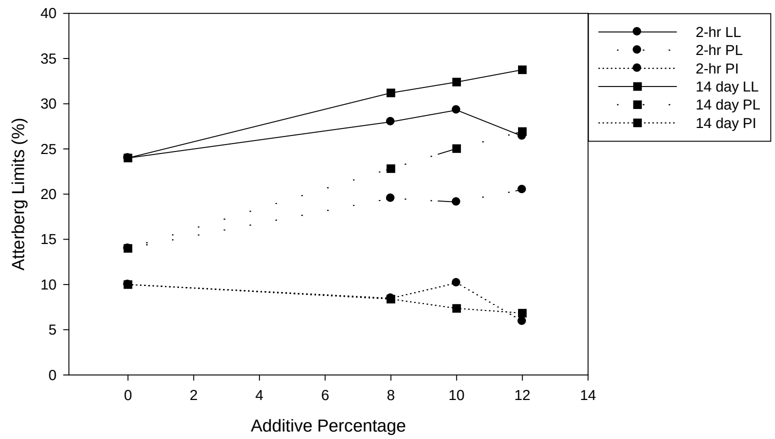

Figure A.34: Stephenville (A-4) Atterberg Limits with CKD

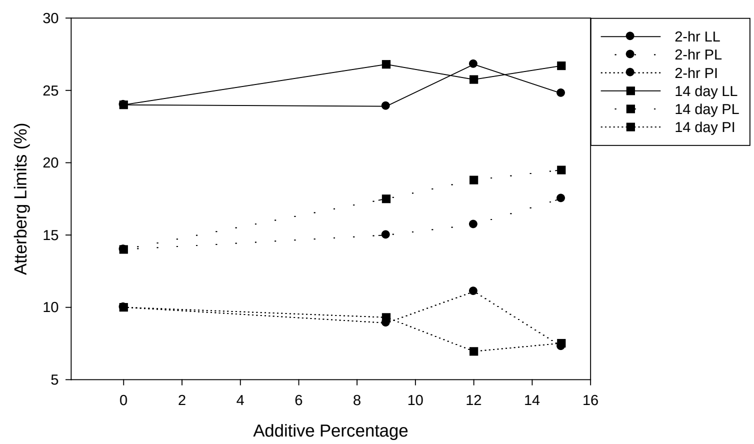

Figure A.35: Stephenville (A-4) Atterberg Limits with Red Rock FA

Table A-10: Minco (A-4) Atterberg Limits

		2-Hour Curing Time			14 Days Curing Time		
Additive Type	Additive Percentage	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
Raw soil	0%	NP	NP	NP			
CKD	8%	NP	NP	NP	NP	NP	NP
	10%	NP	NP	NP	NP	NP	NP
	12%	NP	NP	NP	NP	NP	NP
Red Rock Fly Ash	9%	NP	NP	NP	NP	NP	NP
	12%	NP	NP	NP	NP	NP	NP
	15%	NP	NP	NP	NP	NP	NP

Table A-11: Stephenville (A-4) Atterberg Limits

		2-Hour Curing Time			14 Days Curing Time		
Additive Type	Additive Percentage	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
Raw soil	0%	24.0	14.0	10.0			
CKD	8%	28.0	19.5	8.5	31.2	22.8	8.4
	10%	29.3	19.1	10.2	32.4	25.0	7.4
	12%	26.4	20.5	5.9	33.8	26.8	6.8
Red Rock Fly Ash	9%	23.9	15.0	8.9	26.8	17.5	9.3
	12%	26.8	15.7	11.1	25.8	18.8	7.0
	15%	24.8	17.5	7.3	26.7	19.5	7.5

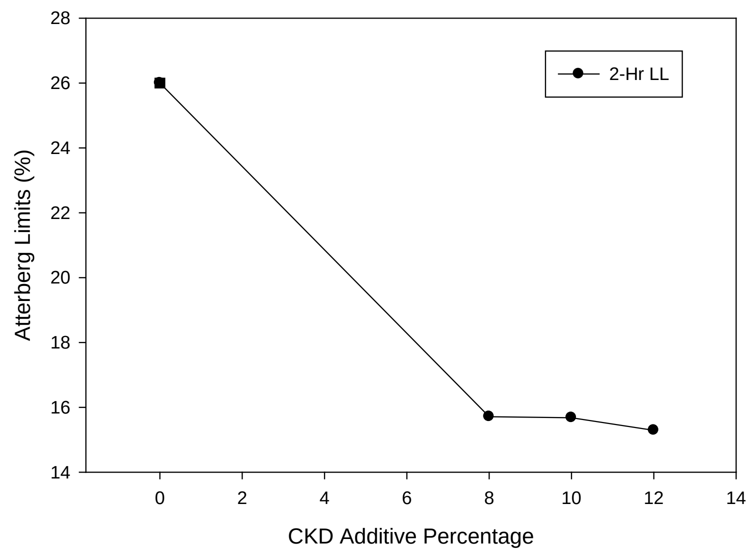

Figure A.36: Devol (A-4) Atterberg Limits with CKD

Table A-12: Devol (A-4) Atterberg Limits

		2-hour Curing Time			14 Days Curing Time		
Additive Type	Additive Percentage	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
Raw soil	0%	26.0	NP	NP			
CKD	8%	15.7	NP	NP	NP	NP	NP
	10%	15.7	NP	NP	NP	NP	NP
	12%	15.3	NP	NP	NP	NP	NP
Red Rock Fly Ash	9%	NP	NP	NP	NP	NP	NP
	12%	NP	NP	NP	NP	NP	NP
	15%	NP	NP	NP	NP	NP	NP

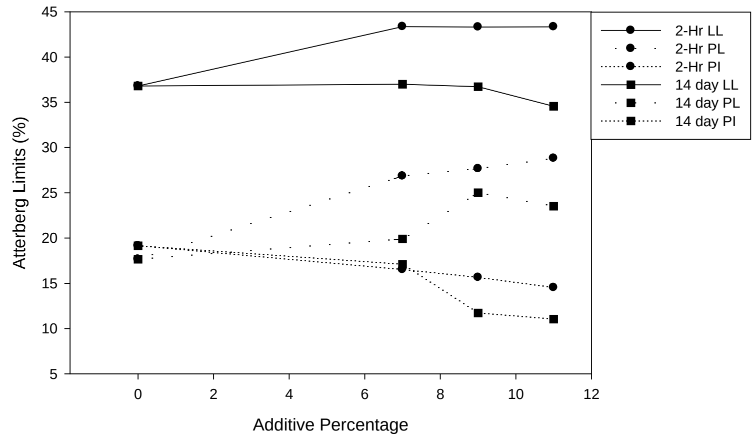

Figure A.37: Ashport-Grainola (A-6) Atterberg Limits with CKD

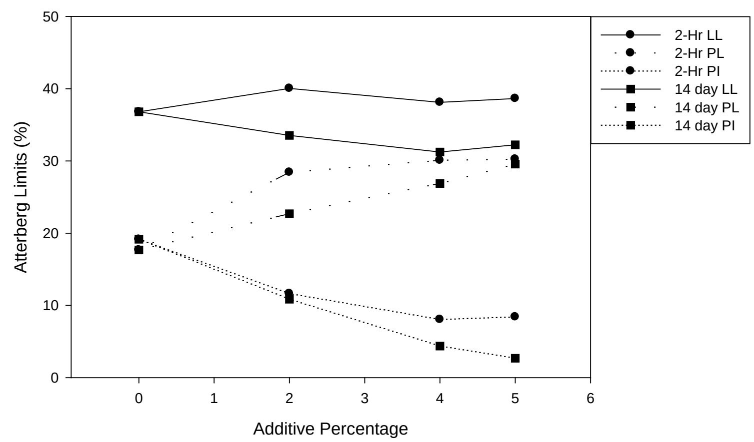

Figure A.38: Ashport-Grainola (A-6) Atterberg Limits with Lime

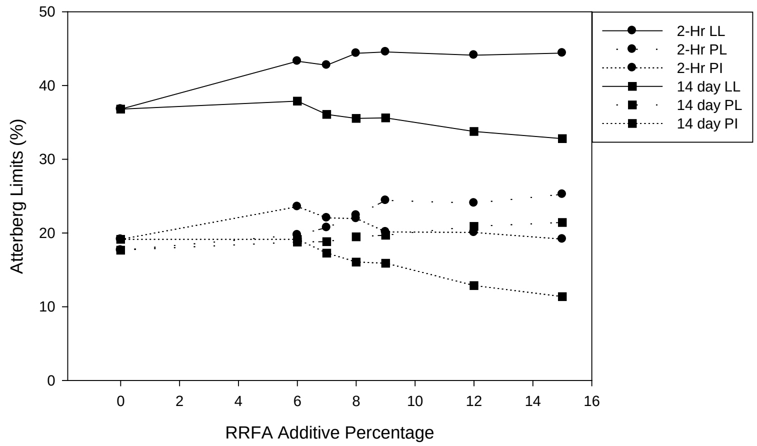

Figure A.39: Ashport-Grainola (A-6) Atterberg Limits with Red Rock FA

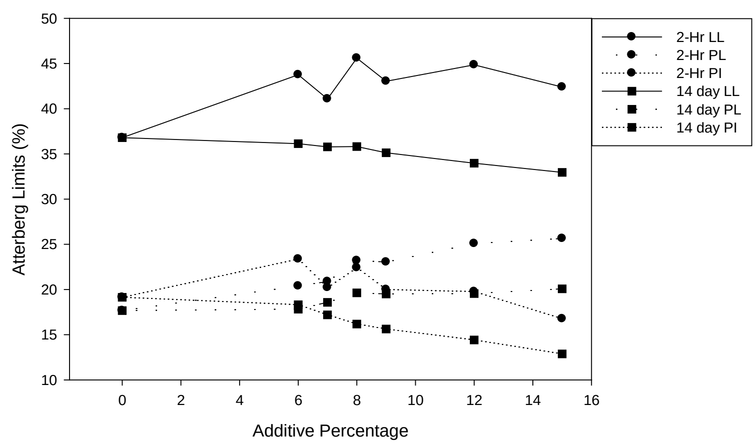

Figure A.40: Ashport-Grainola (A-6) Atterberg Limits with Muskogee FA

Table A-13: Ashport-Grainola (A-6) Atterberg Limits

		2-hour Curing Time			14 Days Curing Time		
Additive Type	Additive Content	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquid Limit (%)	Plastic Index (%)	Plasticity Index (%)
Raw soil	0%	36.8	17.7	19.1			
Lime	2%	40.0	28.4	11.6	33.5	22.7	10.8
	4%	38.1	30.1	8.0	31.2	26.9	4.3
	5%	38.6	30.2	8.4	32.2	29.6	2.6
CKD	7%	43.4	26.9	16.5	37.0	19.9	17.1
	9%	43.3	27.7	15.6	36.7	25.0	11.7
	11%	43.3	28.8	14.5	34.6	23.5	11.1
Red Rock Fly Ash	6%	43.3	19.7	23.6	37.9	18.8	19.1
	7%	42.7	20.7	22.0	36.1	18.8	17.3
	8%	44.4	22.4	22.0	35.5	19.5	16.0
	9%	44.5	24.4	20.1	35.6	19.7	15.9
	12%	44.1	24.1	20.0	33.8	20.9	12.9
	15%	44.4	25.2	19.2	32.8	21.4	11.4
Muskogee Fly Ash	6%	43.8	20.4	23.4	36.1	17.8	18.3
	7%	41.1	20.9	20.2	35.8	18.6	17.2
	8%	45.6	23.2	22.4	35.8	19.6	16.2
	9%	43.0	23.0	20.0	35.1	19.5	15.6
	12%	44.9	25.1	19.8	34.0	19.6	14.4
	15%	42.4	25.6	16.8	33.0	20.1	12.9

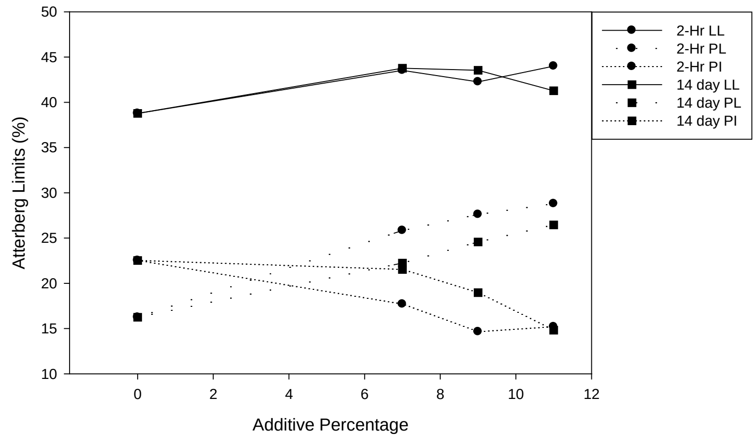

Figure A.41: Kirkland-Pawhuska (A-6) Atterberg Limits with CKD

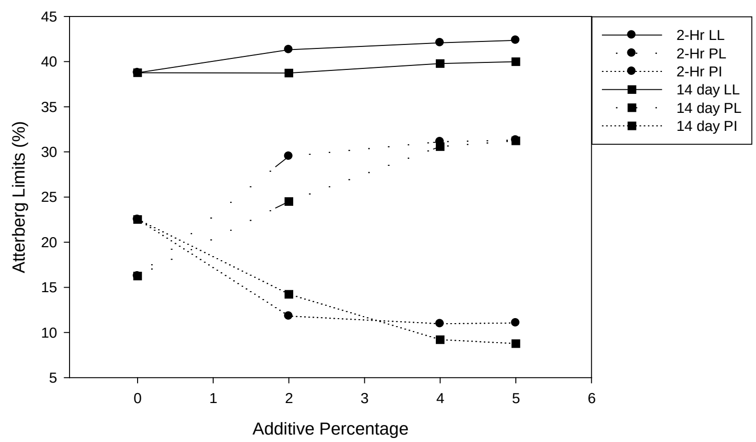

Figure A.42: Kirkland-Pawhuska (A-6) Atterberg Limits with Lime

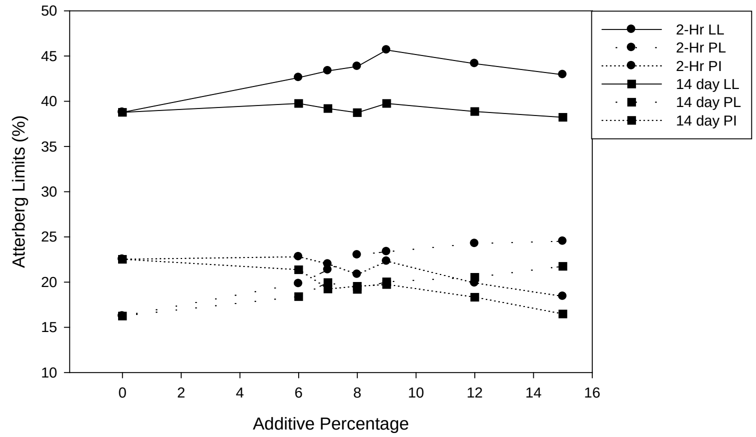

Figure A.43: Kirkland-Pawhuska (A-6) Atterberg Limits with Red Rock FA

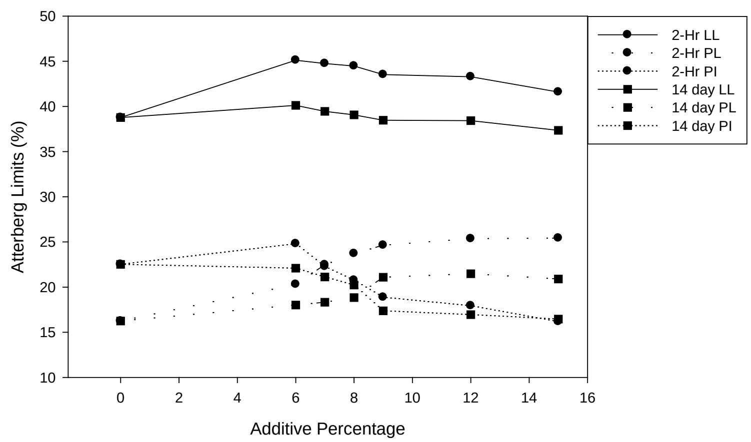

Figure A.44: Kirkland-Pawhuska (A-6) Atterberg Limits with Muskogee FA

Table A-14: Kirkland-Pawhuska (A-6) Atterberg Limits

		2-hour Curing Time			14 Days Curing Time		
Additive Type	Additive Content	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquid Limit (%)	Plastic Index (%)	Plasticity Index (%)
Raw soil	0%	38.8	16.3	22.5			
Lime	2%	41.3	29.5	11.8	38.7	24.5	14.2
	4%	42.1	31.1	11.0	39.8	30.6	9.2
	5%	42.3	31.3	11.0	40.0	31.2	8.8
CKD	7%	43.5	25.8	17.7	43.8	22.2	21.5
	9%	42.3	27.6	14.7	43.5	24.6	18.9
	11%	44.0	28.8	15.2	41.3	26.5	14.8
Red Rock Fly Ash	6%	42.6	19.8	22.8	39.8	18.4	21.4
	7%	43.4	21.4	22.0	39.2	20.0	19.2
	8%	43.8	23.0	20.8	38.7	19.2	19.5
	9%	45.7	23.4	22.3	39.8	20.0	19.7
	12%	44.2	24.3	19.9	38.9	20.5	18.3
	15%	42.9	24.5	18.4	38.2	21.7	16.5
Muskogee Fly Ash	6%	45.1	20.3	24.8	40.1	18.0	22.1
	7%	44.8	22.5	22.3	39.5	18.3	21.1
	8%	44.5	23.7	20.8	39.1	18.8	20.2
	9%	43.5	24.6	18.9	38.5	21.1	17.4
	12%	43.3	25.4	17.9	38.4	21.5	16.9
	15%	41.6	25.4	16.2	37.4	20.9	16.5

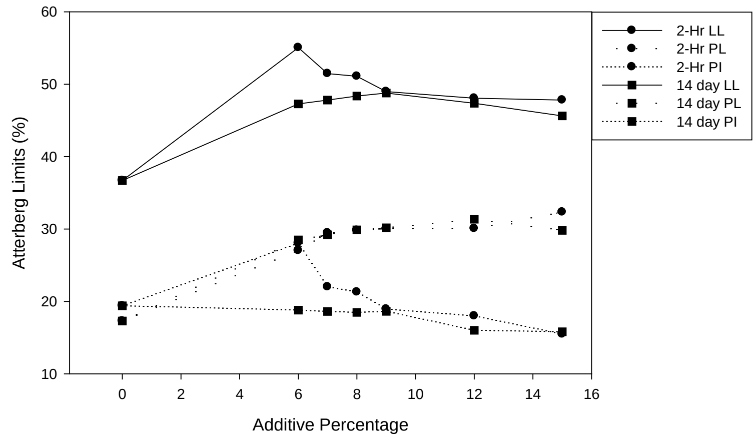

Figure A.45: Flower Pot (A-6) Atterberg Limits with CKD

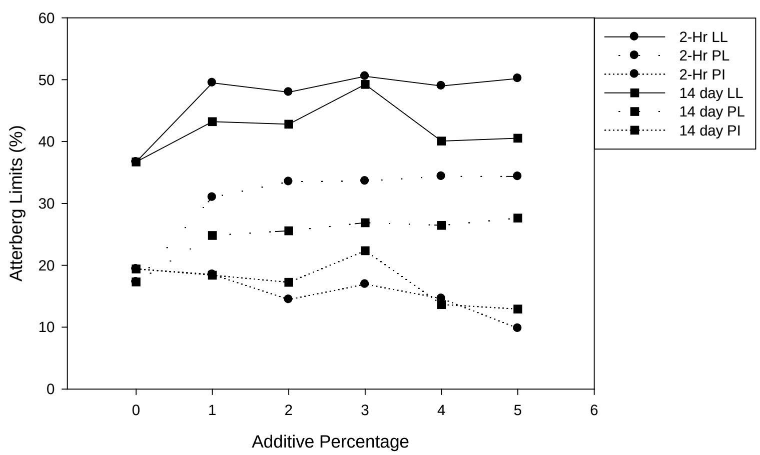

Figure A.46: Flower Pot (A-6) Atterberg Limits with Lime

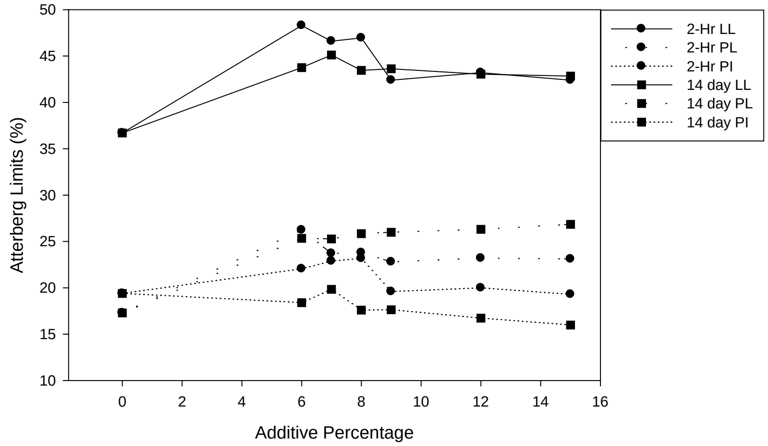

Figure A.47: Flower Pot (A-6) Atterberg Limits with Red Rock FA

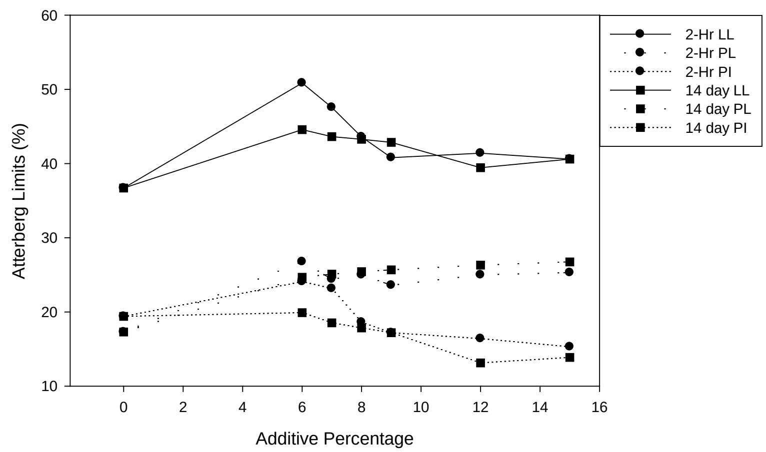

Figure A.48: Flower Pot (A-6) Atterberg Limits with Muskogee FA

Table A-15: Flower Pot (A-6) Atterberg Limits

		2-hour Curing Time			14 Days Curing Time		
Additive Type	Additive Content	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquid Limit (%)	Plastic Index (%)	Plasticity Index (%)
Raw soil	0%	36.7	17.3	19.4			
Lime	1%	49.5	31.0	18.5	43.2	24.8	18.4
	2%	48.0	33.5	14.5	42.8	25.6	17.2
	3%	50.5	33.6	16.9	49.2	26.9	22.3
	4%	49.0	34.4	14.6	40.1	26.4	13.6
	5%	50.2	34.4	9.8	40.5	27.6	12.9
CKD	6%	55.1	27.0	28.0	47.3	28.5	18.8
	7%	51.5	29.5	22.0	47.8	29.2	18.6
	8%	51.1	29.8	21.3	48.4	29.9	18.5
	9%	49.0	30.0	18.9	48.8	30.2	18.6
	12%	48.1	30.1	18.0	47.4	31.4	16.0
	15%	47.8	32.3	15.5	45.6	29.8	15.8
Red Rock Fly Ash	6%	48.3	26.2	22.1	43.8	25.3	18.4
	7%	46.6	23.7	22.9	45.1	25.3	19.8
	8%	47.0	23.8	23.2	43.5	25.9	17.6
	9%	42.4	22.8	19.6	43.6	26.0	17.6
	12%	43.2	23.2	20.0	43.1	26.3	16.7
	15%	42.4	23.1	19.3	42.8	26.8	16.0
Muskogee Fly Ash	6%	50.9	26.8	24.1	44.6	24.7	19.9
	7%	47.6	24.4	23.2	43.6	25.1	18.5
	8%	43.6	25.0	18.6	43.3	25.4	17.8
	9%	40.8	23.6	17.2	42.9	25.7	17.2
	12%	41.4	25.0	16.4	39.4	26.3	13.1
	15%	40.6	25.3	15.3	40.6	26.7	13.9

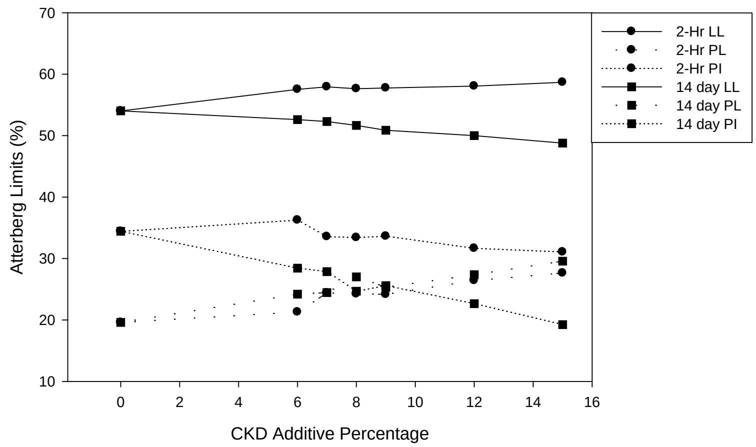

Figure A.49: Hollywood (A-7-6) Atterberg Limits with CKD

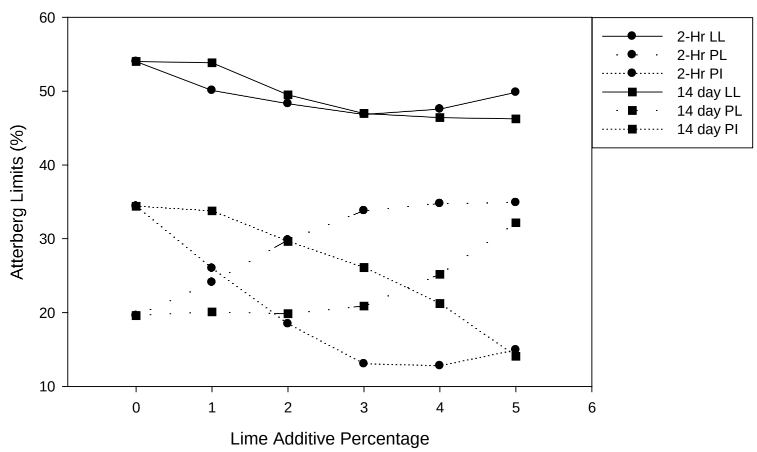

Figure A.50: Hollywood (A-7-6) Atterberg Limits with Lime

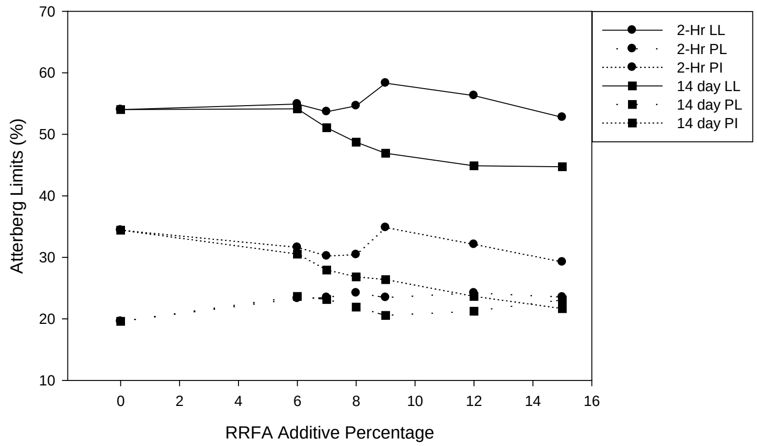

Figure A.51: Hollywood (A-7-6) Atterberg Limits with Red Rock FA

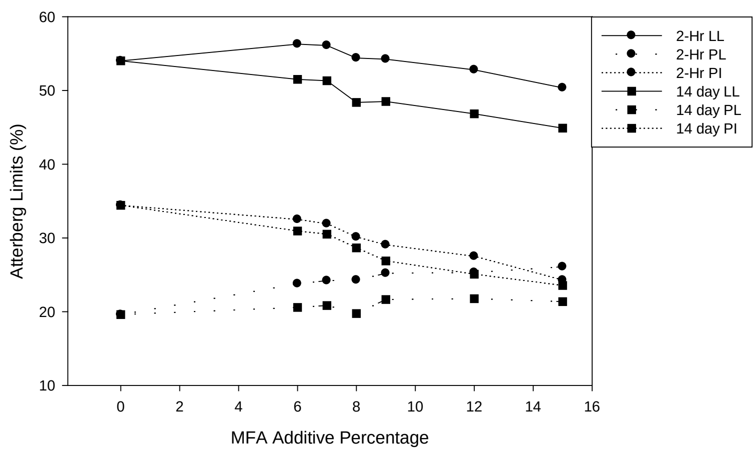

Figure A.52: Hollywood (A-7-6) Atterberg Limits with Muskogee FA

Table A-16: Hollywood (A-7-6) Atterberg Limits

		2-hour Curing Time			14 Days Curing Time		
Additive Type	Additive Content	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquid Limit (%)	Plastic Index (%)	Plasticity Index (%)
Raw soil	0%	54.0	19.6	34.4			
Lime	1%	50.1	24.1	26.0	53.8	20.1	33.7
	2%	48.3	29.8	18.5	49.5	19.8	29.7
	3%	46.8	33.8	13.0	47.0	20.9	26.1
	4%	47.6	34.8	12.8	46.4	25.2	21.2
	5%	49.8	34.9	14.9	46.2	32.1	14.1
CKD	6%	57.5	21.3	36.2	52.6	24.2	28.4
	7%	57.9	24.4	33.5	52.3	24.5	27.8
	8%	57.6	24.2	33.4	51.7	27.0	24.7
	9%	57.8	24.2	33.6	50.9	25.3	25.6
	12%	58.1	26.4	31.7	50.0	27.4	22.6
	15%	58.7	27.6	31.1	48.8	29.6	19.2
Red Rock Fly Ash	6%	54.9	23.3	31.6	54.1	23.6	30.5
	7%	53.7	23.5	30.2	51.1	23.1	27.9
	8%	54.6	24.2	30.4	48.7	21.9	26.8
	9%	58.3	23.5	34.8	46.9	20.6	26.3
	12%	56.3	24.2	32.1	44.9	21.2	23.6
	15%	52.8	23.5	29.3	44.7	23.1	21.6
Muskogee Fly Ash	6%	56.3	23.8	32.5	51.5	20.6	30.9
	7%	56.1	24.2	31.9	51.3	20.8	30.5
	8%	54.4	24.3	30.1	48.4	19.7	28.6
	9%	54.2	25.2	29.0	48.5	21.6	26.9
	12%	52.8	25.3	27.5	46.8	21.7	25.1
	15%	50.4	26.1	24.3	44.9	21.4	23.5

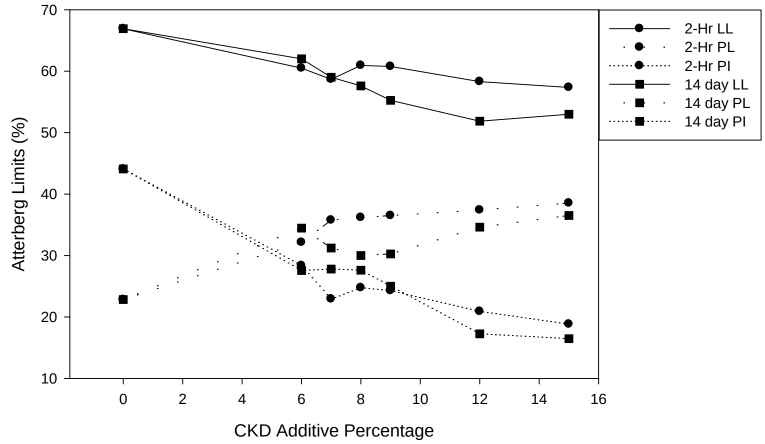

Figure A.53: Heiden (A-7-6) Atterberg Limits with CKD

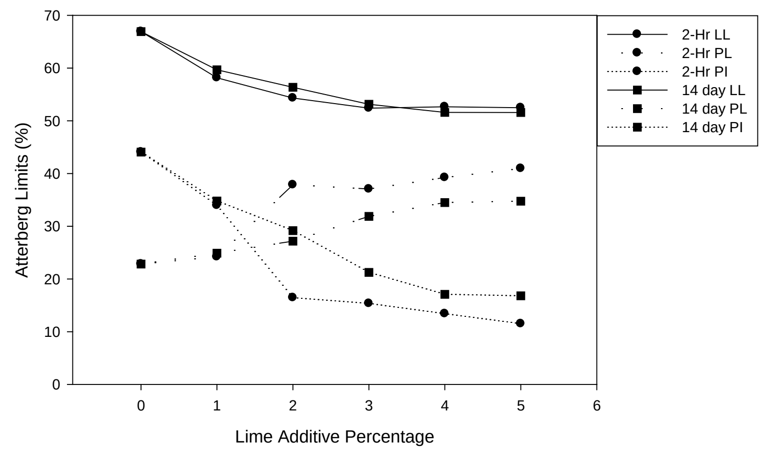

Figure A.54: Heiden (A-7-6) Atterberg Limits with Lime

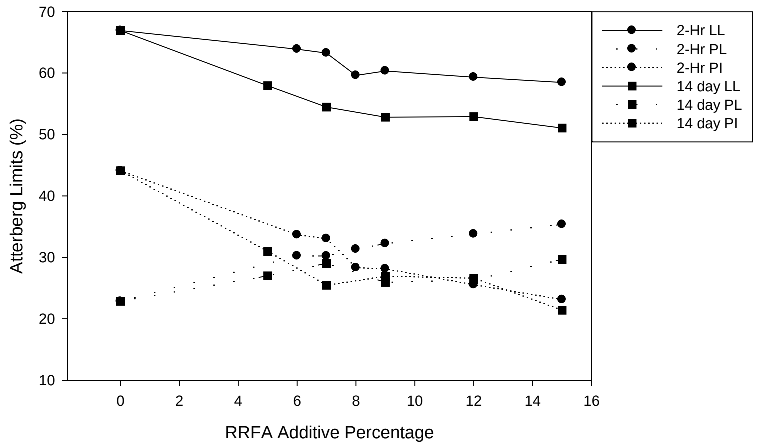

Figure A.55: Heiden (A-7-6) Atterberg Limits with Red Rock FA

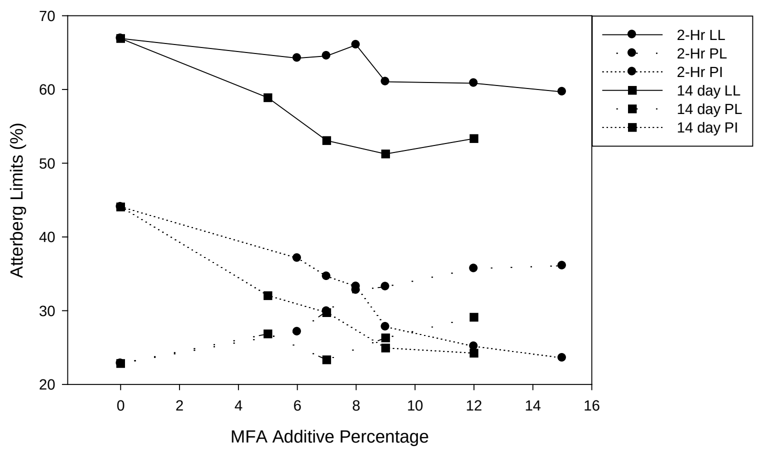

Figure A.56: Heiden (A-7-6) Atterberg Limits with Muskogee FA

Table A-17: Heiden (A-7-6) Atterberg Limits

		2-hour Curing Time			14 Days Curing Time		
Additive Type	Additive Content	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquid Limit (%)	Plastic Index (%)	Plasticity Index (%)
Raw soil	0%	66.9	22.8	44.1			
Lime	1%	58.2	24.2	34.0	59.7	24.9	34.8
	2%	54.3	37.8	16.5	56.3	27.2	29.1
	3%	52.4	37.0	15.4	53.1	31.9	21.2
	4%	52.7	39.2	13.5	51.6	34.5	17.1
	5%	52.5	41.0	11.5	51.6	34.8	16.8
CKD	6%	60.5	32.1	28.4	62.0	34.5	27.5
	7%	58.7	35.8	22.9	59.0	31.2	27.8
	8%	60.9	36.2	24.7	57.6	30.0	27.6
	9%	60.8	36.5	24.3	55.3	30.3	25.0
	12%	58.3	37.4	20.9	51.9	34.6	17.3
	15%	57.4	38.5	18.9	53.0	36.5	16.5
Red Rock Fly Ash	5%	-	-	-	57.9	27.0	30.9
	6%	63.9	30.2	33.7	-	-	-
	7%	63.2	30.2	33.0	54.4	29.0	25.4
	8%	59.6	31.3	28.3	-	-	-
	9%	60.3	32.2	28.1	52.8	25.9	26.9
	12%	59.3	33.8	25.5	52.9	26.3	26.6
	15%	58.5	35.4	23.1	51.0	29.7	21.3
Muskogee Fly Ash	5%	-	-	-	58.9	26.9	32.0
	6%	64.2	27.1	37.1	-	-	-
	7%	64.5	29.9	34.6	53.1	23.3	29.8
	8%	66.0	32.8	33.2	-	-	-
	9%	61.0	33.2	27.8	51.3	26.4	24.9
	12%	60.8	35.7	25.1	53.3	29.1	24.2
	15%	59.7	36.1	23.6	-	-	-

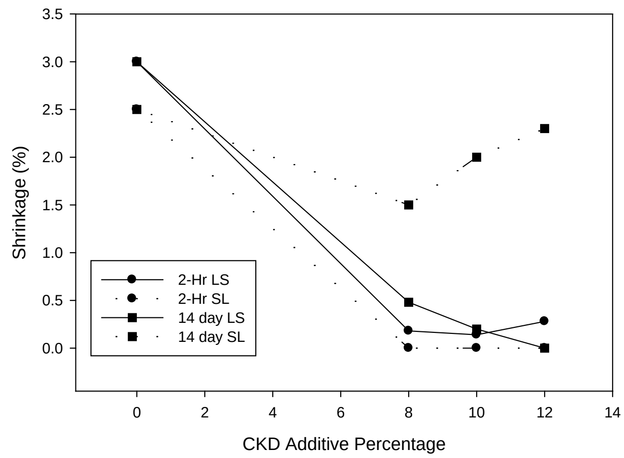

Figure A.57: Devol (A-4) Shrinkage Curves with CKD

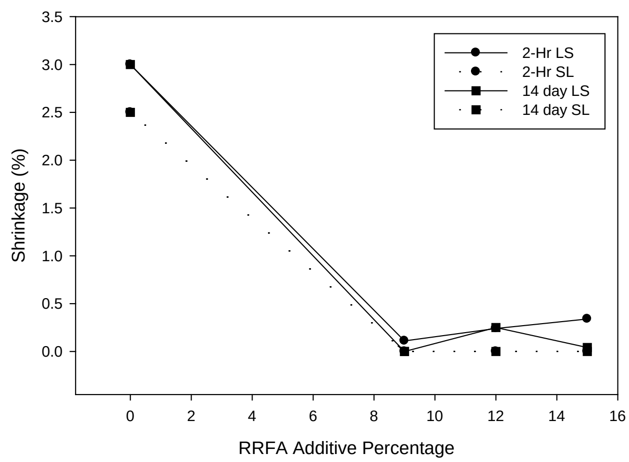

Figure A.58: Devol (A-4) Shrinkage Curves with Red Rock FA

Table A-18: Devol (A-4) Shrinkage Values

		2-hour Curing Time		14 Days Curing Time	
Additive Type	Additive Percentage	Linear Shrinkage (%)	Shrinkage Limit (%)	Linear Shrinkage (%)	Shrinkage Limit (%)
Raw soil	0%	3.00	2.50		
CKD	8%	0.18	0.00	0.48	1.50
	10%	0.14	0.00	0.20	2.00
	12%	0.28	0.00	0.00	2.30
Red Rock Fly Ash	9%	0.11	0.00	0.00	0.00
	12%	0.24	0.00	0.25	0.00
	15%	0.34	0.00	0.04	0.00

Table A-19: Minco (A-4) Shrinkage Values

		2 Hour Curing Time		14 Days Curing Time	
Additive Type	Additive Percentage	Linear Shrinkage (%)	Shrinkage Limit (%)	Linear Shrinkage (%)	Shrinkage Limit (%)
Raw soil	0%	2.04	4.50		
CKD	8%	-	-	-	-
	10%	-	-	-	-
	12%	-	-	-	-
Red Rock Fly Ash	9%	-	-	-	-
	12%	-	-	-	-
	15%	-	-	-	-

Table A-20: Stephenville (A-4) Shrinkage Values

		2-hour Curing Time		14 Days Curing Time	
Additive Type	Additive Percentage	Linear Shrinkage (%)	Shrinkage Limit (%)	Linear Shrinkage (%)	Shrinkage Limit (%)
Raw soil	0%	9.02	9.50		
CKD	8%	-	-	-	-
	10%	-	-	-	-
	12%	-	-	-	-
Red Rock Fly Ash	9%	-	-	-	-
	12%	-	-	-	-
	15%	-	-	-	-

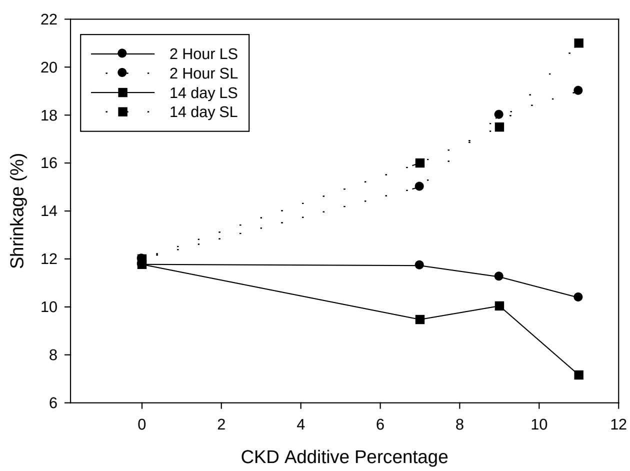

Figure A.59: Ashport-Grainola (A-6) Shrinkage Curves with CKD

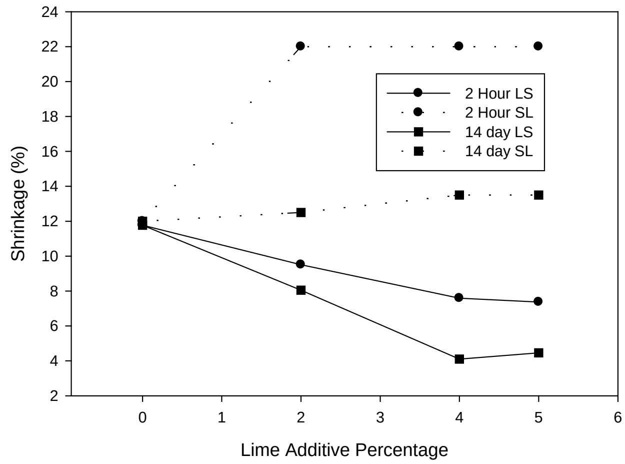

Figure A.60: Ashport-Grainola (A-6) Shrinkage Curves with Lime

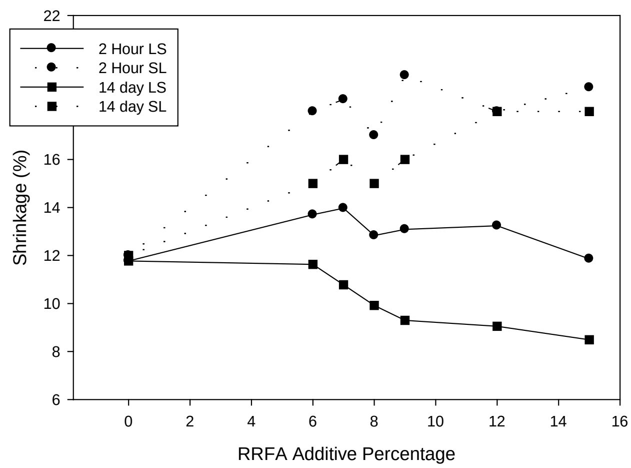

Figure A.61: Ashport-Grainola (A-6) Shrinkage Curves with Red Rock FA

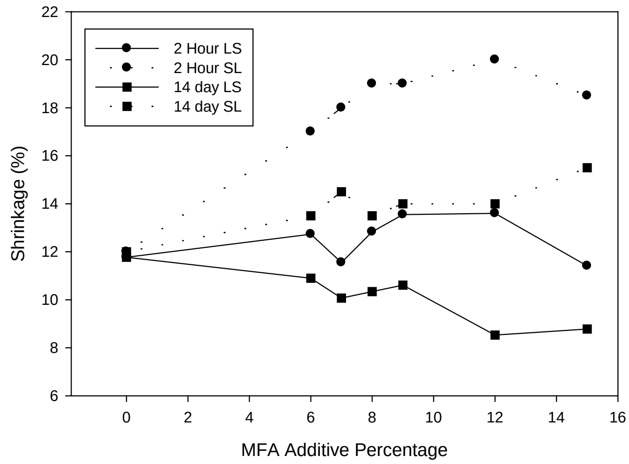

Figure A.62: Ashport-Grainola (A-6) Shrinkage Curves with Muskogee FA

Table A-21: Ashport-Grainola (A-6) Shrinkage Values

		2-hour Curing Time		14 Days Curing Time	
Additive Type	Additive Content	Linear Shrinkage (%)	Shrinkage Limit (%)	Linear Shrinkage (%)	Shrinkage Limit (%)
Raw soil	0%	11.8	12.0		
Lime	2%	9.5	22.0	8.1	12.5
	4%	7.6	22.0	4.1	13.5
	5%	7.4	22.0	4.5	13.5
CKD	7%	11.7	15.0	9.5	16.0
	9%	11.3	18.0	10.0	17.5
	11%	10.4	19.0	7.2	21.0
Red Rock Fly Ash	6%	13.7	18.0	11.6	15.0
	7%	14.0	18.5	10.8	16.0
	8%	12.8	17.0	9.9	15.0
	9%	13.1	19.5	9.3	16.0
	12%	13.2	18.0	9.1	18.0
	15%	11.9	19.0	8.5	18.0
Muskogee Fly Ash	6%	12.7	17.0	10.9	13.5
	7%	11.6	18.0	10.1	14.5
	8%	12.8	19.0	10.3	13.5
	9%	13.6	19.0	10.6	14.0
	12%	13.6	20.0	8.5	14.0
	15%	11.4	18.5	8.8	15.5

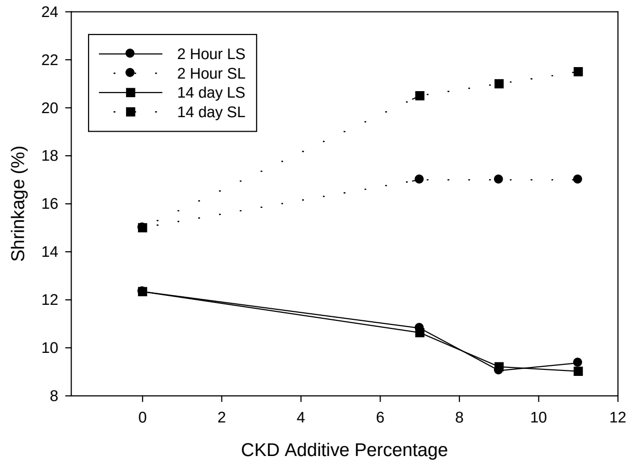

Figure A.63: Kirkland-Pawhuska (A-6) Shrinkage Curves with CKD

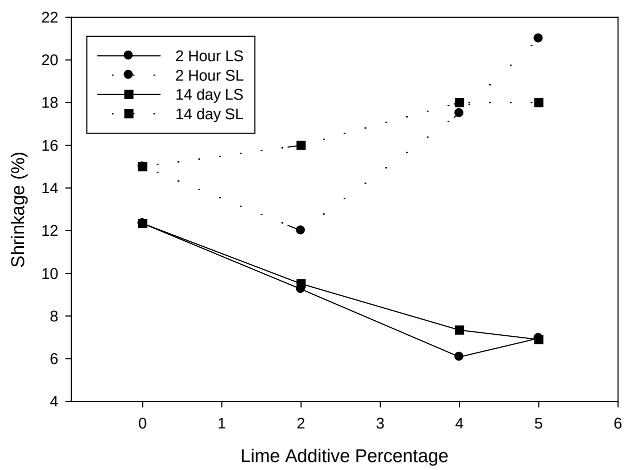

Figure A.64: Kirkland-Pawhuska (A-6) Shrinkage Curves with Lime

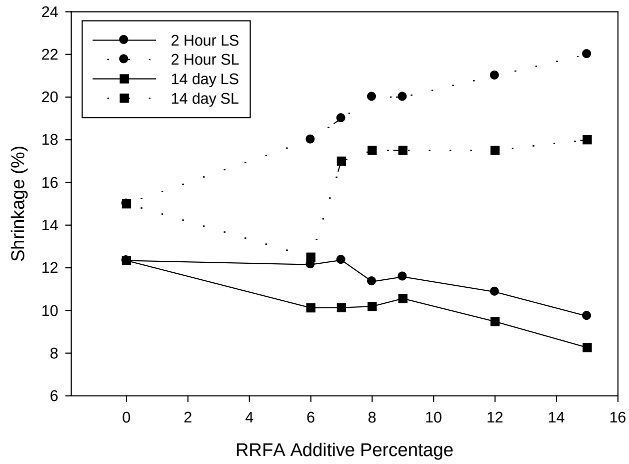

Figure A.65: Kirkland-Pawhuska (A-6) Shrinkage Curves with Red Rock FA

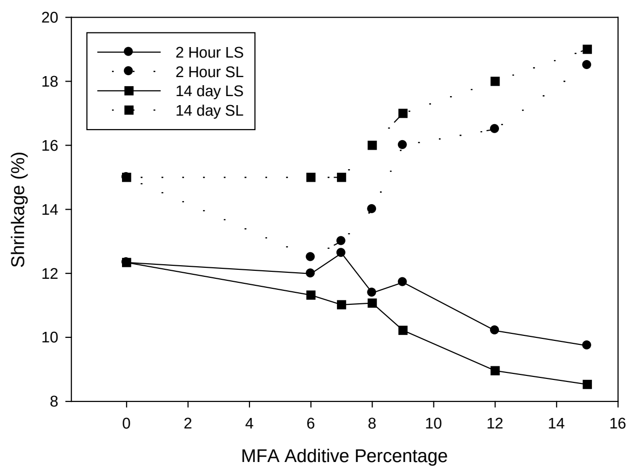

Figure A.66: Kirkland-Pawhuska (A-6) Shrinkage Curves with Muskogee FA

Table A-22: Kirkland-Pawhuska (A-6) Shrinkage Values

		2-hour Curing Time		14 Days Curing Time	
Additive Type	Additive Content	Linear Shrinkage (%)	Shrinkage Limit (%)	Linear Shrinkage (%)	Shrinkage Limit (%)
Raw soil	0%	12.3	15.0		
Lime	2%	9.3	12.0	9.5	16.0
	4%	6.1	17.5	7.3	18.0
	5%	7.0	21.0	6.9	18.0
CKD	7%	10.8	17.0	10.6	20.5
	9%	9.1	17.0	9.2	21.0
	11%	9.4	17.0	9.0	21.5
Red Rock Fly Ash	6%	12.2	18.0	10.1	12.5
	7%	12.4	19.0	10.1	17.0
	8%	11.4	20.0	10.2	17.5
	9%	11.6	20.0	10.6	17.5
	12%	10.9	21.0	9.5	17.5
	15%	9.7	22.0	8.3	18.0
Muskogee Fly Ash	6%	12.0	12.5	11.3	15.0
	7%	12.6	13.0	11.0	15.0
	8%	11.4	14.0	11.1	16.0
	9%	11.7	16.0	10.2	17.0
	12%	10.2	16.5	9.0	18.0
	15%	9.7	18.5	8.5	19.0

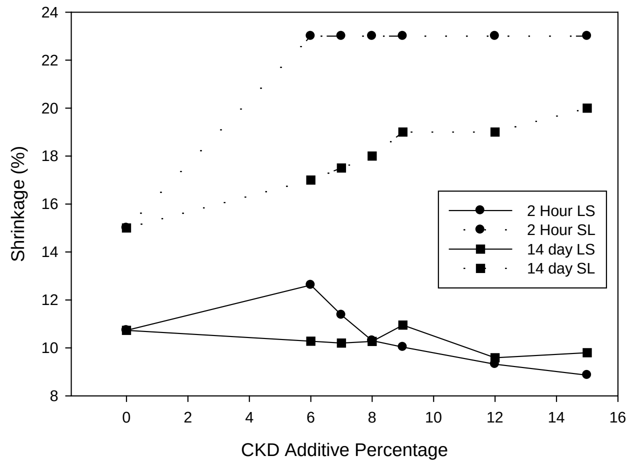

Figure A.67: Flower Pot (A-6) Shrinkage Curves with CKD

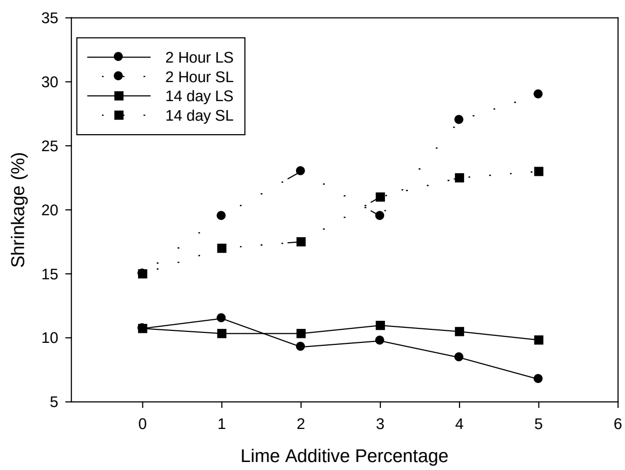

Figure A.68: Flower Pot (A-6) Shrinkage Curves with Lime

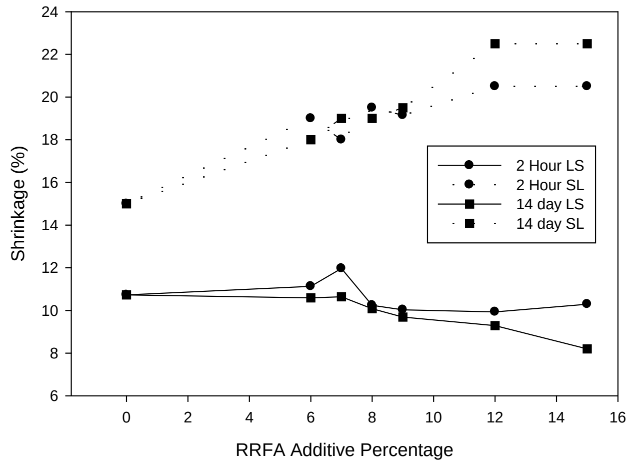

Figure A.69: Flower Pot (A-6) Shrinkage Curves with Red Rock FA

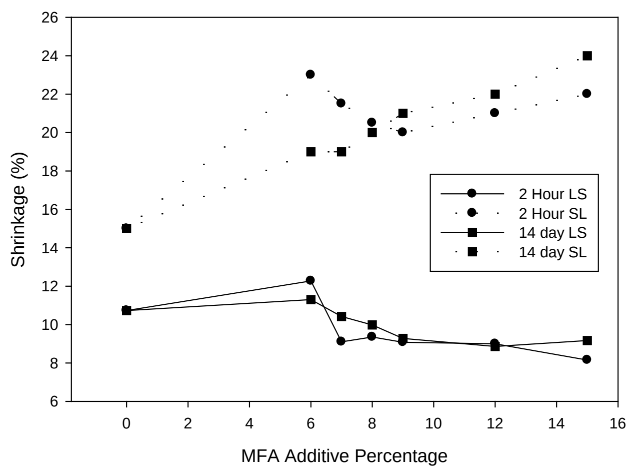

Figure A.70: Flower Pot (A-6) Shrinkage Curves with Muskogee FA

Table A-23: Flower Pot (A-6) Shrinkage Values

		2-hour Curing Time		14 Days Curing Time	
Additive Type	Additive Content	Linear Shrinkage (%)	Shrinkage Limit (%)	Linear Shrinkage (%)	Shrinkage Limit (%)
Raw soil	0%	10.7	15.0		
Lime	1%	11.5	19.5	10.3	17.0
	2%	9.3	23.0	10.3	17.5
	3%	9.8	19.5	11.0	21.0
	4%	8.5	27.0	10.5	22.5
	5%	6.8	29.0	9.8	23.0
CKD	6%	12.6	23.0	10.3	17.0
	7%	11.4	23.0	10.2	17.5
	8%	10.3	23.0	10.3	18.0
	9%	10.0	23.0	11.0	19.0
	12%	9.3	23.0	9.6	19.0
	15%	8.9	23.0	9.8	20.0
Red Rock Fly Ash	6%	11.1	19.0	10.6	18.0
	7%	12.0	18.0	10.6	19.0
	8%	10.2	19.5	10.1	19.0
	9%	10.0	19.5	9.7	19.5
	12%	9.9	20.5	9.3	22.5
	15%	10.3	20.5	8.2	22.5
Muskogee Fly Ash	6%	12.3	23.0	11.3	19.0
	7%	9.1	21.5	10.4	19.0
	8%	9.4	20.5	10.0	20.0
	9%	9.1	20.0	9.3	21.0
	12%	9.0	21.0	8.9	22.0
	15%	8.2	22.0	9.2	24.0

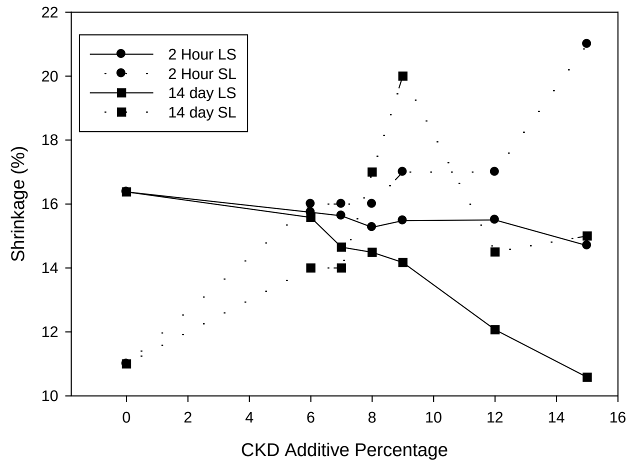

Figure A.71: Hollywood (A-7-6) Shrinkage Curves with CKD

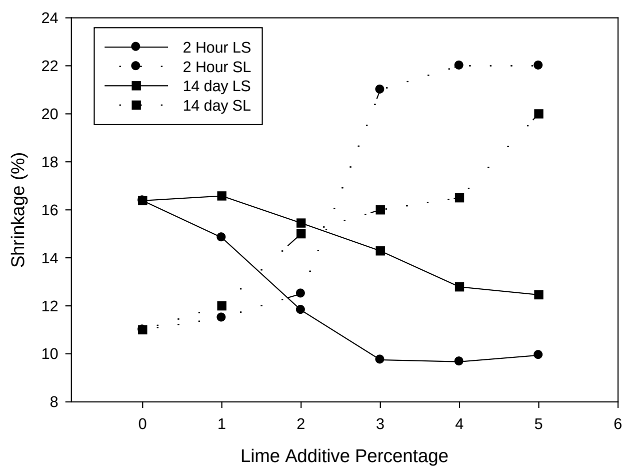

Figure A.72: Hollywood (A-7-6) Shrinkage Curves with Lime

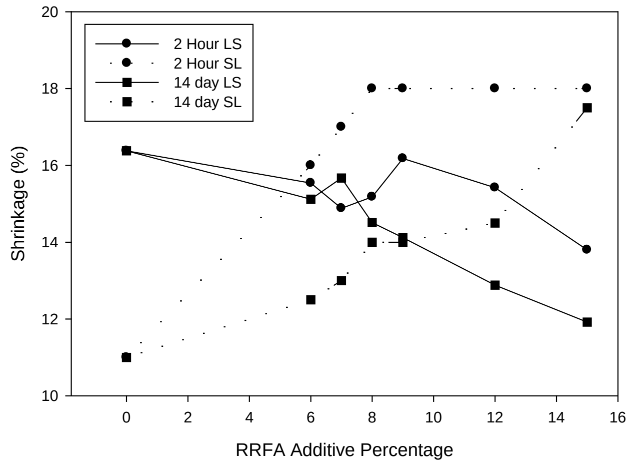

Figure A.73: Hollywood (A-7-6) Shrinkage Curves with Red Rock FA

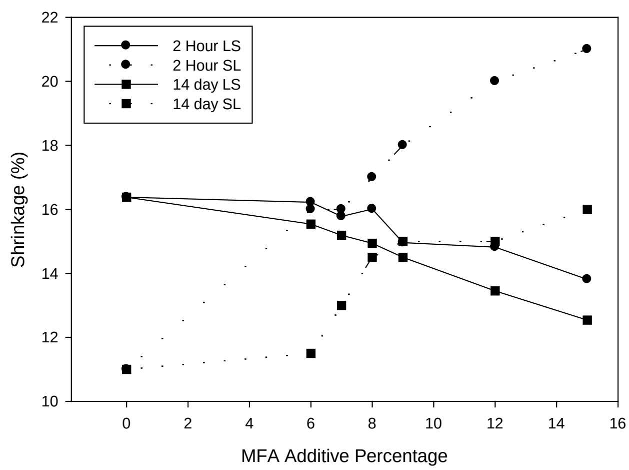

Figure A.74: Hollywood (A-7-6) Shrinkage Curves with Muskogee FA

Table A-24: Hollywood (A-7-6) Shrinkage Values

		2-hour Curing Time		14 Days Curing Time	
Additive Type	Additive Content	Linear Shrinkage (%)	Shrinkage Limit (%)	Linear Shrinkage (%)	Shrinkage Limit (%)
Raw soil	0%	16.4	11.0		
Lime	1%	14.8	11.5	16.6	12.0
	2%	11.8	12.5	15.5	15.0
	3%	9.8	21.0	14.3	16.0
	4%	9.7	22.0	12.8	16.5
	5%	9.9	22.0	12.5	20.0
CKD	6%	15.7	16.0	15.6	14.0
	7%	15.6	16.0	14.7	14.0
	8%	15.3	16.0	14.5	17.0
	9%	15.5	17.0	14.2	20.0
	12%	15.5	17.0	12.1	14.5
	15%	14.7	21.0	10.6	15.0
Red Rock Fly Ash	6%	15.5	16.0	15.1	12.5
	7%	14.9	17.0	15.7	13.0
	8%	15.2	18.0	14.5	14.0
	9%	16.2	18.0	14.1	14.0
	12%	15.4	18.0	12.9	14.5
	15%	13.8	18.0	11.9	17.5
Muskogee Fly Ash	6%	16.2	16.0	15.5	11.5
	7%	15.8	16.0	15.2	13.0
	8%	16.0	17.0	14.9	14.5
	9%	15.0	18.0	14.5	15.0
	12%	14.8	20.0	13.5	15.0
	15%	13.8	21.0	12.5	16.0

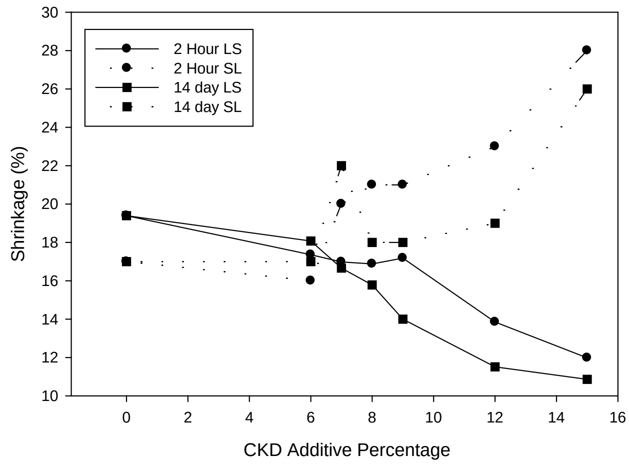

Figure A.75: Heiden (A-7-6) Shrinkage Curves with CKD

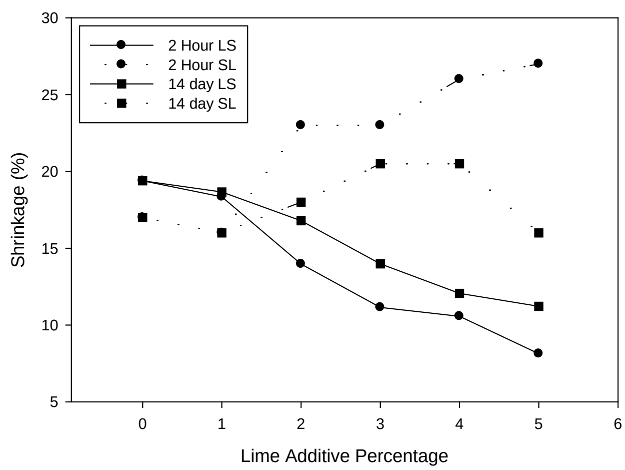

Figure A.76: Heiden (A-7-6) Shrinkage Curves with Lime

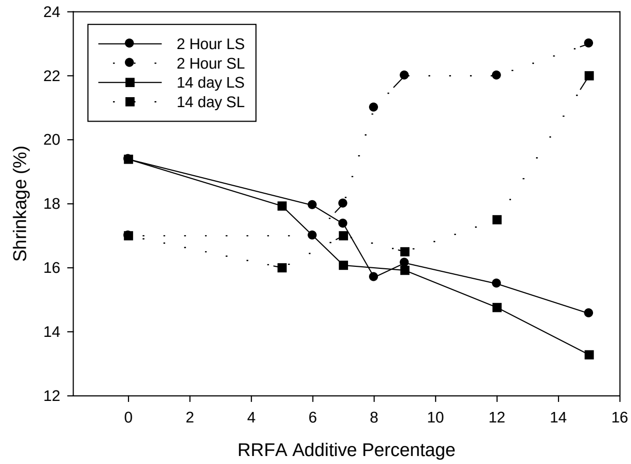

Figure A.77: Heiden (A-7-6) Shrinkage Curves with Red Rock FA

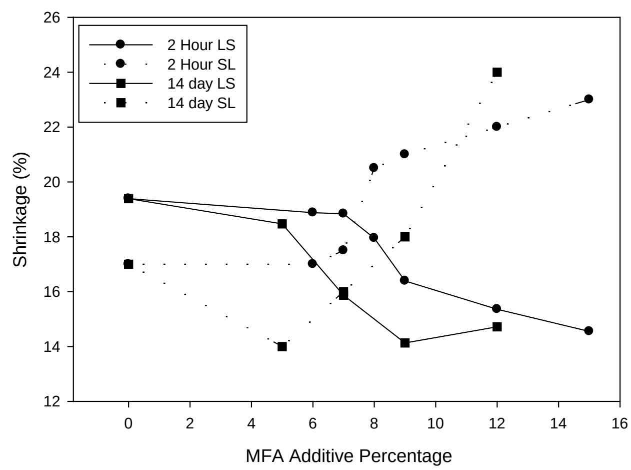

Figure A.78: Heiden (A-7-6) Shrinkage Curves with Muskogee FA

Table A-25: Heiden (A-7-6) Shrinkage Values

		2-hour Curing Time		14 Days Curing Time	
Additive Type	Additive Content	Linear Shrinkage (%)	Shrinkage Limit (%)	Linear Shrinkage (%)	Shrinkage Limit (%)
Raw soil	0%	19.4	17.0		
Lime	1%	18.4	16.0	18.7	16.0
	2%	14.0	23.0	16.8	18.0
	3%	11.2	23.0	14.0	20.5
	4%	10.6	26.0	12.1	20.5
	5%	8.1	27.0	11.2	16.0
CKD	6%	17.4	16.0	18.1	17.0
	7%	17.0	20.0	16.7	22.0
	8%	16.9	21.0	15.8	18.0
	9%	17.2	21.0	14.0	18.0
	12%	13.9	23.0	11.5	19.0
	15%	12.0	28.0	10.9	26.0
Red Rock Fly Ash	5%	-	-	17.9	16.0
	6%	18.0	17.0	-	-
	7%	17.4	18.0	16.1	17.0
	8%	15.7	21.0	-	-
	9%	16.2	22.0	15.9	16.5
	12%	15.5	22.0	14.7	17.5
	15%	14.6	23.0	13.3	22.0
Muskogee Fly Ash	5%	-	-	18.5	14.0
	6%	18.9	17.0	-	-
	7%	18.8	17.5	15.9	16.0
	8%	18.0	20.5	-	-
	9%	16.4	21.0	14.1	18.0
	12%	15.4	22.0	14.7	24.0
	15%	14.6	23.0	-	-

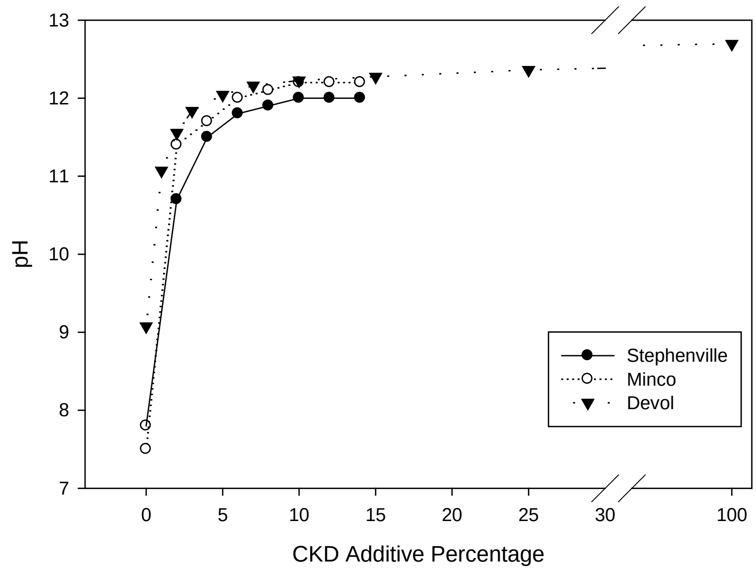

Figure A.79: pH Curves for A-4 Soils with CKD

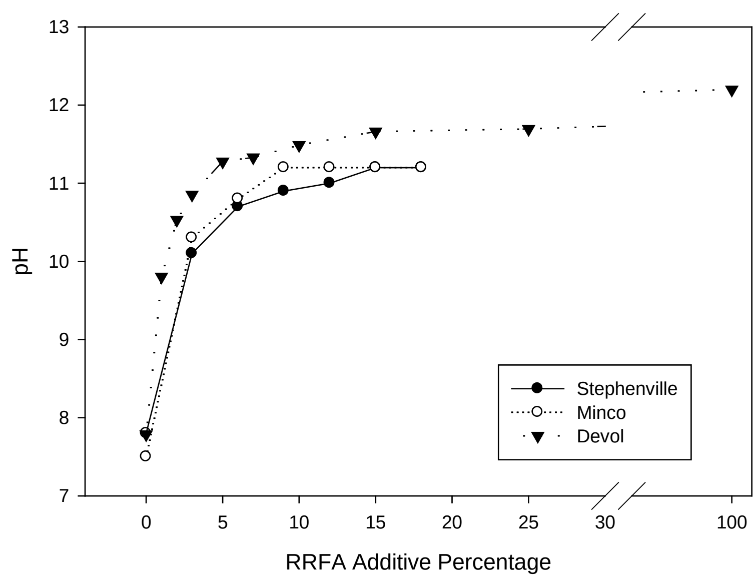

Figure A.80: pH Curves for A-4 Soils with Red Rock FA

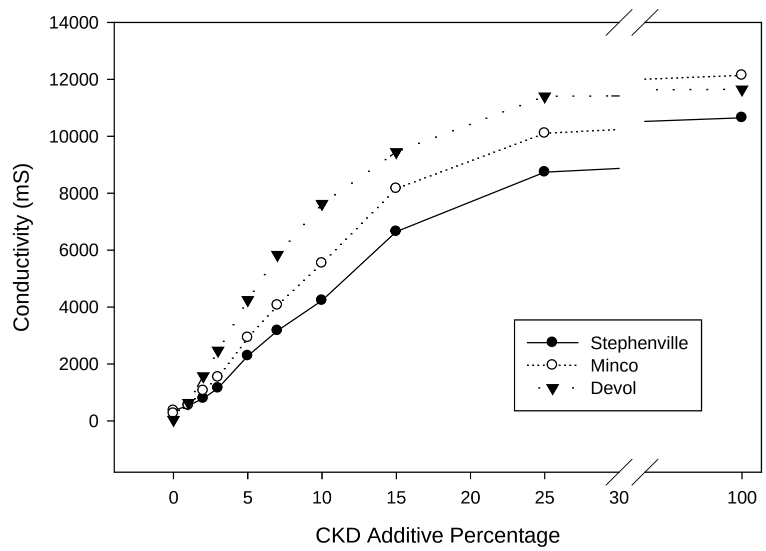

Figure A.81: Conductivity Curves for A-4 Soils with CKD

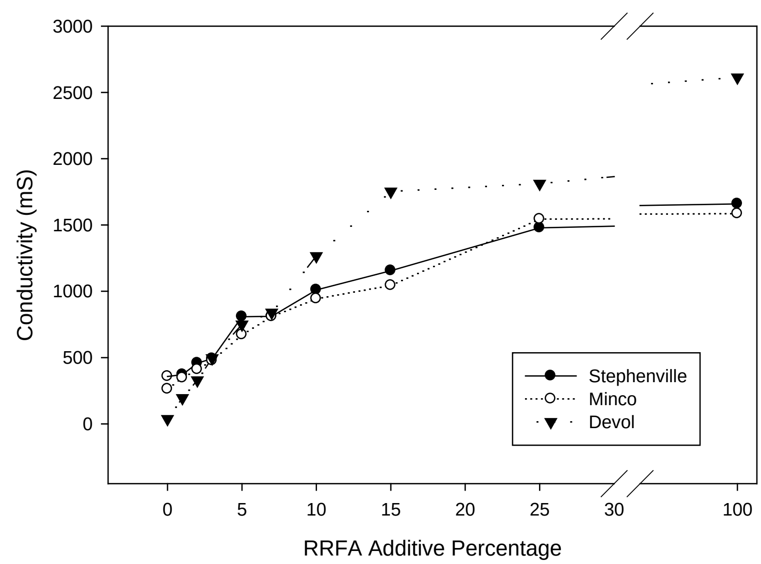

Figure A.82: Conductivity Curves for A-4 Soils with Red Rock FA

Table A-26: Measured pH and Conductivity Values for A-4 Soils

		Stephenville		Minco		Devol	
Additive Type	Additive Content	pH	Conductivity (mS)	pH	Conductivity (mS)	pH	Conductivity (mS)
Raw soil	0%	7.8	358.00	7.5	262.20	9.1	37.81
CKD	1%	-	539.00	-	551.00	11.1	637.33
	2%	10.7	788.00	11.4	1061.00	11.6	1576.67
	3%	-	1148.00	-	1534.00	11.8	2474.67
	4%	11.5	-	11.7	-	-	-
	5%	-	2284.00	-	2924.00	12.0	4253.33
	6%	11.8	-	12.0	-	-	-
	7%	-	3170.00	-	4060.00	12.2	5836.67
	8%	11.9	-	12.1	-	-	-
	10%	12.0	4230.00	12.2	5540.00	12.2	7626.67
	12%	12.0	-	12.2	-	-	-
	14%	12.0	-	12.2	-	-	-
	15%	-	6650.00	-	8160.00	12.3	9446.67
	25%	-	8740.00	-	10100.00	12.4	11400.00
	100%	-	10650.00	-	12140.00	12.7	11646.67
Red Rock Fly Ash	1%	-	372.00	-	347.00	9.8	194.77
	2%	-	458.00	-	410.00	10.5	329.67
	3%	10.1	492.00	10.3	477.00	10.9	495.67
	5%	-	808.00	-	672.00	11.3	749.67
	6%	10.7	-	10.8	-	-	-
	7%	-	811.00	-	809.00	11.3	839.33
	9%	10.9	-	11.2	-	-	-
	10%	-	1010.00	-	943.00	11.5	1265.67
	12%	11.0	-	11.2	-	-	-
	15%	11.2	1155.00	11.2	1044.00	11.7	1752.67
	18%	11.2	-	11.2	-	-	-
	25%	-	1479.00	-	1544.00	11.7	1811.67
	100%	-	1659.00	-	1585.00	12.2	2613.33

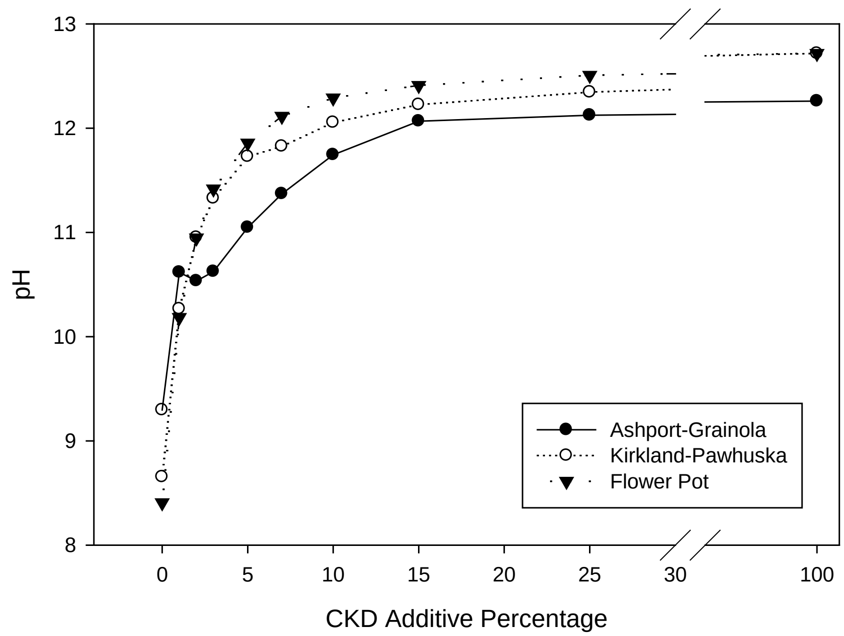

Figure A.83: pH Curves for A-6 Soils with CKD

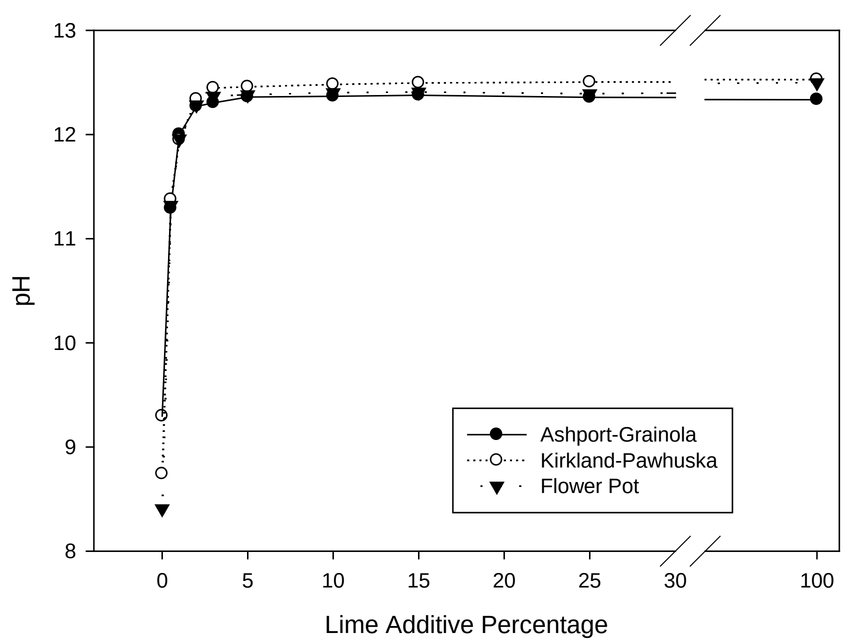

Figure A.84: pH Curves for A-6 Soils with Lime

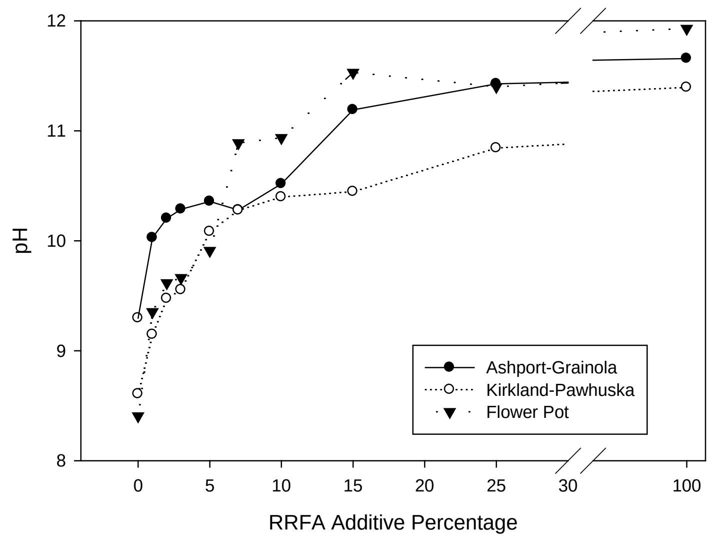

Figure A.85: pH Curves for A-6 Soils with Red Rock FA

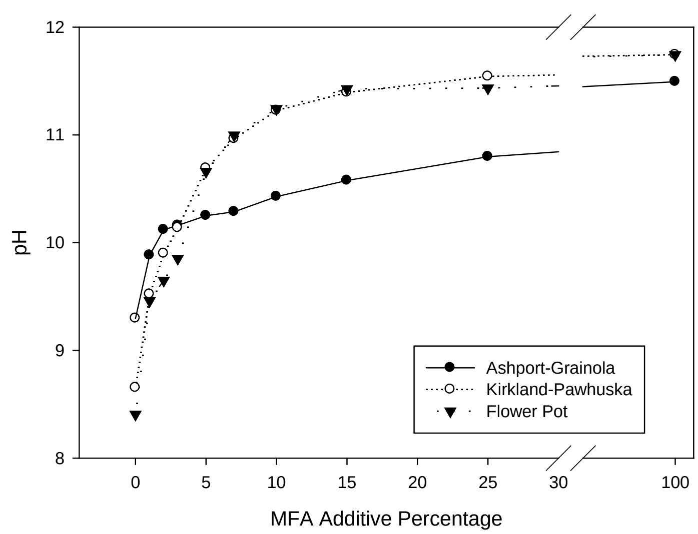

Figure A.86: pH Curves for A-6 Soils with Muskogee FA

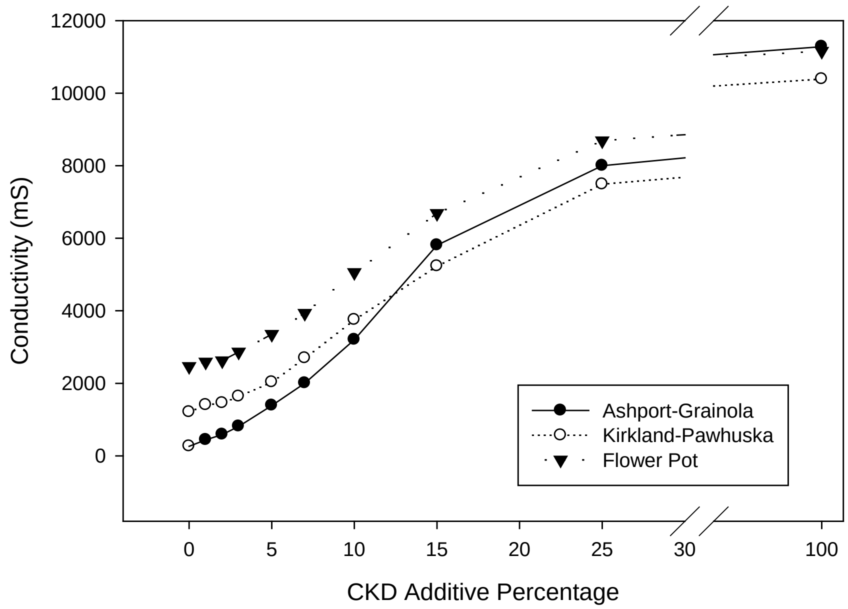

Figure A.87: Conductivity Curves for A-6 Soils with CKD

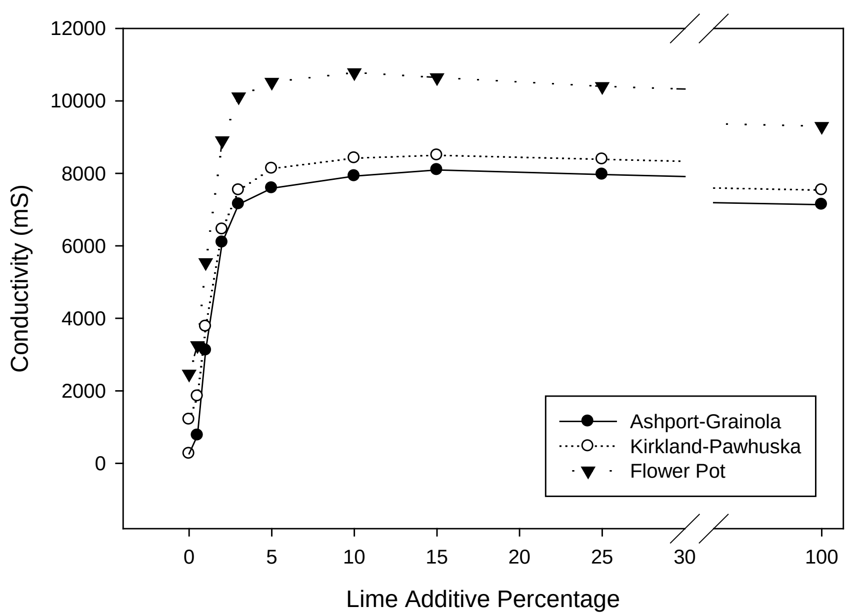

Figure A.88: Conductivity Curves for A-6 Soils with Lime

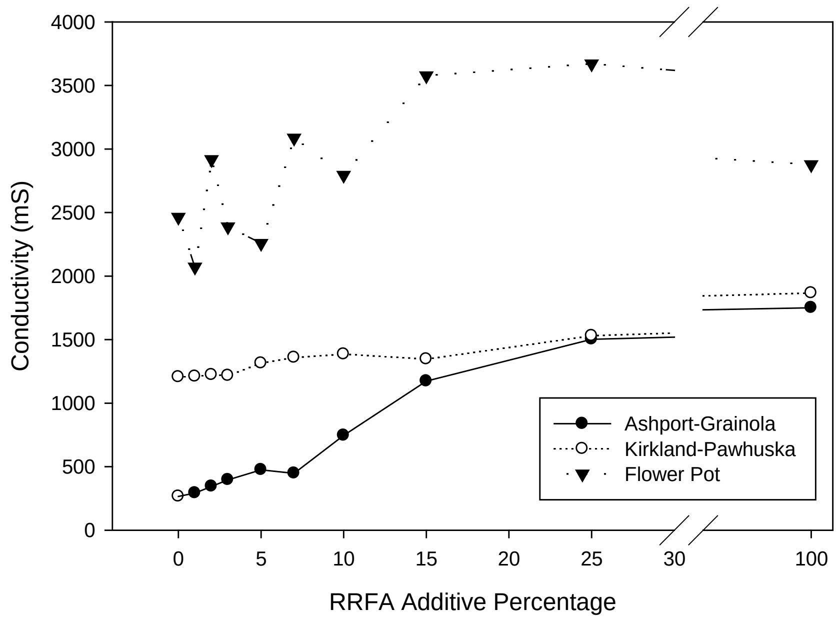

Figure A.89: Conductivity Curves for A-6 Soils with Red Rock FA

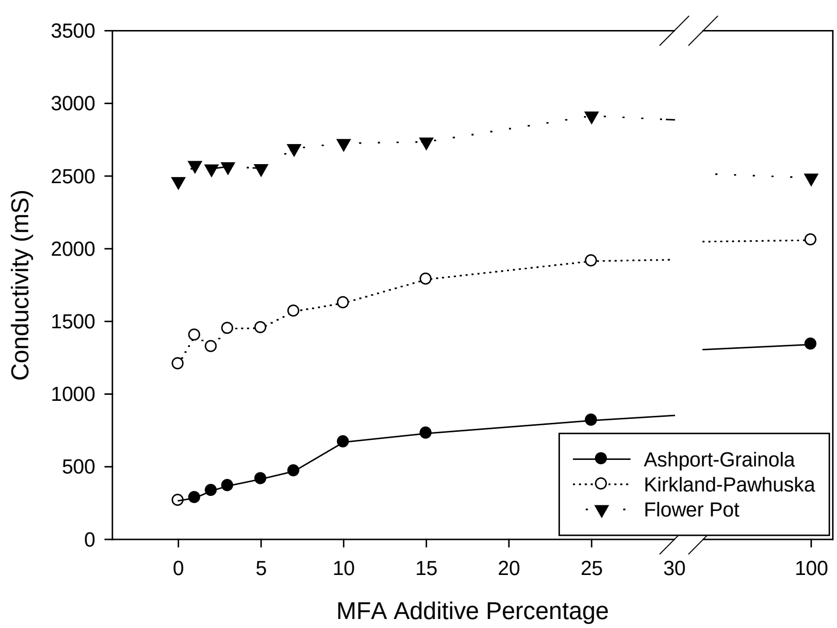

Figure A.90: Conductivity Curves for A-6 Soils with Muskogee FA

Table A-27: Measured pH and Conductivity Values for A-6 Soils

		Ashport-Grainola		Kirkland-Pawhuska		Flower Pot	
Additive Type	Additive Content	pH	Conductivity (mS)	pH	Conductivity (mS)	pH	Conductivity (mS)
Raw soil	0%	9.30	265.67	8.61	1205.33	8.41	2463.00
CKD	1%	10.62	439.67	10.27	1404.67	10.18	2587.33
	2%	10.53	587.67	10.95	1455.00	10.95	2623.00
	3%	10.62	811.67	11.33	1635.33	11.42	2862.33
	5%	11.05	1386.00	11.73	2030.00	11.86	3350.00
	7%	11.37	2003.33	11.83	2691.67	12.11	3930.00
	10%	11.74	3201.00	12.05	3750.00	12.29	5053.33
	15%	12.07	5806.67	12.23	5226.67	12.41	6683.33
	25%	12.12	8000.00	12.35	7486.67	12.51	8686.67
	100%	12.26	11280.00	12.72	10386.67	12.72	11153.33
Lime	0.5%	11.29	767.00	11.38	1848.33	11.32	3250.00
	1%	12.00	3116.67	11.95	3773.33	11.96	5540.00
	2%	12.27	6096.67	12.34	6453.33	12.28	8903.33
	3%	12.30	7150.00	12.45	7533.33	12.37	10113.33
	5%	12.36	7590.00	12.46	8130.00	12.38	10516.67
	10%	12.37	7926.67	12.48	8416.67	12.40	10780.00
	15%	12.38	8093.33	12.49	8496.67	12.41	10640.00
	25%	12.36	7966.67	12.50	8386.67	12.39	10396.67
	100%	12.33	7136.67	12.53	7536.67	12.50	9296.67
Red Rock Fly Ash	1%	10.03	292.33	9.15	1210.00	9.35	2071.00
	2%	10.20	345.00	9.47	1222.67	9.62	2916.67
	3%	10.29	395.67	9.55	1216.67	9.66	2388.33
	5%	10.36	475.00	10.08	1313.67	9.91	2257.67
	7%	10.28	448.00	10.28	1358.33	10.89	3086.67
	10%	10.52	745.33	10.40	1384.67	10.94	2793.67
	15%	11.19	1172.67	10.45	1345.33	11.53	3576.67
	25%	11.43	1502.33	10.84	1529.33	11.40	3670.00
	100%	11.66	1750.33	11.39	1865.33	11.93	2877.33
Muskogee Fly Ash	1%	9.88	284.43	9.52	1403.00	9.46	2574.00
	2%	10.12	334.00	9.90	1324.00	9.65	2549.67
	3%	10.16	367.33	10.14	1448.67	9.85	2564.33
	5%	10.25	414.33	10.69	1453.67	10.66	2551.67
	7%	10.29	468.33	10.96	1567.33	11.00	2689.33
	10%	10.43	668.33	11.23	1625.67	11.24	2724.67
	15%	10.58	729.00	11.39	1788.00	11.43	2734.33
	25%	10.80	818.00	11.54	1913.67	11.43	2913.67
	100%	11.49	1340.67	11.74	2057.33	11.74	2486.67

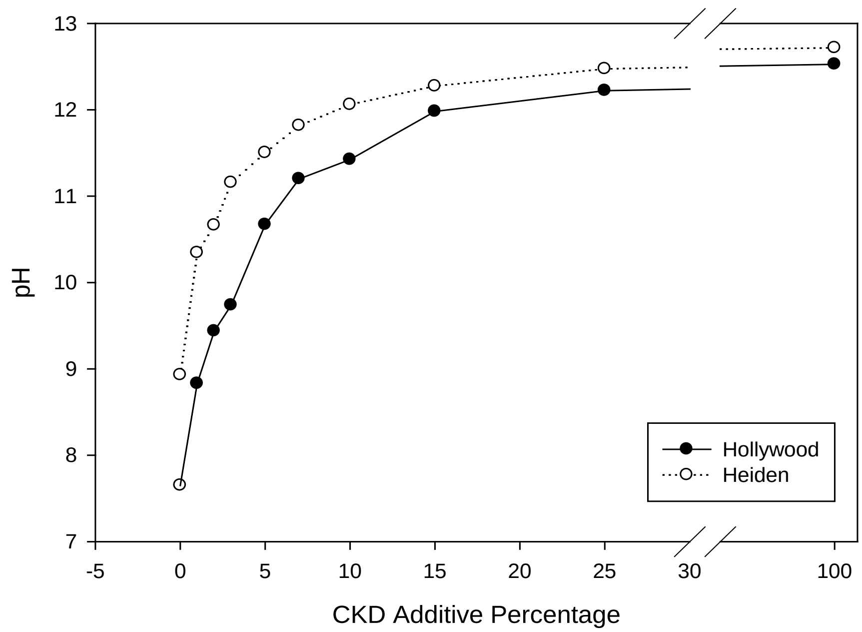

Figure A.91: pH Curves for A-7-6 Soils with CKD

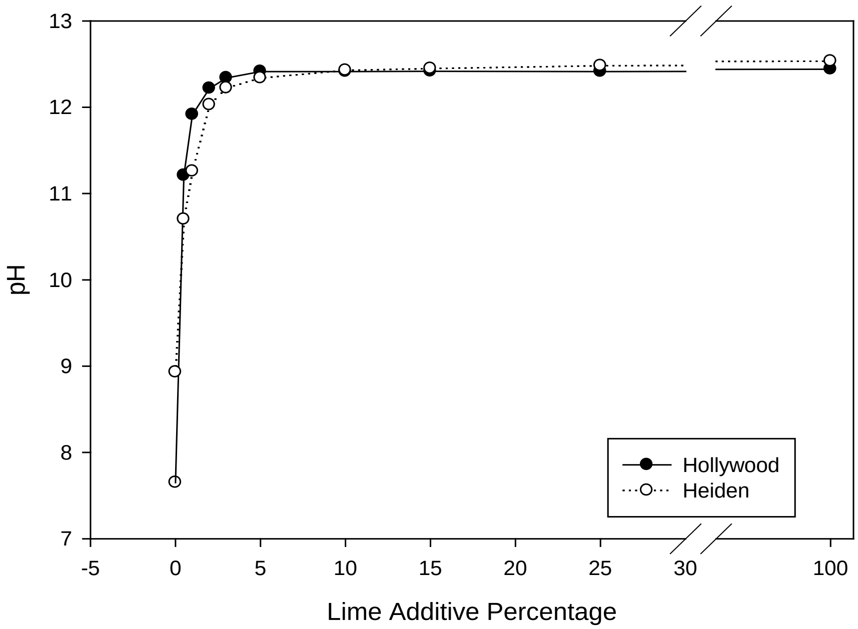

Figure A.92: pH Curves for A-7-6 Soils with Lime

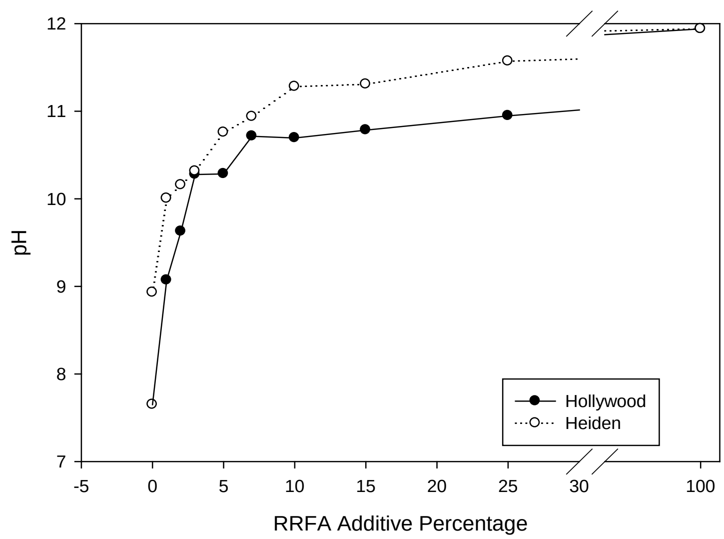

Figure A.93: pH Curves for A-7-6 Soils with Red Rock FA

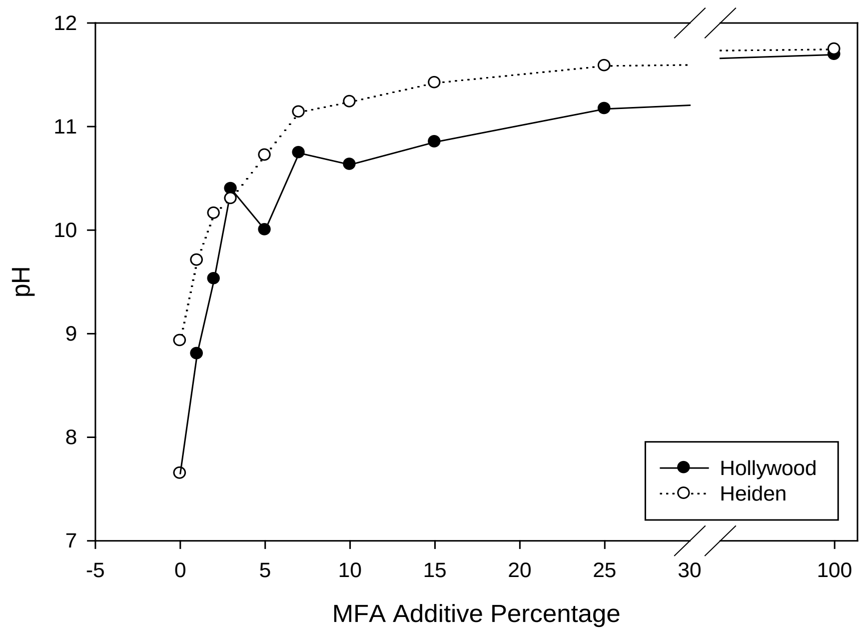

Figure A.94: pH Curves for A-7-6 Soils with Muskogee FA

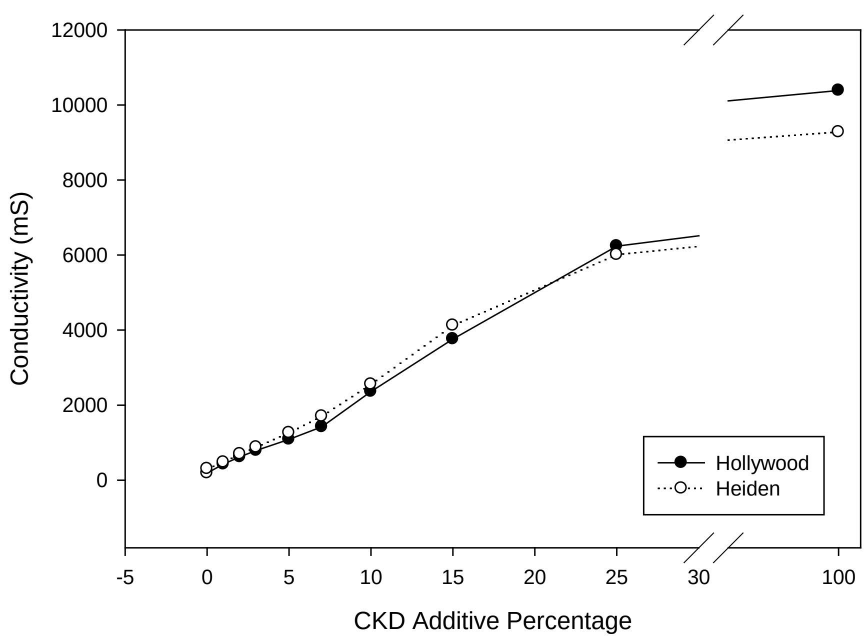

Figure A.95: Conductivity Curves for A-7-6 Soils with CKD

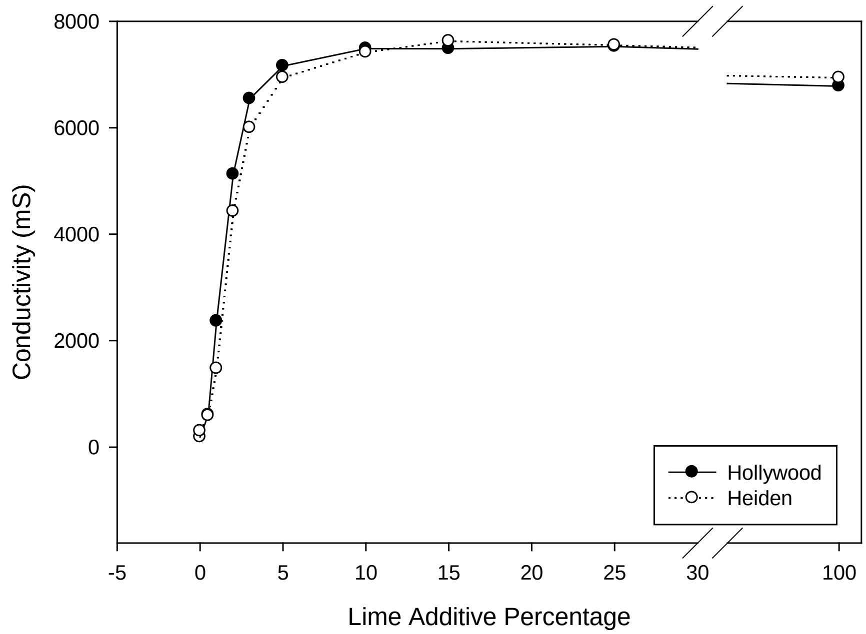

Figure A.96: Conductivity Curves for A-7-6 Soils with Lime

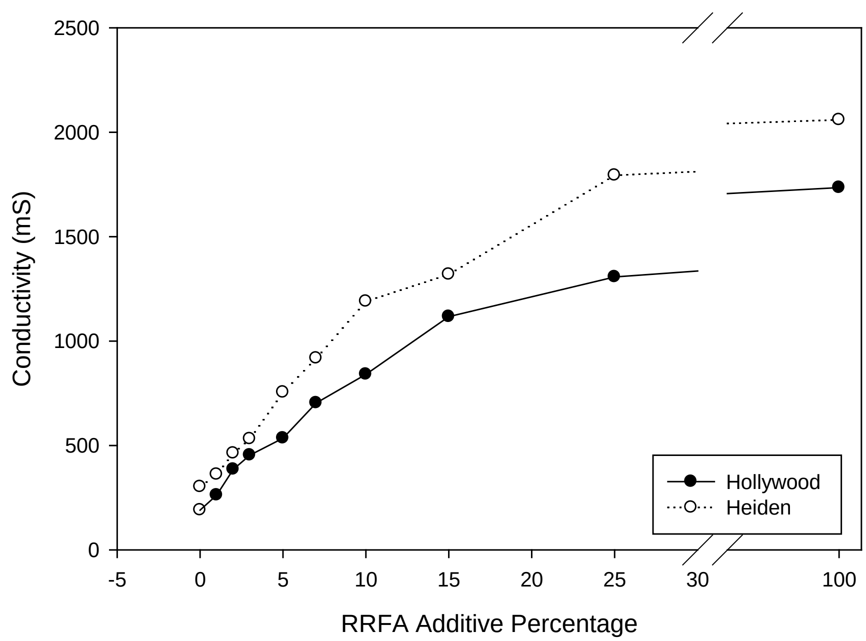

Figure A.97: Conductivity Curves for A-7-6 Soils with Red Rock FA

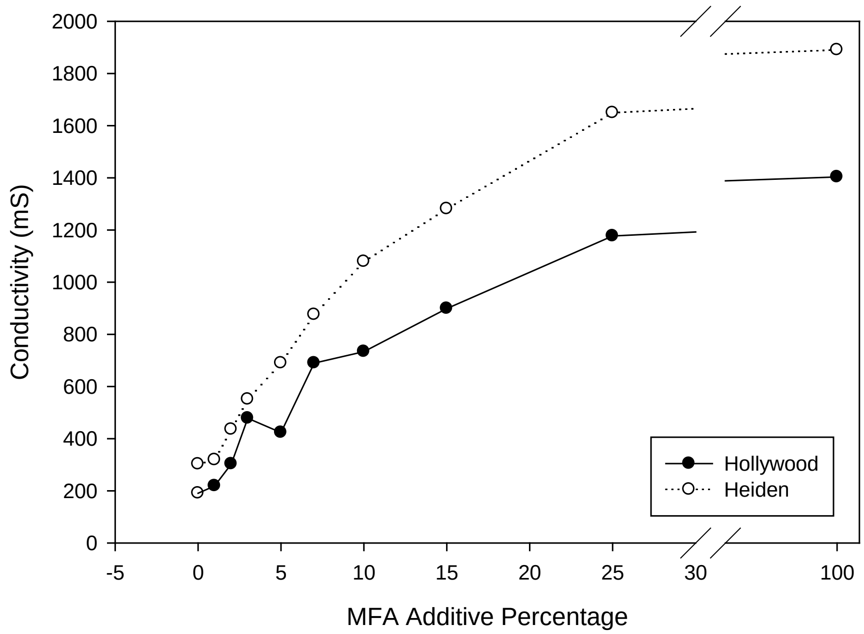

Figure A.98: Conductivity Curves for A-7-6 Soils with Muskogee FA

Table A-28: Measured pH and Conductivity Values for A-7-6 Soils

		Hollywood		Heiden	
Additive Type	Additive Content	pH	Conductivity (mS)	pH	Conductivity (mS)
Raw soil	0%	7.65	190.67	8.93	301.73
CKD	1%	8.83	431.33	10.34	475.33
	2%	9.44	622.00	10.66	699.33
	3%	9.74	793.33	11.16	879.33
	5%	10.67	1087.67	11.50	1260.33
	7%	11.20	1425.00	11.82	1704.00
	10%	11.42	2360.67	12.06	2555.67
	15%	11.98	3763.33	12.27	4123.33
	25%	12.22	6236.67	12.47	6010.00
	100%	12.53	10386.67	12.72	9276.67
Lime	0.5%	11.21	608.00	10.70	590.00
	1%	11.91	2366.00	11.26	1475.67
	2%	12.22	5123.33	12.03	4426.67
	3%	12.34	6543.33	12.22	6000.00
	5%	12.41	7160.00	12.34	6940.00
	10%	12.41	7486.67	12.43	7416.67
	15%	12.42	7483.33	12.45	7626.67
	25%	12.41	7526.67	12.48	7546.67
	100%	12.44	6780.00	12.53	6936.67
Red Rock Fly Ash	1%	9.07	261.43	10.00	361.00
	2%	9.63	385.67	10.16	462.33

	3%	10.28	453.33	10.31	531.33
	5%	10.28	534.33	10.76	754.67
	7%	10.71	703.00	10.94	917.33
	10%	10.69	840.67	11.28	1190.00
	15%	10.78	1116.67	11.31	1318.67
	25%	10.95	1306.67	11.57	1793.33
	100%	11.94	1734.67	11.94	2058.67
Muskogee Fly Ash	1%	8.80	218.60	9.71	318.57
	2%	9.53	302.67	10.16	435.00
	3%	10.40	478.00	10.30	550.33
	5%	10.00	423.27	10.72	689.33
	7%	10.74	689.33	11.14	875.33
	10%	10.63	733.67	11.24	1078.67
	15%	10.85	898.33	11.42	1280.67
	25%	11.17	1177.00	11.58	1648.67
	100%	11.69	1403.33	11.74	1890.00

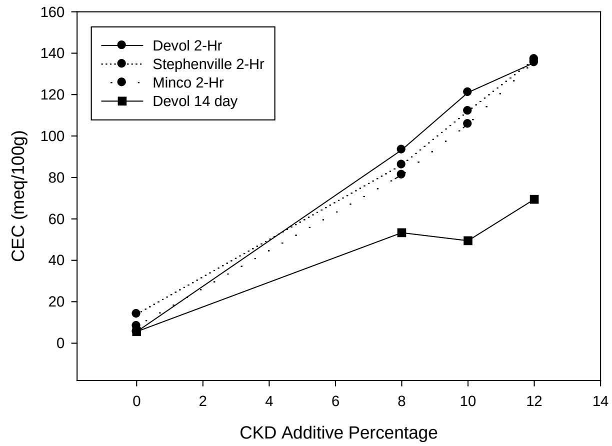

Figure A.99: Cation Exchange Capacity Curves for A-4 Soils with CKD

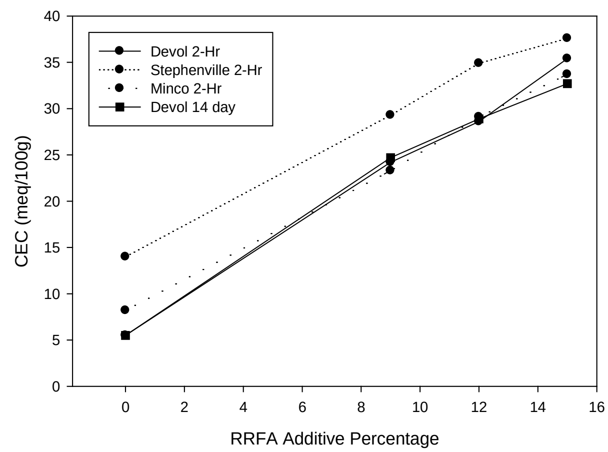

Figure A.100: Cation Exchange Capacity Curves for A-4 Soils with Red Rock FA

Table A-29: Cation Exchange Capacity Values for A-4 Soils

		Uncured CEC (meq/100g)			Cured CEC (meq/100g)		
Additive Type	Additive Content	Devol	Stephenville	Minco	Devol	Stephenville	Minco
Raw soil	0%	5.5	14.0	8.2			
CKD	8%	93.3	86.1	81.2	53.3	-	-
	10%	121	112	105.7	49.4	-	-
	12%	135.4	137.1	136.1	69.4	-	-
RRFA	9%	24.2	29.3	23.3	24.7	-	-
	12%	28.6	34.9	29.1	28.9	-	-

	15%	35.4	37.6	33.7	32.7	-	-

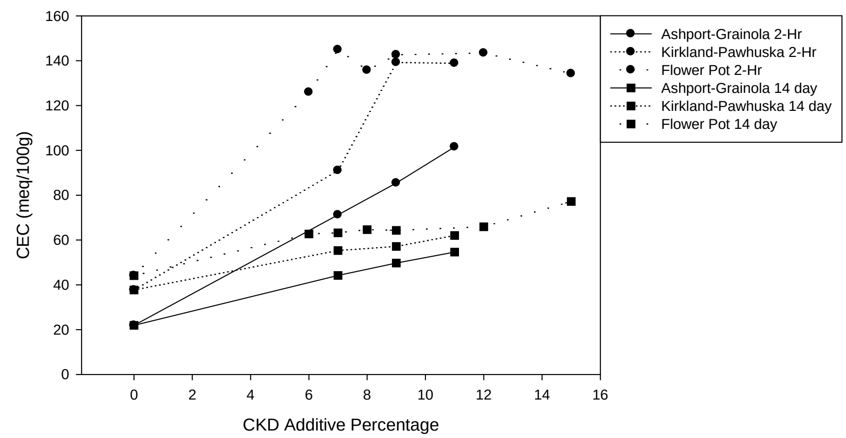

Figure A.101: Cation Exchange Capacity Curves for A-6 Soils with CKD

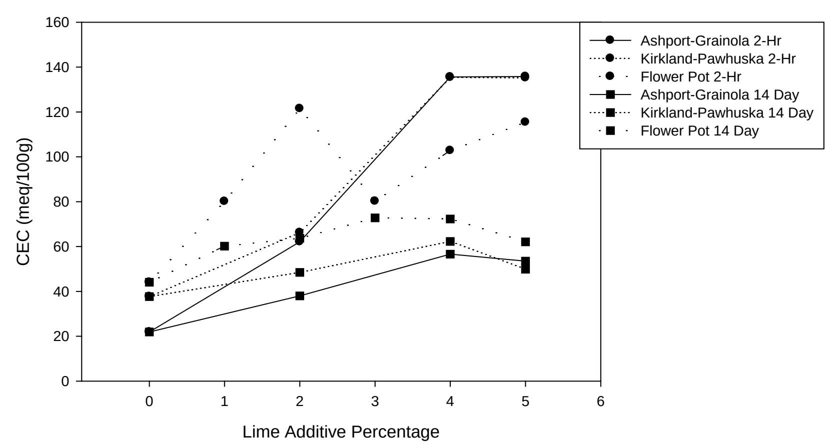

Figure A.102: Cation Exchange Capacity Curves for A-6 Soils with Lime

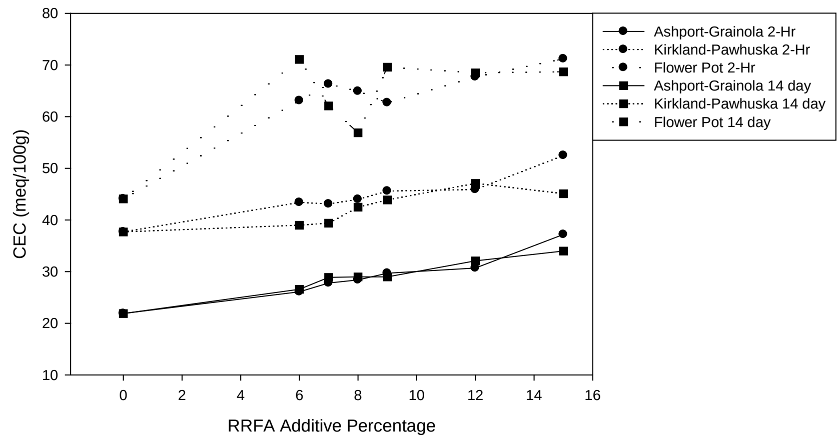

Figure A.103: Cation Exchange Capacity Curves for A-6 Soils with Red Rock FA

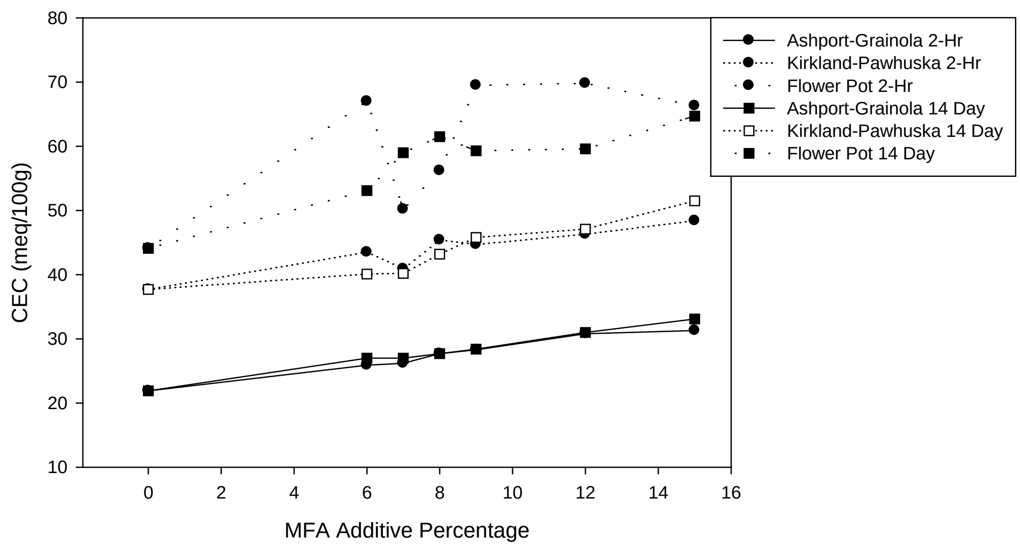

Figure A.104: Cation Exchange Capacity Curves for A-6 Soils with Muskogee FA

Table A-30: Cation Exchange Capacity Values for A-6 Soils

		2-Hour CEC (meq/100g)			14-Day CEC (meq/100g)		
Additive Type	Additive Content	Ashport-Grainola	Kirkland-Pawhuska	Flower Pot	Ashport-Grainola	Kirkland-Pawhuska	Flower Pot
Raw soil	0%	21.9	37.7	44.1			
Lime	1%	-	-	80.1	-	-	60.2
	2%	62.1	66.2	121.5	38.0	48.5	63.7
	3%	-	-	80.2	-	-	72.8
	4%	135.6	135.4	102.8	56.6	62.3	72.3
	5%	135.8	135.2	115.4	53.5	49.9	62.1
CKD	6%	-	-	125.9	-	-	62.7
	7%	71.2	91.0	144.9	44.2	55.3	63.2
	8%	-	-	135.7	-	-	64.6
	9%	85.4	139.2	142.6	49.7	57.1	64.3
	11%	101.5	138.8	-	54.6	62.0	
	12%	-	-	143.4	-	-	65.9
	15%	-	-	134.2	-	-	77.2
Red Rock Fly Ash	6%	26.1	43.4	63.1	26.6	39.0	71.1
	7%	27.8	43.1	66.3	28.9	39.4	62.1
	8%	28.4	44.0	64.9	29.0	42.5	56.9
	9%	29.7	45.6	62.7	29.0	43.9	69.6
	12%	30.7	45.9	67.7	32.1	47.1	68.5
	15%	37.2	52.5	71.2	34.0	45.1	68.7
Muskogee Fly Ash	6%	25.9	43.5	67.0	27.0	40.1	53.1
	7%	26.2	40.9	50.2	27.0	40.2	59.0
	8%	27.7	45.4	56.2	27.7	43.2	61.5
	9%	28.3	44.7	69.5	28.4	45.8	59.3
	12%	30.8	46.3	69.8	31.0	47.1	59.6
	15%	31.3	48.4	66.3	33.1	51.5	64.7

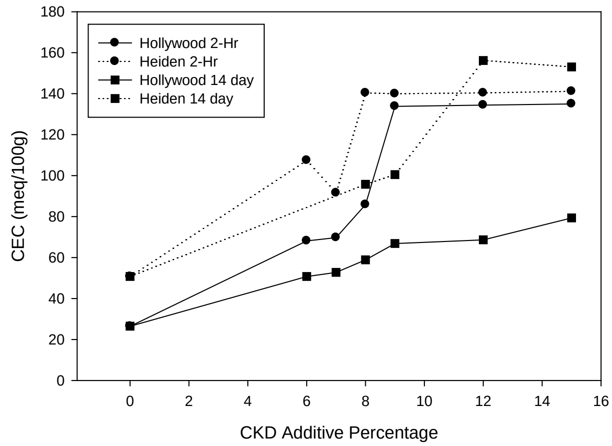

Figure A.105: Cation Exchange Capacity Curves for A-7-6 Soils with CKD

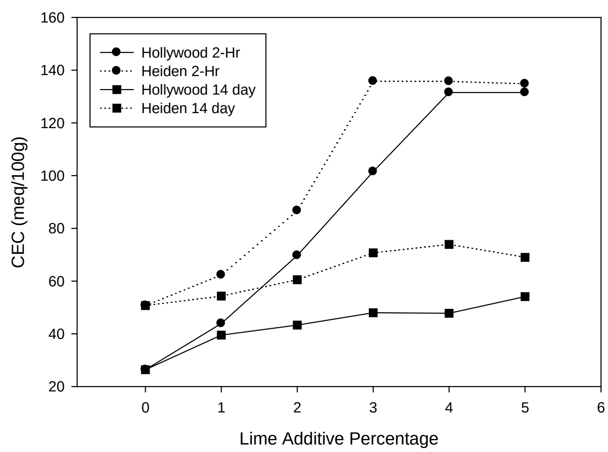

Figure A.106: Cation Exchange Capacity Curves for A-7-6 Soils with Lime

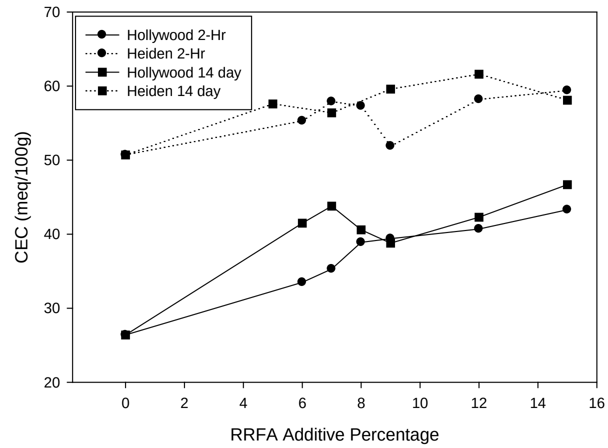

Figure A.107: Cation Exchange Capacity Curves for A-7-6 Soils with Red Rock FA

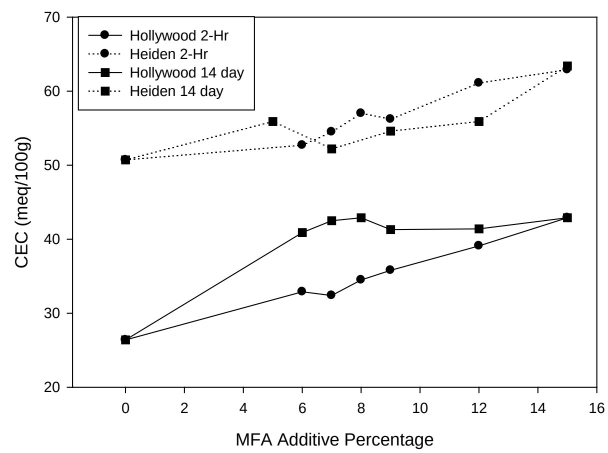

Figure A.108: Cation Exchange Capacity Curves for A-7-6 Soils with Muskogee FA

Table A-31: Cation Exchange Capacity Values for A-7-6 Soils

		2-Hr CEC (meq/100g)		14 Day CEC (meq/100g)	
Additive Type	Additive Content	Hollywood	Heiden	Hollywood	Heiden
Raw soil	0%	26.4	50.7		
Lime	1%	43.9	62.3	39.5	54.3
	2%	69.7	86.7	43.3	60.5
	3%	101.5	135.8	48.0	70.7
	4%	131.5	135.7	47.8	73.9
	5%	131.5	134.8	54.1	69.0
CKD	6%	68.1	107.4	50.7	-
	7%	69.7	91.5	52.7	-
	8%	85.8	140.3	58.8	95.7
	9%	133.8	139.9	66.8	100.4
	12%	134.4	140.3	68.6	156.1
	15%	135.0	141.1	79.3	153.0
Red Rock Fly Ash	5%	-	-	-	57.6
	6%	33.5	55.3	41.5	-
	7%	35.3	57.9	43.8	56.4
	8%	38.9	57.3	40.6	-
	9%	39.4	51.9	38.8	59.6
	12%	40.7	58.2	42.3	61.6
	15%	43.3	59.4	46.7	58.1
Muskogee Fly Ash	5%	-	-	-	55.9
	6%	32.9	52.7	40.9	-
	7%	32.4	54.5	42.5	52.2
	8%	34.5	57.0	42.9	-
	9%	35.8	56.2	41.3	54.6
	12%	39.1	61.1	41.4	55.9
	15%	42.9	62.9	42.9	63.4

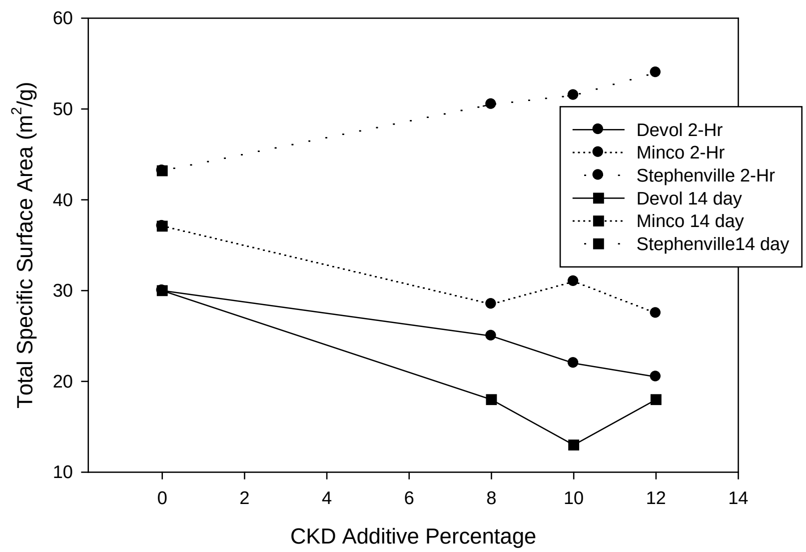

Figure A.109: Total SSA Curves for A-4 Soils with CKD

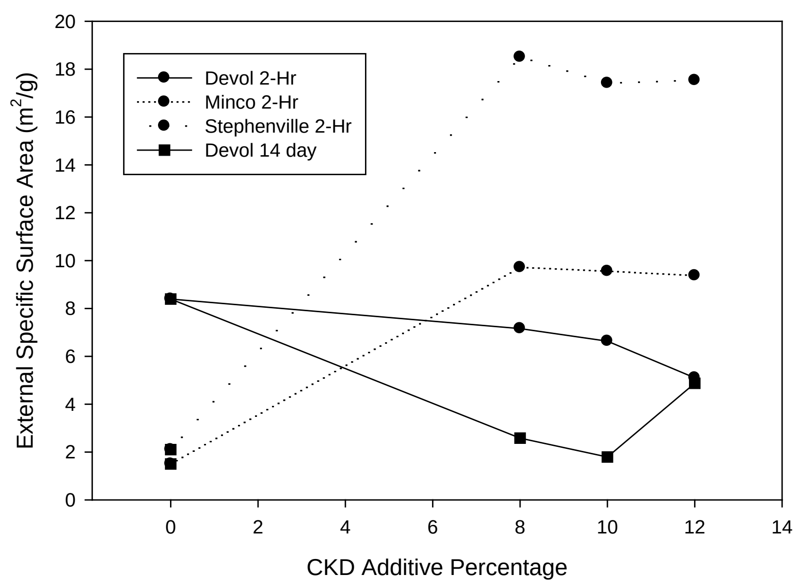

Figure A.110: External SSA Curves for A-4 Soils with CKD

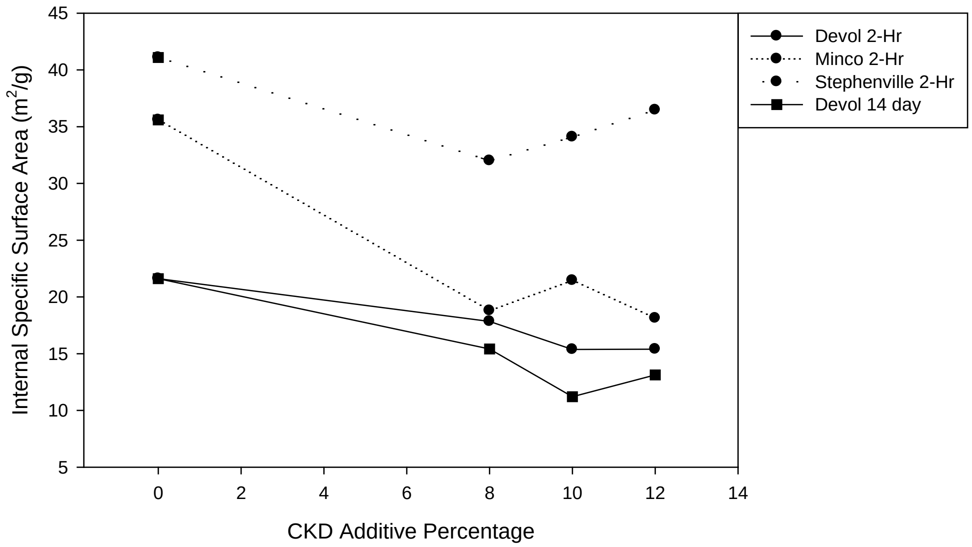

Figure A.111: Internal SSA Curves for A-4 Soils with CKD

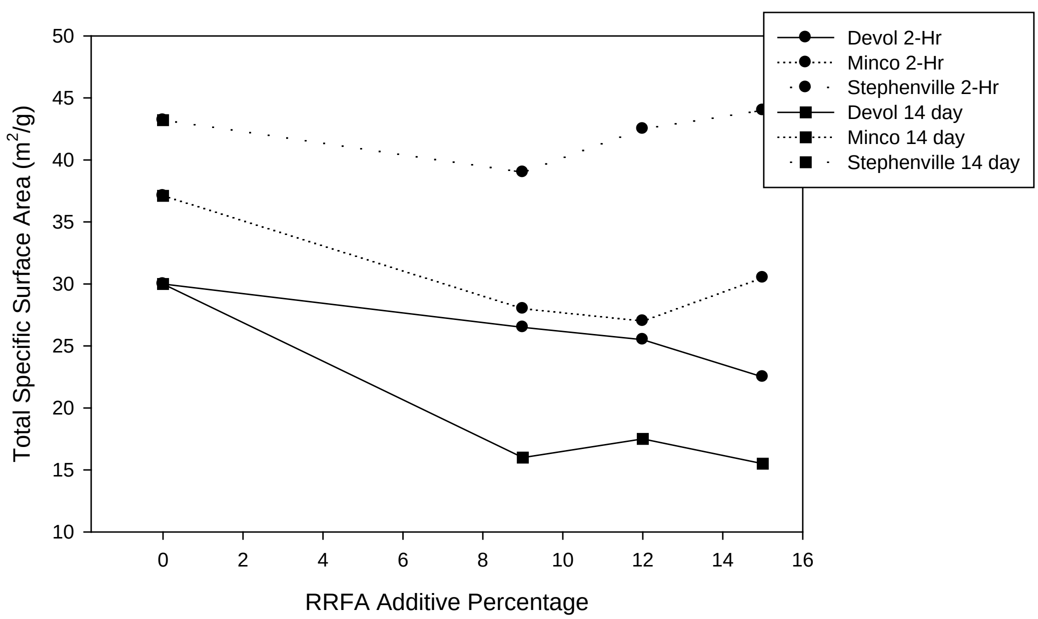

Figure A.112: Total SSA Curves for A-4 Soils with Red Rock FA

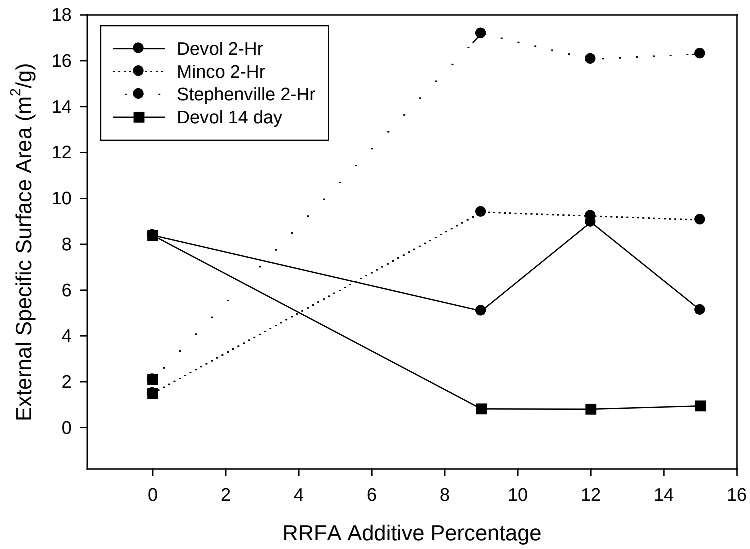

Figure A.113: External SSA Curves for A-4 Soils with Red Rock FA

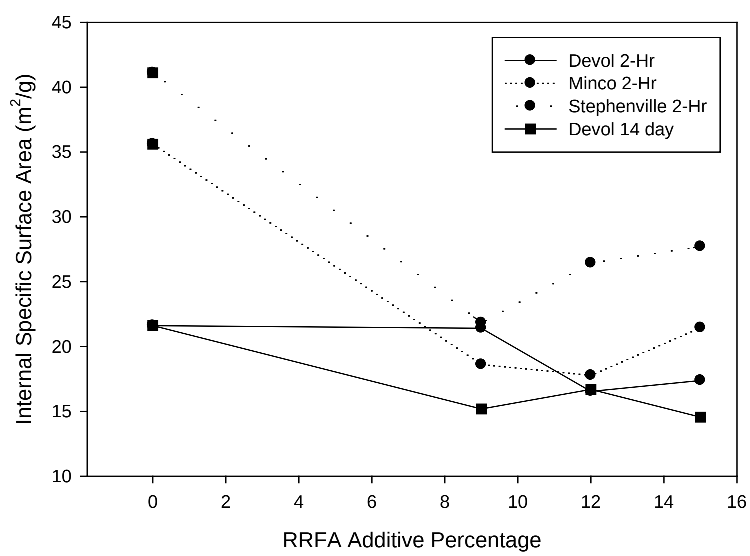

Figure A.114: Internal SSA Curves for A-4 Soils with Red Rock FA

Table A-32: Devol (A-4) Specific Surface Area Values

		2-Hour Curing Time			14 Days Curing Time		
Additive Type	Additive Percentage	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)
Raw soil	0%	30.0	8.4	21.6			
CKD	8%	25.0	7.2	17.8	18.0	2.6	15.4
	10%	22.0	6.6	15.4	13.0	1.8	11.2
	12%	20.5	5.1	15.4	18.0	4.9	13.1
RRFA	9%	26.5	5.1	21.4	16.0	0.8	15.2
	12%	25.5	9.0	16.5	17.5	0.8	16.7
	15%	22.5	5.1	17.4	15.5	1.0	14.5

Table A-33: Minco (A-4) Specific Surface Area Values

		2-Hour Curing Time			14 Days Curing Time		
Additive Type	Additive Percentage	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)
Raw soil	0%	40.5	1.5	39.0			
CKD	8%	28.5	9.7	18.8	-	-	-
	10%	31.0	9.6	21.4	-	-	-
	12%	27.5	9.4	18.1	-	-	-
RRFA	9%	28.0	9.4	18.6	-	-	-
	12%	27.0	9.2	17.8	-	-	-
	15%	30.5	9.1	21.4	-	-	-

Table A-34: Stephenville (A-4) Specific Surface Area Values

		2-Hour Curing Time			14 Days Curing Time		
Additive Type	Additive Percentage	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)
Raw soil	0%	50.0	18.8	31.2			
CKD	8%	50.5	18.5	32.0	-	-	-
	10%	51.5	17.4	34.1	-	-	-
	12%	54.0	17.5	36.5	-	-	-
RRFA	9%	39.0	17.2	21.8	-	-	-

	12%	42.5	16.1	26.4	-	-	-
	15%	44.0	16.3	27.7	-	-	-

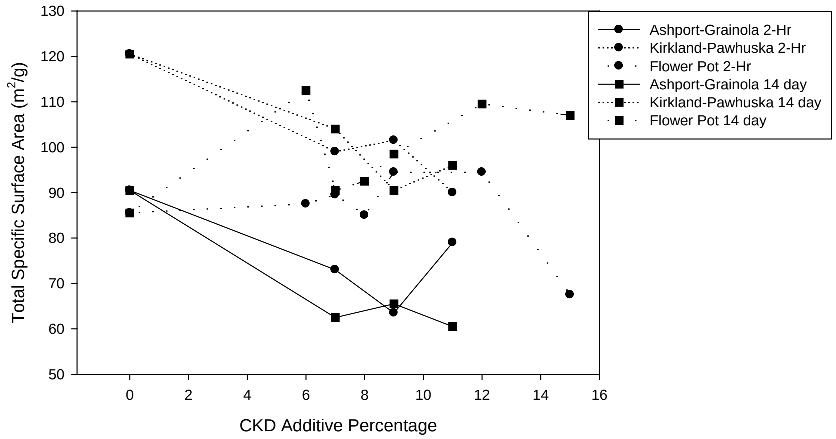

Figure A.115: Total SSA Curves for A-6 Soils with CKD

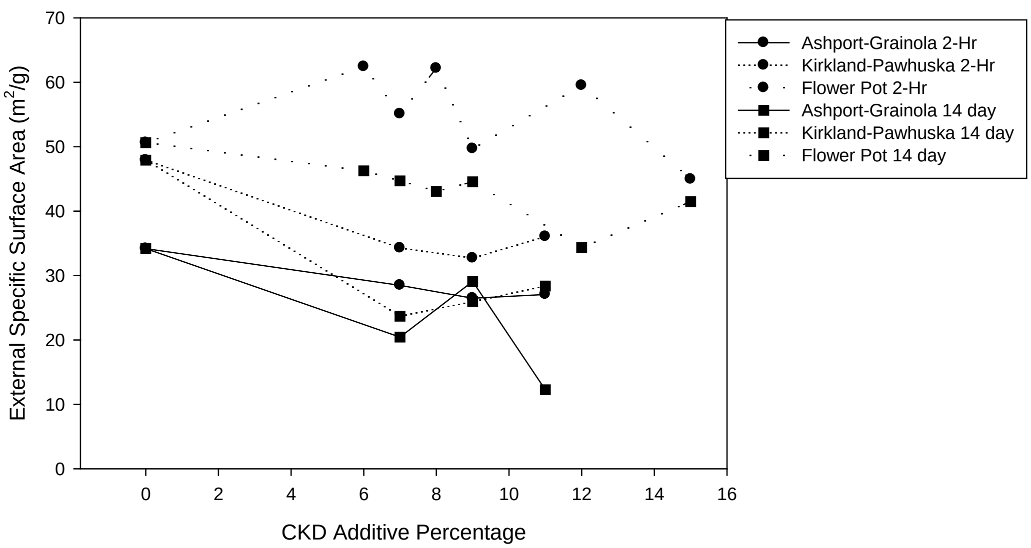

Figure A.116: External SSA Curves for A-6 Soils with CKD

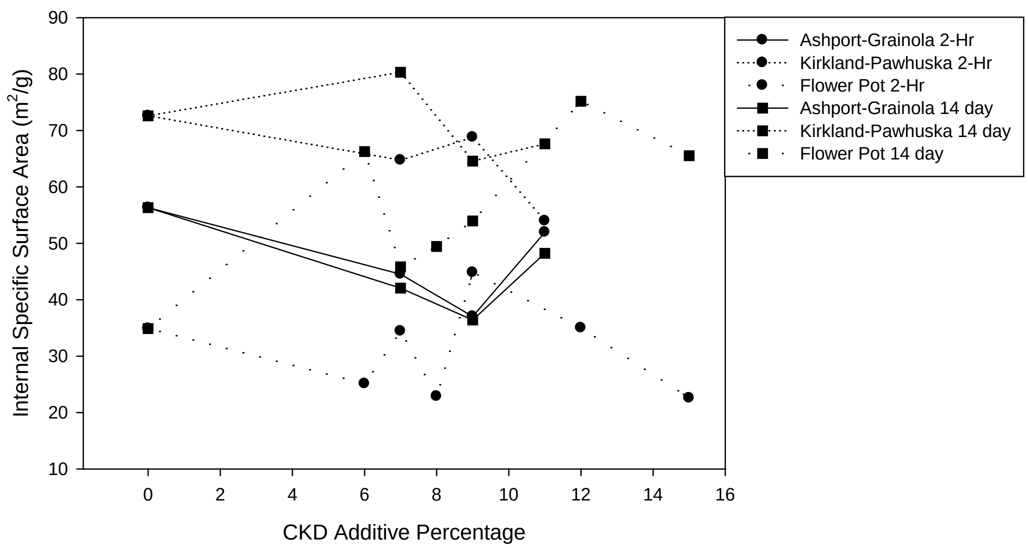

Figure A.117: Internal SSA Curves for A-6 Soils with CKD

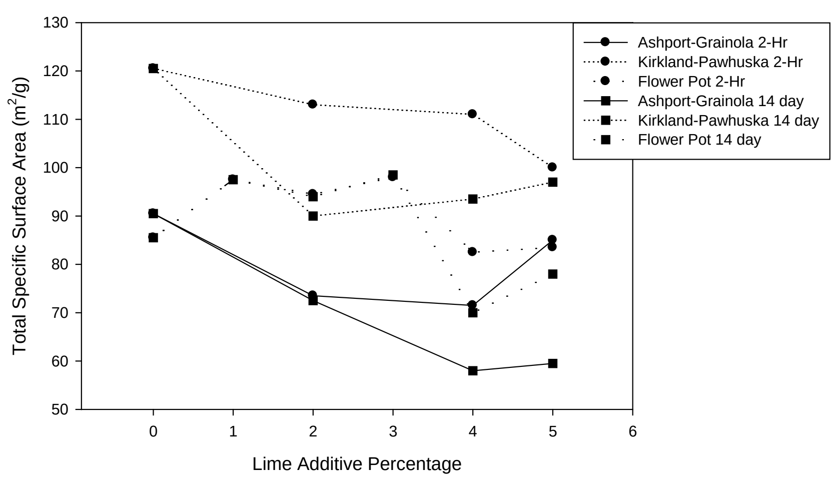

Figure A.118: Total SSA Curves for A-6 Soils with Lime

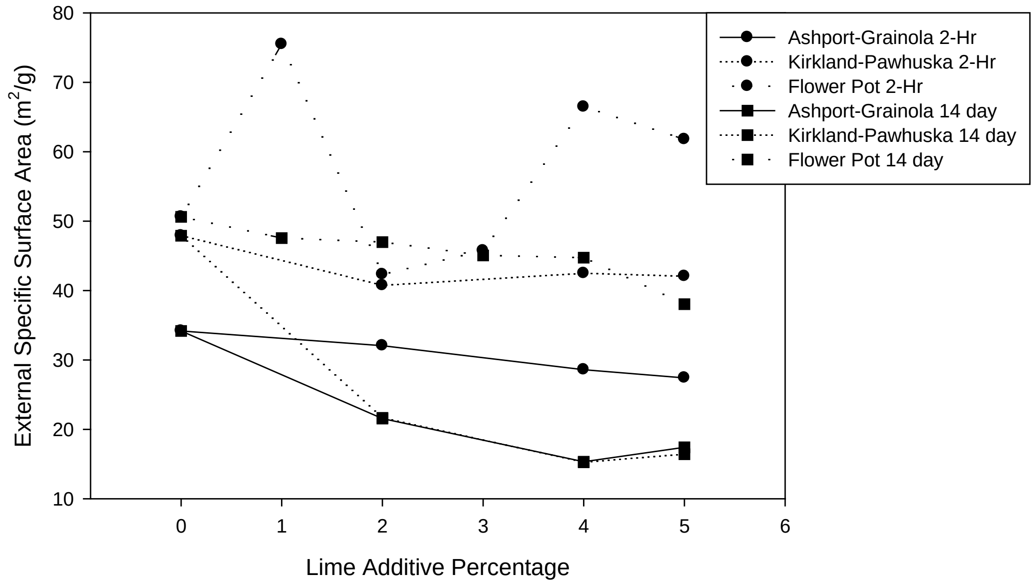

Figure A.119: External SSA Curves for A-6 Soils with Lime

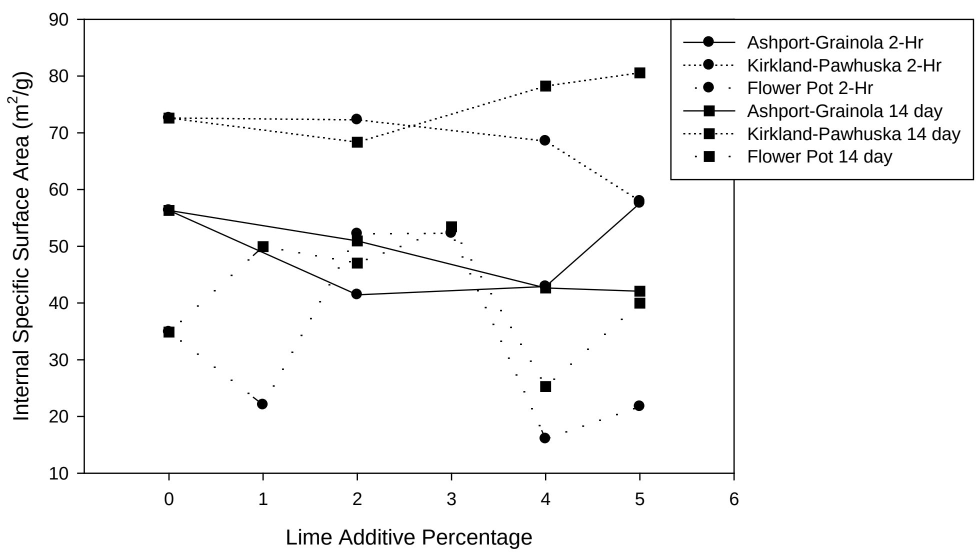

Figure A.120: Internal SSA Curves for A-6 Soils with Lime

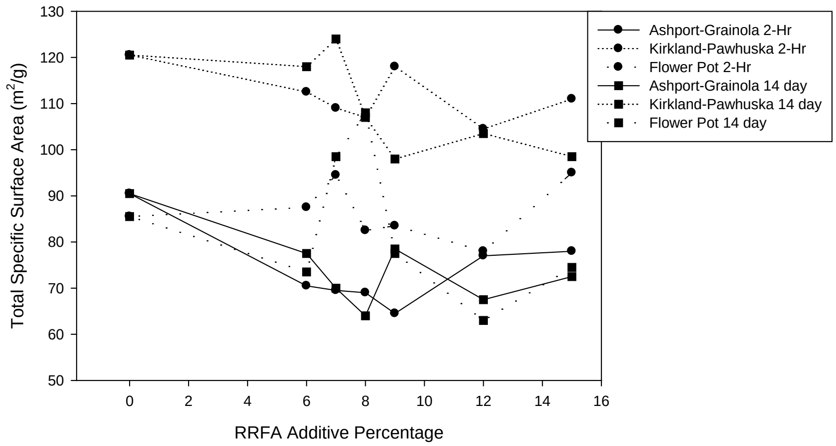

Figure A.121: Total SSA Curves for A-6 Soils with Red Rock FA

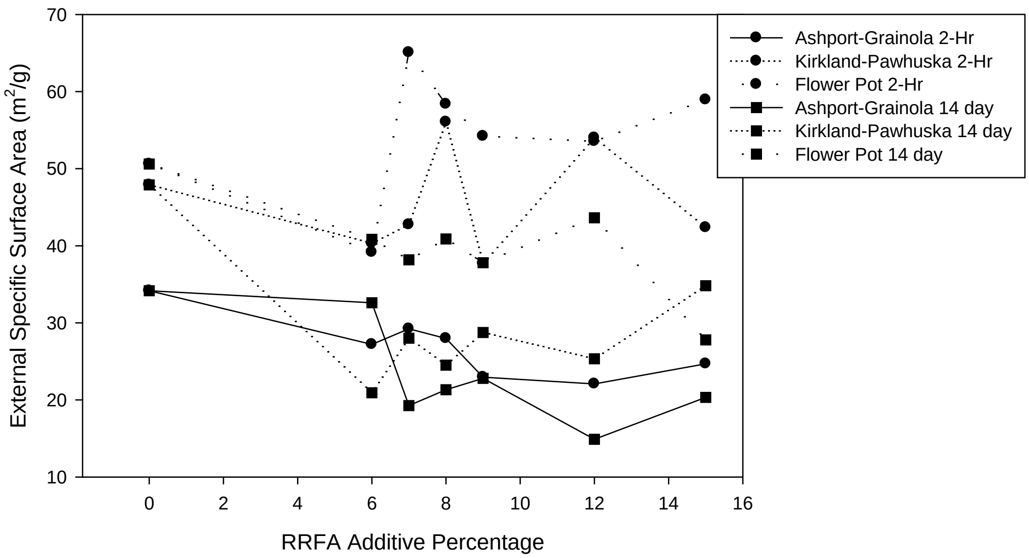

Figure A.122: External SSA Curves for A-6 Soils with Red Rock FA

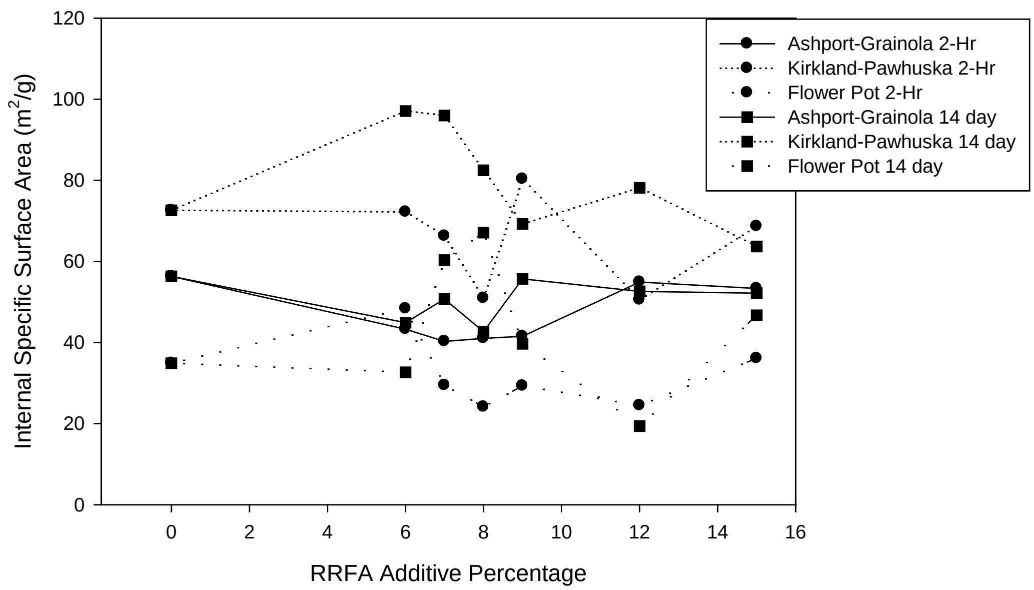

Figure A.123: Internal SSA Curves for A-6 Soils with Red Rock FA

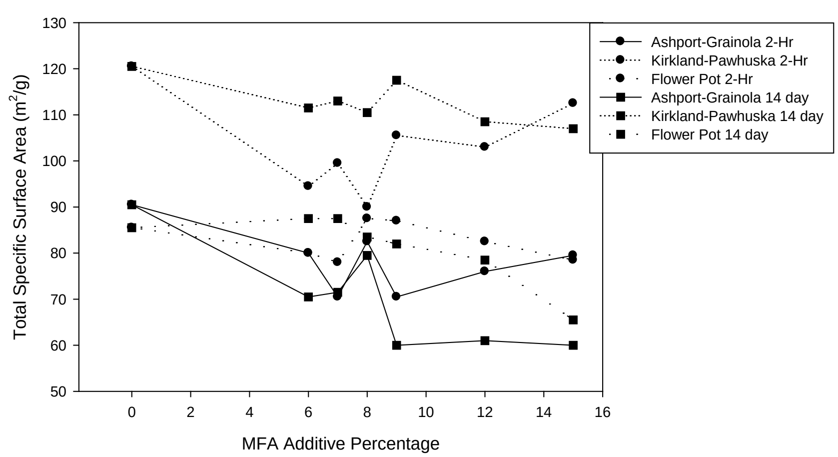

Figure A.124: Total SSA Curves for A-6 Soils with Muskogee FA

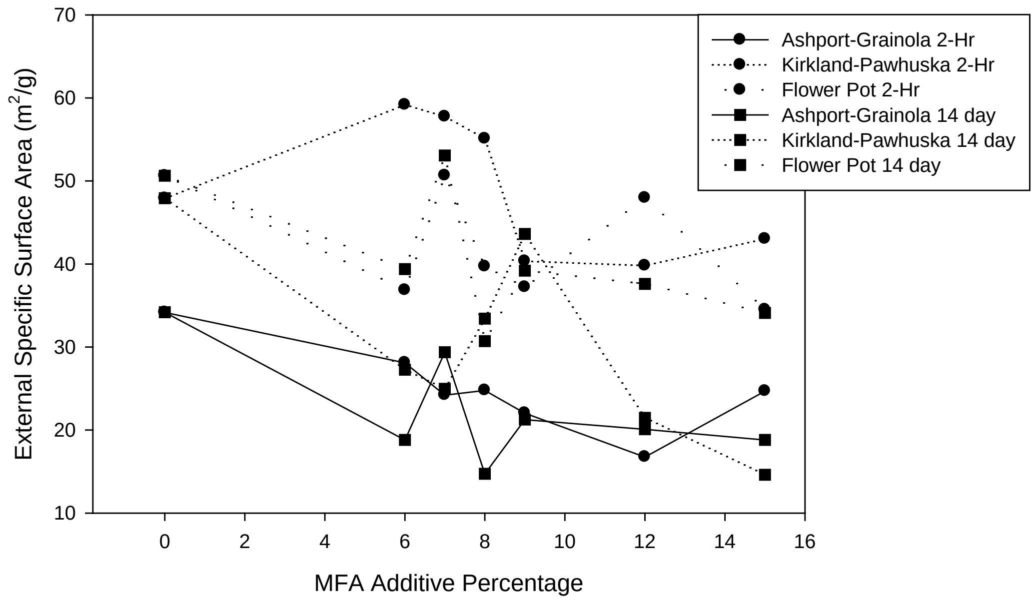

Figure A.125: External SSA Curves for A-6 Soils with Muskogee FA

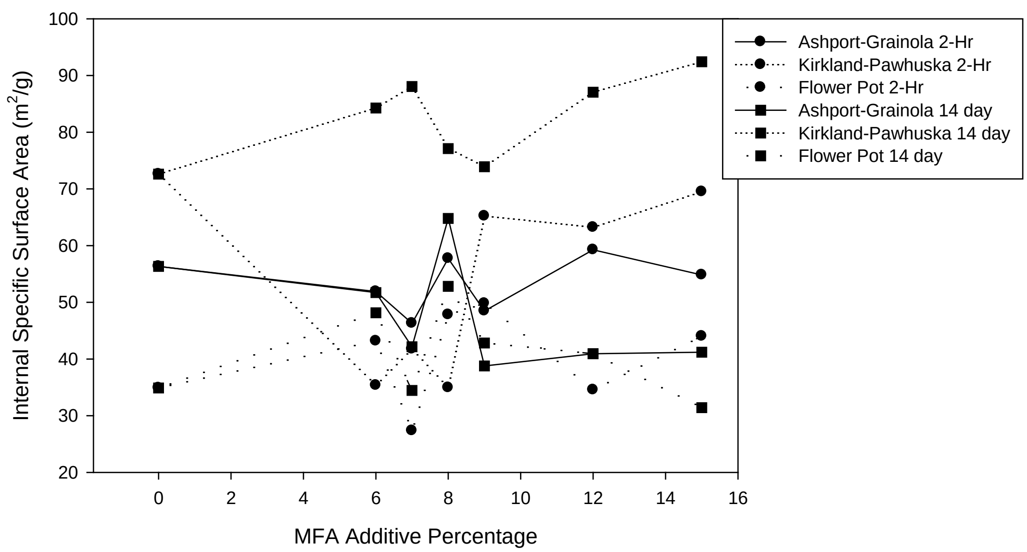

Figure A.126: Internal SSA Curves for A-6 Soils with Muskogee FA

Table A-35: Ashport-Grainola (A-6) Specific Surface Area Values

		2-hour Curing Time			14 Days Curing Time		
Additive Type	Additive Content	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)
Raw soil	0%	90.5	34.2	56.3			
Lime	2%	73.5	32.1	41.4	72.5	21.5	51.0
	4%	71.5	28.6	42.9	58.0	15.3	42.7
	5%	85.0	27.4	57.6	59.5	17.4	42.1
CKD	7%	73.0	28.5	44.5	62.5	20.4	42.1
	9%	63.5	26.5	37.0	65.5	29.1	36.4
	11%	79.0	27.1	51.9	60.5	12.3	48.2
RRFA	6%	70.5	27.2	43.3	77.5	32.6	44.9
	7%	69.5	29.2	40.3	70.0	19.3	50.7
	8%	69.0	28.0	41.0	64.0	21.3	42.7
	9%	64.5	23.0	41.5	78.5	22.8	55.7
	12%	77.0	22.1	54.9	67.5	14.9	52.6
	15%	78.0	24.7	53.3	72.5	20.3	52.2
MFA	6%	80.0	28.1	51.9	70.5	18.8	51.7
	7%	70.5	24.2	46.3	71.5	29.4	42.1
	8%	82.5	24.8	57.7	79.5	14.7	64.8
	9%	70.5	22.0	48.5	60.0	21.2	38.8
	12%	76.0	16.7	59.3	61.0	20.1	40.9
	15%	79.5	24.7	54.8	60.0	18.8	41.2

Table A-36: Kirkland-Pawhuska (A-6) Specific Surface Area Values

		2-hour Curing Time			14 Days Curing Time		
Additive Type	Additive Content	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)
Raw soil	0%	120.5	47.9	72.6			
Lime	2%	113.0	40.7	72.3	90.0	21.7	68.3
	4%	111.0	42.5	68.5	93.5	15.3	78.2
	5%	100.0	42.1	58.0	97.0	16.4	80.6
CKD	7%	99.0	34.3	64.7	104.0	23.7	80.3
	9%	101.5	32.7	68.8	90.5	25.9	64.6
	11%	90.0	36.0	54.0	96.0	28.4	67.6
RRFA	6%	112.5	40.3	72.2	118.0	20.9	97.1
	7%	109.0	42.7	66.3	124.0	28.0	96.0
	8%	107.0	56.1	50.9	107.0	24.5	82.5
	9%	118.0	37.7	80.3	98.0	28.8	69.2
	12%	104.5	54.0	50.5	103.5	25.3	78.2
	15%	111.0	42.4	68.6	98.5	34.8	63.7
MFA	6%	94.5	59.2	35.3	111.5	27.2	84.3
	7%	99.5	57.7	41.8	113.0	24.9	88.1
	8%	90.0	55.1	34.9	110.5	33.4	77.1
	9%	105.5	40.3	65.2	117.5	43.6	73.9
	12%	103.0	39.8	63.2	108.5	21.5	87.0
	15%	112.5	43.0	69.5	107.0	14.6	92.4

Table A-37: Flower Pot (A-6) Specific Surface Area Values

		2-hour Curing Time			14 Days Curing Time		
Additive Type	Additive Content	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)
Raw soil	0%	85.5	50.6	34.9			
Lime	1%	97.5	75.5	22.0	97.5	47.6	49.9
	2%	94.5	42.3	52.2	94.0	47.0	47.0
	3%	98.0	45.7	52.3	98.5	45.1	53.4
	4%	82.5	66.5	16.0	70.0	44.7	25.3
	5%	83.5	61.8	21.7	78.0	38.0	40.0
CKD	6%	87.5	62.4	25.1	112.5	46.2	66.3
	7%	89.5	55.1	34.4	90.5	44.7	45.8
	8%	85.0	62.1	22.9	92.5	43.1	49.4
	9%	94.5	49.7	44.8	98.5	44.5	54.0
	12%	94.5	59.5	35.0	109.5	34.3	75.2
	15%	67.5	44.9	22.6	107.0	41.5	65.5
RRFA	6%	87.5	39.2	48.3	73.5	40.8	32.7
	7%	94.5	65.1	29.4	98.5	38.2	60.3
	8%	82.5	58.4	24.1	108.0	40.9	67.1
	9%	83.5	54.2	29.3	77.5	37.8	39.7
	12%	78.0	53.5	24.5	63.0	43.6	19.4
	15%	95.0	58.9	36.1	74.5	27.8	46.7
MFA	6%	80.0	36.8	43.2	87.5	39.4	48.1
	7%	78.0	50.6	27.4	87.5	53.0	34.5
	8%	87.5	39.7	47.8	83.5	30.7	52.8
	9%	87.0	37.2	49.8	82.0	39.2	42.8
	12%	82.5	47.9	34.6	78.5	37.6	40.9
	15%	78.5	34.5	44.0	65.5	34.1	31.4

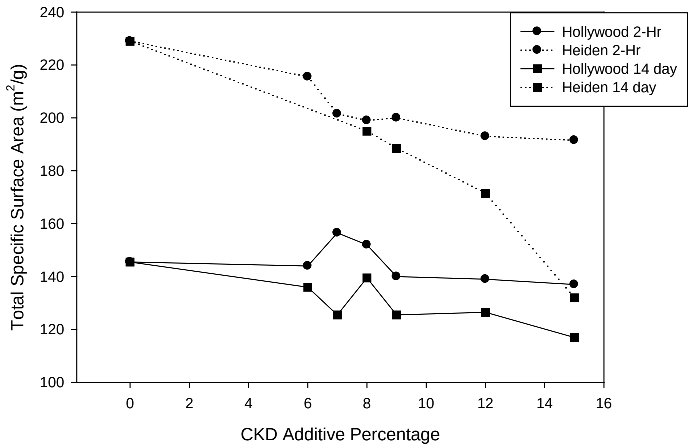

Figure A.127: Total SSA Curves for A-7-6 Soils with CKD

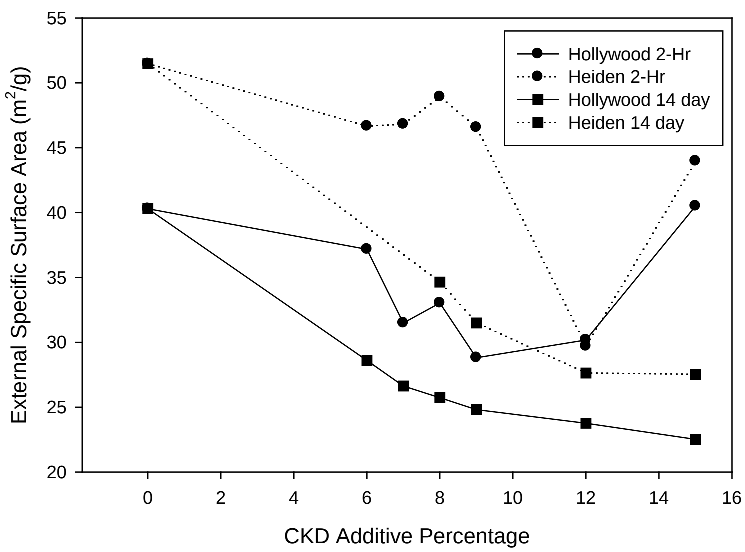

Figure A.128: External SSA Curves for A-7-6 Soils with CKD

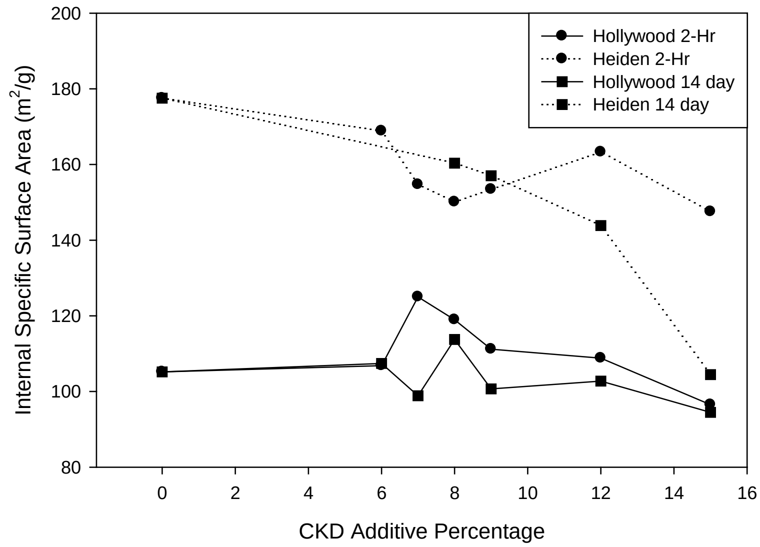

Figure A.129: Internal SSA Curves for A-7-6 Soils with CKD

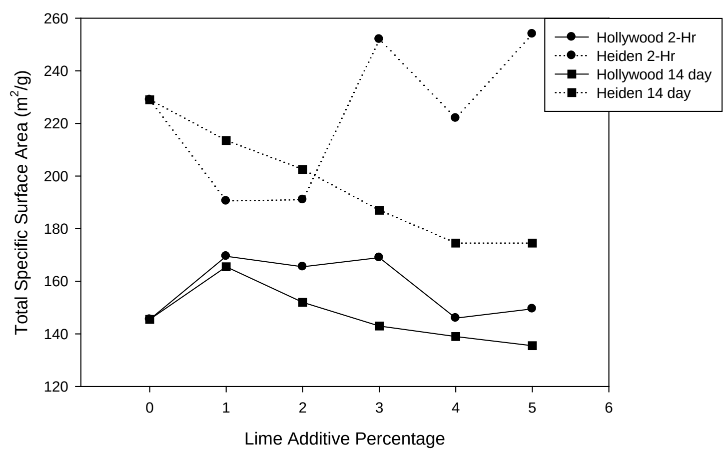

Figure A.130: Total SSA Curves for A-7-6 Soils with Lime

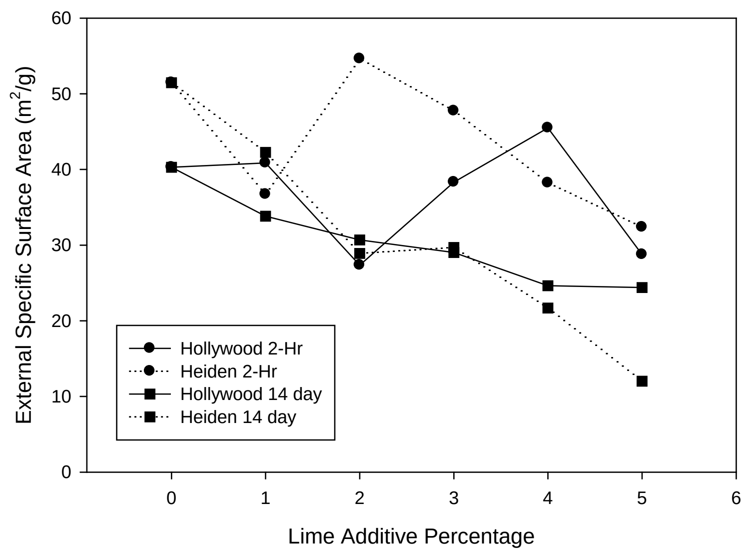

Figure A.131: External SSA Curves for A-7-6 Soils with Lime

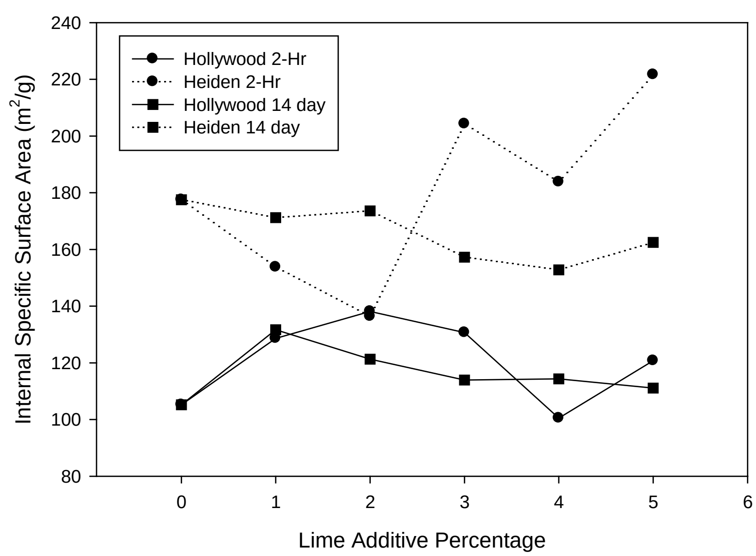

Figure A.132: Internal SSA Curves for A-7-6 Soils with Lime

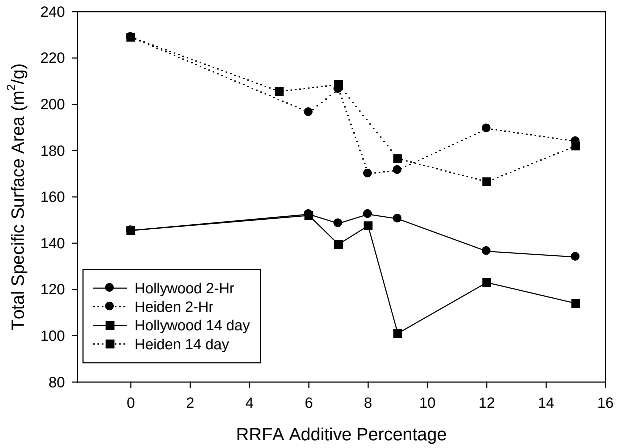

Figure A.133: Total SSA Curves for A-7-6 Soils with Red Rock FA

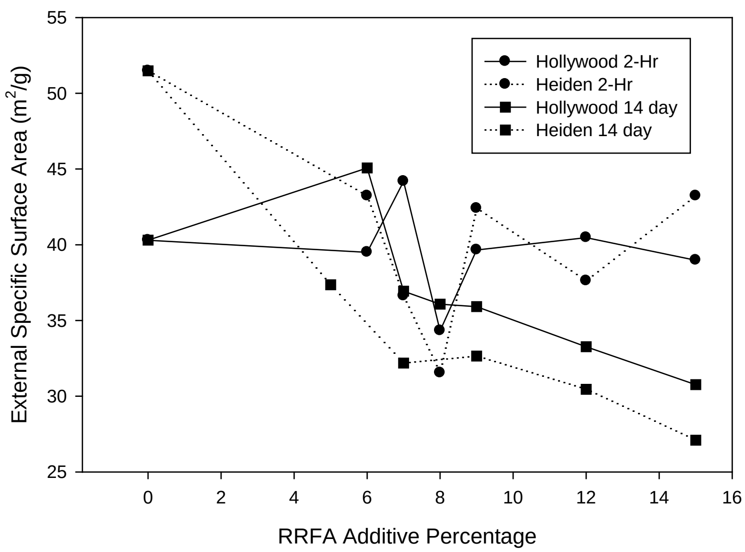

Figure A.134: External SSA Curves for A-7-6 Soils with Red Rock FA

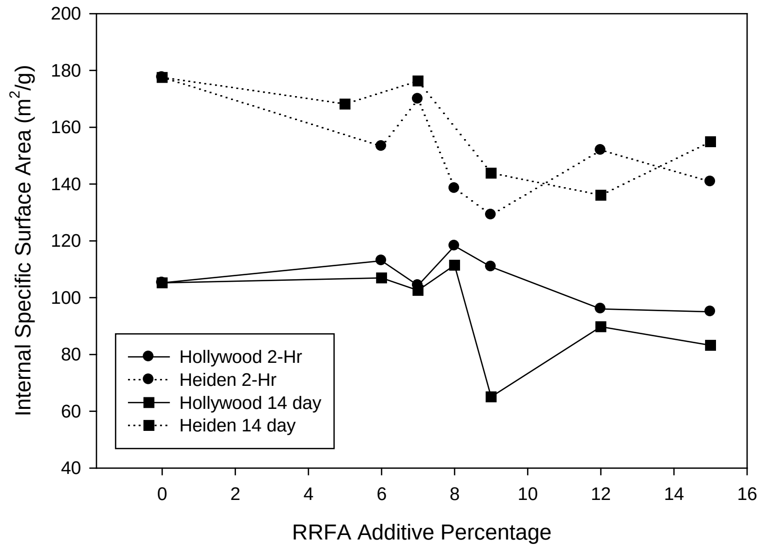

Figure A.135: Internal SSA Curves for A-7-6 Soils with Red Rock FA

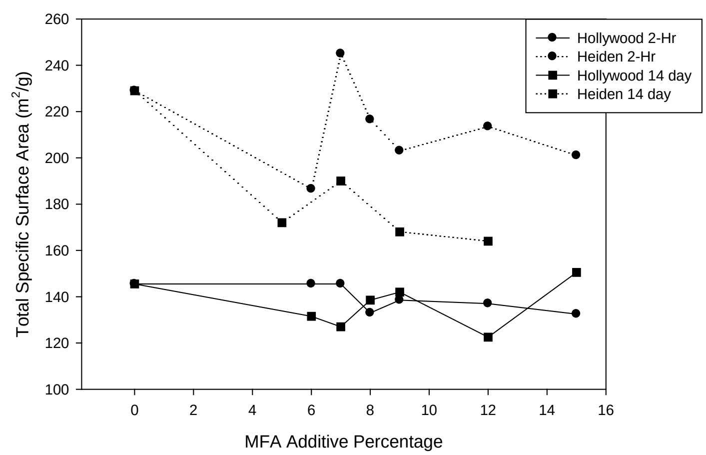

Figure A.136: Total SSA Curves for A-7-6 Soils with Muskogee FA

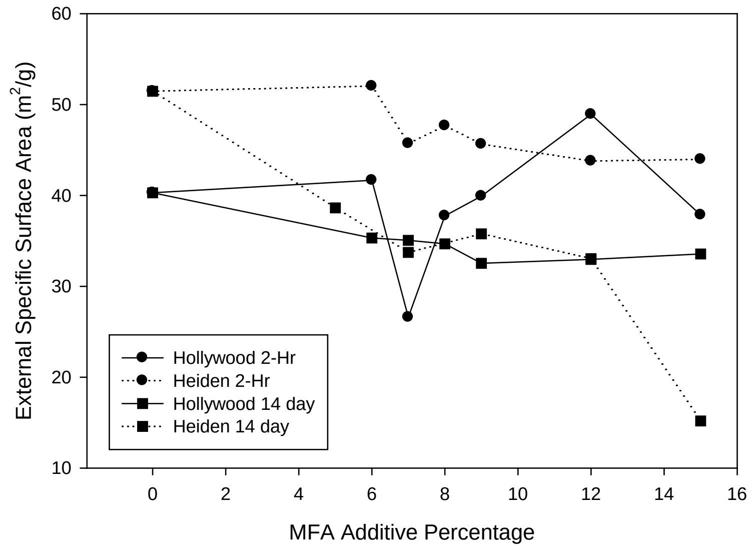

Figure A.137: External SSA Curves for A-7-6 Soils with Muskogee FA

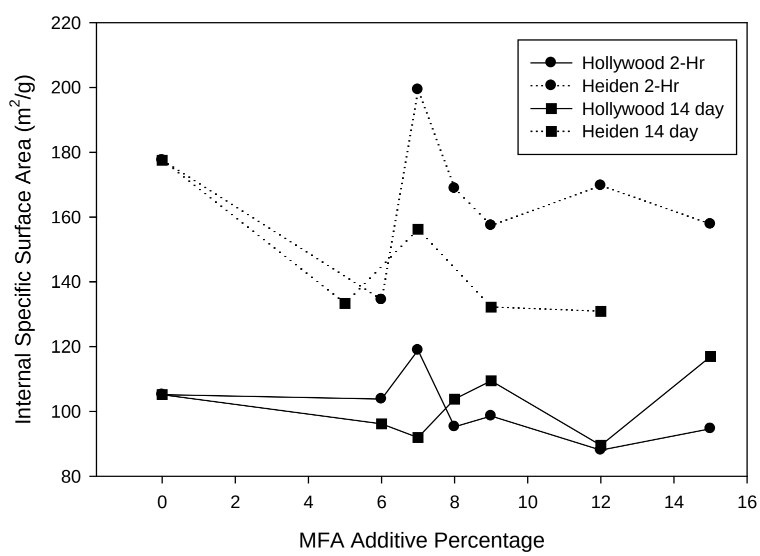

Figure A.138: Internal SSA Curves for A-7-6 Soils with Muskogee FA

Table A-38: Hollywood (A-7-6) Specific Surface Area Values

		2-hour Curing Time			14 Days Curing Time		
Additive Type	Additive Content	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)
Raw soil	0%	145.5	40.3	105.2			
Lime	1%	169.5	40.9	128.6	165.5	33.8	131.7
	2%	165.5	27.4	138.1	152.0	30.7	121.3
	3%	169.0	38.3	130.7	143.0	29.0	114.0
	4%	146.0	45.5	100.5	139.0	24.6	114.4
	5%	149.5	28.8	120.7	135.5	24.4	111.1
CKD	6%	144.0	37.2	106.8	136.0	28.6	107.4
	7%	156.5	31.5	125.0	125.5	26.6	98.9
	8%	152.0	33.0	119.0	139.5	25.7	113.8
	9%	140.0	28.8	111.2	125.5	24.8	100.7
	12%	139.0	30.2	108.8	126.5	23.8	102.7
	15%	137.0	40.5	96.5	117.0	22.5	94.5
RRFA	6%	152.5	39.5	113.0	152.0	45.1	106.9
	7%	148.5	44.2	104.3	139.5	36.9	102.6
	8%	152.5	34.3	118.2	147.5	36.1	111.4
	9%	150.5	39.7	110.8	101.0	35.9	65.1
	12%	136.5	40.5	96.0	123.0	33.3	89.7
	15%	134.0	39.0	95.0	114.0	30.8	83.2
MFA	6%	145.5	41.7	103.8	131.5	35.3	96.2
	7%	145.5	26.6	118.9	127.0	35.1	91.9
	8%	133.0	37.8	95.2	138.5	34.7	103.8
	9%	138.5	39.9	98.6	142.0	32.5	109.5
	12%	137.0	48.9	88.1	122.5	33.0	89.5
	15%	132.5	37.9	94.6	150.5	33.6	116.9

Table A-39: Heiden (A-7-6) Specific Surface Area Values

		2-hour Curing Time			14 Days Curing Time		
Additive Type	Additive Content	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)
Raw soil	0%	229.0	51.5	177.5			
Lime	1%	190.5	36.7	153.8	213.5	42.3	171.2
	2%	191.0	54.6	136.4	202.5	28.9	173.6
	3%	252.0	47.7	204.3	187.0	29.7	157.3
	4%	222.0	38.2	183.8	174.5	21.7	152.8
	5%	254.0	32.4	221.6	174.5	12.0	162.5
CKD	6%	215.5	46.7	168.8	-	-	-
	7%	201.5	46.8	154.7	-	-	-
	8%	199.0	48.9	150.1	195.0	34.6	160.4
	9%	200.0	46.6	153.4	188.5	31.5	157.0
	12%	193.0	29.7	163.3	171.5	27.6	143.9
	15%	191.5	44.0	147.5	132.0	27.5	104.5
RRFA	5%	-	-	-	205.5	37.4	168.1
	6%	196.5	43.2	153.3	-	-	-
	7%	206.5	36.6	169.9	208.5	32.2	176.3
	8%	170.0	31.5	138.5	-	-	-
	9%	171.5	42.4	129.1	176.5	32.6	143.9
	12%	189.5	37.6	151.9	166.5	30.5	136.0
	15%	184.0	43.2	140.8	182.0	27.1	154.9
MFA	5%	-	-	-	172.0	38.6	133.4
	6%	186.5	52.0	134.5	-	-	-
	7%	245.0	45.7	199.3	190.0	33.7	156.3
	8%	216.5	47.7	168.8	-	-	-
	9%	203.0	45.6	157.4	168.0	35.8	132.2
	12%	213.5	43.8	169.7	164.0	33.1	130.9
	15%	201.0	44.0	157.0	-	15.2	-