Tube Suction Test for Evaluating Durability of Cementitiously Stabilized Soils

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16. ABSTRACT

In a comprehensive laboratory study, different tests namely, unconfined compressive strength (UCS) at the end of freeze-thaw/wet-dry (F-T/W-D) cycles, resilient modulus (M_r) at the end of F-T/W-D cycles, vacuum saturation, tube suction, and moisture susceptibility tests were used for evaluating durability of cementitiously stabilized subgrade soils. Five clay soils commonly encountered as subgrades in Oklahoma, namely, Port (silty clay with sand), Kingfisher (lean clay), Carnasaw (fat clay), Dennis (fat clay), and Lomill (fat clay) series, were utilized. These soils were stabilized with 6% hydrated lime (or lime), 10% class C fly ash (CFA), and 10% cement kiln dust (CKD). Cylindrical specimens of three different sizes were compacted and cured for 7 days. Then, Harvard miniature specimens were tested for UCS at the end of F-T/W-D cycles and moisture susceptibility (5-hour soaking). Additionally, cylindrical specimens were tested for M_r at the end of F-T and W-D cycles for evaluating the effect of F-T and W-D cycles on M_r values. Further, Proctor size specimens were tested for UCS after vacuum saturation test. Additionally, a total of three different methods were used for conducting tube suction tests by taking into account different specimen sizes (4.0 in. x 4.0 in., 6.0 in. x 6.0 in., 4.0 in. x 8.0 in.) and compaction methods (standard Proctor and Superpave gyratory compactor). All the specimens showed a decrease in the UCS values at the end of F-T cycles and vacuum saturation. All the specimens tested in this study, in general, showed an increase in the UCS values at the end of 1 W-D cycle. The M_r values of both raw and stabilized soil specimens were found to decrease with an increase in the number of F-T or W-D cycles. Overall, the Port series soil specimens (silty clay with sand) stabilized with 10% CKD offered maximum resistance towards F-T and W-D cycles. A similar trend of behavior is evident from the results obtained by moisture susceptibility and vacuum saturation tests where the Port series soil specimens stabilized with 10% CKD produced the highest retained UCS values. The Kingfisher series soil specimens (lean clay) did not show any clear trend with one particular additive. However, specimens stabilized with 6% lime and 10% CKD showed better performance, as compared to specimens stabilized with 10% CFA. All three fat clays used in this study (Carnasaw, Dennis, and Lomill) showed maximum resistance towards F-T and W-D cycles after stabilizing with 6% lime as compared to 10% CFA and 10% CKD. This fact was also evident from both moisture susceptibility and vacuum saturation tests. Further, a strong correlation ($R^2 \approx 0.70 - 0.86$) between retained UCS after moisture susceptibility test and other durability indicators such as retained UCS after 1 F-T cycle, retained UCS after 1 W-D cycle, and retained M_r after 1 F-T cycle is evident from this study. This is an indication that moisture susceptibility could be used for evaluating long-term performance of stabilized soil specimens.

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Approximate Conversions to SI Units					Approximate Conversions from SI Units				
Symbol	When you know	Multiply by	To Find	Symbol	Symbol	When you know	Multiply by	To Find	Symbol
LENGTH					**LENGTH**				
in	inches	25.4000	millimeters	mm	mm	millimeters	0.0394	inches	in
ft	feet	0.3048	meters	m	m	meters	3.2810	feet	ft
yd	yards	0.9144	meters	m	m	meters	1.0940	yards	yds
mi	miles	1.6090	kilometers	km	km	kilometers	0.6214	miles	mi
AREA					**AREA**				
in^2	square inches	645.2000	square millimeters	mm^2	mm^2	square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.0929	square meters	m^2	m^2	square meters	10.7640	square feet	ft^2
yd^2	square yards	0.8361	square meters	m^2	m^2	square meters	1.1960	square yards	yd^2
ac	acres	0.4047	hectacres	ha	ha	hectacres	2.4710	acres	ac
mi^2	square miles	2.5900	square kilometers	km^2	km^2	square kilometers	0.3861	square miles	mi^2
VOLUME					**VOLUME**				
fl oz	fluid ounces	29.5700	milliliters	mL	mL	milliliters	0.0338	fluid ounces	fl oz
gal	gallon	3.7850	liters	L	L	liters	0.2642	gallon	gal
ft^3	cubic feet	0.0283	cubic meters	m^3	m^3	cubic meters	35.3150	cubic feet	ft^3
yd^3	cubic yards	0.7645	cubic meters	m^3	m^3	cubic meters	1.3080	cubic yards	yd^3
MASS					**MASS**				
oz	ounces	28.3500	grams	g	g	grams	0.0353	ounces	oz
lb	pounds	0.4536	kilograms	kg	kg	kilograms	2.2050	pounds	lb
T	short tons (2000 lb)	0.9070	megagrams	Mg	Mg	megagrams	1.1023	short tons (2000 lb)	T
TEMPERATURE (exact)					**TEMPERATURE (exact)**				
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C	°C	degrees Celsius	9/5(°C)+32	degrees Fahrenheit	°F
FORCE and PRESSURE or STRESS					**FORCE and PRESSURE or STRESS**				
lbf	poundforce	4.4480	Newtons	N	N	Newtons	0.2248	poundforce	lbf
lbf/in^2	poundforce per square inch	6.8950	kilopascals	kPa	kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

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1.1 Background

The demand for pavement networks in the United States is greater than ever, and the conditions of existing roadways are worsening due to heavier vehicles and increased volume. According to the recent report by AASHTO/TRIP, only half of the nation's major roads are in good condition (AASHTO, 2009). This report found that major urban centers have the roughest roads – some with more than 60% of roads in poor condition. Weak subgrade soils are a leading factor in this regard. In the last few decades, pavement engineers have been challenged to build, repair and maintain pavement systems with enhanced longevity and reduced costs. Specifically, efforts have been made to improve the design methodology (AASHTO, 2004) and to establish techniques for modification of highway pavement materials. Cementitious stabilization is one of these techniques; it enhances the engineering properties of subgrade soils, which is essential for structurally sound pavements.

Although cementitious stabilization is widely used in the United States including Oklahoma to improve subgrade soil properties, the effect of freeze-thaw (F-T) and wet-dry (W-D) conditions, referred to as "durability" (or long-term performance), is not frequently addressed. Also, detrimental effects of climatic conditions (F-T and W-D) on our national pavement infrastructure have been highlighted by AASHTO and recent NCHRP reports (Little and Nair, 2009; AASHTO/TRIP, 2009). Knowledge about the long-term performance of cementitiously stabilized subgrade soils is expected to be helpful in the development of rational design procedures for better pavements in Oklahoma.

1.2 Need for This Study

Previous studies reveal no widely accepted laboratory procedure to evaluate the durability of cementitiously stabilized subgrade soils. Among "conventional" laboratory procedures, the ASTM D 559 (Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures) and ASTM D 560 (Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures) test methods are standardized procedures for evaluating the effect of W-D and F-T cycles on cement-stabilized materials, respectively. On the other hand, the durability of materials treated with fly ash, lime-fly ash, and lime is determined using the vacuum saturation test in accordance with the ASTM C 593 (Standard Specification for Fly Ash and Other Pozzolans for Use with Lime) test method. However, these different durability tests exhibit varying degrees of severity. For example, the "conventional" ASTM tests that are based on the weight loss are considered overly severe and abrasive and do not simulate the field conditions (Kalankamary and Donald, 1963).

Furthermore, most of the agencies (e.g., AFJMAN, 1994; ILDOT, 2005; INDOT, 2008; OHDOT, 2007) including ODOT (*OHD L-50: Soil Stabilization Mix Design Procedure*) use unconfined compressive strength testing as the sole criterion for determining additive content for the soil stabilization mix design (see summary in Table 1.1). However, the current AASHTO 2002 Mechanistic-Empirical Pavement Design Guide (MEPDG) recommends verification of durability requirements in the mix design process (AASHTO, 2004). Also, this requirement is emphasized in a Transportation Research Circular E-C086: Evaluation of Chemical Stabilizers (Petry and Sobhan, 2005) and a recent NCHRP report (Little and Nair, 2009).

From the aforementioned reviews it is evident that although durability is an important pavement design parameter, many transportation agencies, including ODOT, do not evaluate durability partly due to time/financial constraints and non-availability of standardized procedures. For this reason, the present study compared different tests including the new Tube Suction Test (TST) for evaluating durability of cementitiously stabilized soils. A greater understanding of these tests is needed to enable more objective selection of durability tests by pavement engineers and to facilitate more meaningful comparisons of data obtained for different cementitious additive (or stabilizer) treatments using different evaluation procedures. The experimental program undertaken in the present study is an attempt to address this concern.

1.3 Objectives

The primary objective of this study is to evaluate the effect of durability of cementitiously stabilized subgrades in Oklahoma. To that end, five different types of soils, namely, Port series (silty clay with sand), Kingfisher series (lean clay), Carnasaw series (fat clay), Dennis series (fat clay), and Lomill series (fat clay) collected from composite B and/or C horizons were stabilized with hydrated lime, class C fly ash (CFA), and cement kiln dust (CKD). The more specific tasks include the following:

1. Classify the collected soils and develop moisture-density relationship for all five soils stabilized with three different cementitious additives.
2. Evaluate the deleterious effects of conventional F-T and W-D on the properties namely, unconfined compressive strength (UCS) and resilient modulus (M_r) of cementitiously stabilized soil specimens.

3. Evaluate the durability comparing UCS values by conducting moisture susceptibility tests, i.e,. soaking of specimens for 5 hours.
4. Evaluate the durability by comparing UCS values of cementitiously stabilized specimens before and after vacuum saturation testing.
5. Determine the dielectric constant values (DV) of the stabilized specimens by conducting tube suction test.
6. Conduct statistical analyses for developing correlations among different long-term performance parameters collected by conducting different durability tests.

1.4 Organization of the Report

This report is organized into five chapters including this "Introduction" chapter. Chapter 2 presents a literature review of different durability tests including F-T, W-D, vacuum saturation, and TST studies conducted at research institutions around the world. Chapter 3 focuses on the properties of different soils and stabilizers used in this study. This chapter also discusses the various laboratory durability tests and sample preparation methods that are used in this study. The final results are presented and discussed in Chapter 4 in the form of graphs and tables. And lastly, the summary, conclusions and recommendations are given in the final chapter – Chapter 5.

Table 1.1: Summary of Recommended Procedures by Different Agencies for Evaluating Durability of Stabilized Soils

Agency	Specification/ Reference	Type of additive	Procedure	Requirements
American Society for Testing and Materials (ASTM)	ASTM D 4609 (2001)	Chemicals	Unconfined compressive strength on raw, cured specimens and 2-day moisture conditioned samples	UCS_t > 50 psi + UCS_r
Department of Air Force and Army	AFJMAN (1994)	Lime, PC	Cured specimens (28-day for lime-stabilized, 7-day cement-stabilized at 73^{o}F) are subjected to 12 cycles of W-D or F-T in accordance with ASTM D 559 or 560, respectively and tested for UCS	UCS_t≥250 psi (for flexible pavement), UCS_t≥200 psi (for rigid pavement)
Illinois DOT (ILDOT)	PTA-D7/ IDOT (2005)	Lime, PC	Unconfined compressive strength on raw and treated specimens	$UCS_{t,L}$ > 50 psi + UCS_r $UCS_{t,L}$ ≥ 100 psi $UCS_{t,PC}$ ≥ 500 psi
Indiana DOT (INDOT)	INDOT (2008)	Lime, PC	Unconfined compressive strength on cured specimens (2-days at 120^{o}F)	$UCS_{t,L}$ > 50 psi + UCS_r $UCS_{t,c}$ ≥ 100 psi + UCS_r
Ohio DOT (OHDOT)	Supplement 1120/ OHDOT (2007)	Lime, PC	Cured specimens (7-day at 104^{o}F) followed by moisture conditioning of specimens through capillary soaking for 1-day before UCS test	$UCS_{t,L}$> 50 psi + UCS_r $UCS_{t,L}$ ≥ 100 psi $UCS_{t,PC}$ > 50 psi + UCS_r $UCS_{t,\ PC}$≥ 150 psi
Oklahoma DOT (ODOT)	OHD L-50/ ODOT (2006)	PC, CFA, CKD	Cured specimens (one for 7-day, another for 5-day followed by 2-day of moisture conditioning through immersion in water) at 73^{o}F before UCS test	Without moisture conditioning: $UCS_{t,PC,\ CFA,\ CKD}$ > 50 psi + UCS_r $UCS_{t,PC,\ CFA,\ CKD}$ < 150 psi Moisture conditioned: $UCS_{t,PC,\ CFA,\ CKD}$ > 50 psi + UCS_r
Texas DOT (TXDOT)	Tex 121-E/ TXDOT (2002)	Lime	Cured specimens (7-day at room temperature) and air dried at 140^{o}F to loose 1/3 – ½ of molding moisture content	$UCS_{t,L}$ > 50 psi + UCS_r
Texas DOT (TXDOT)	Tex 135-E/ TXDOT (2002)	PC	Cured specimens (7-day at 140^{o}F) are subjected to 12 cycles of F-T in accordance with ASTM D 560, and weight loss is determined	---

DOT: Department of Transportation; UCS: unconfined compressive strength; t: treated soil; r: raw soil
W-D: wet-dry; F-T: freeze-thaw; L: Lime; PC: Portland cement; CFA: class C fly ash; CKD: cement kiln dust

2.1 General

A review of previous studies reveals no widely accepted laboratory procedure to evaluate the durability of cementitiously stabilized subgrade soils. Hence, a summary of the different experimental procedures for evaluating durability of stabilized soil specimens is presented in this chapter.

2.2 Freeze-Thaw (F-T) and Wet-Dry (W-D) Cycling

Soil specimens subjected to F-T or W-D cycles provide an indication of how those specimens will maintain engineering parameters in the field when exposed to diverse environmental conditions. Among "conventional" laboratory procedures, the ASTM D 559 and ASTM D 560 test methods are the only existing standardized procedures for evaluating the effect of W-D and F-T cycles on cement-stabilized soil specimens. These methods consist of mixing soil and additive at optimum moisture content and compacting with standard effort in a 4-in. diameter Proctor mold. After compaction, the specimens are cured for 7 days in a humidity room and then subjected to a series of F-T or W-D cycles. After completion of each cycle, the specimen is brushed on all sides with a wire brush and effect of F-T or W-D cycles is measured in terms of percent weight loss. As a result of the variability associated with the brushing process, many agencies and researchers omit the brushing portion of the test and replace it with unconfined compressive strength (UCS) testing after completion of all 12 cycles (Shihata and Baghdadi, 2001).

The effects of F-T cycles on the durability of stabilized materials were addressed by Dempsey et al. (1973). In that study, two typical Illinois soils, namely, Illinoisan till and

Ridgeville fine sandy loam were used. Soils were mixed with lime and cement, and then compacted in a 2-in. diameter by 4-in. height mold in three layers. Then, lime- and cement-stabilized specimens were cured for 48 hours at 120^{o}F and 7 days at 77^{o}F, respectively. The main objective of this study was to evaluate the different parameters for developing a characteristic F-T cycle for laboratory use. A total of four parameters namely, cooling rate, freezing temperature, length of freezing period and thawing temperature were evaluated. It was found that a slow cooling rate between 0.2 and 1^{o}F/hr, a freezing period not necessarily greater than that required for accomplishing a complete freezing of the test specimen, and number of cycles related to geographical location and climatic conditions are the main parameters that influenced the development of the laboratory F-T test.

Petry and Wohlgemuth (1988) prepared specimens of highly plastic soils (PI 64 to 77) stabilized with lime and Portland cement. After 7 days of curing, specimens were subjected to 12 W-D cycles in accordance with the ASTM D 559 test method; however, the wire brushing called for in the specification was not performed. The results indicated that the lime-stabilized specimens retained their integrity better than the Portland cement specimens, at each gradation level. The theory of "water proofing" was used to explain the performance differences between cement and lime.

In a laboratory study from Malaysia, Noor (1994) examined the durability and strength characteristics of cement-stabilized Melaka series. A comparison of the relationship between strength and durability of cement-stabilized Melaka series was carried out. Five cylindrical specimens were prepared at varying cement content and tested for UCS after being subjected to wetting and drying in accordance with the ASTM D 559 test method. Results showed that the stabilized specimens of Melaka series satisfied the strength criterion of 247 psi in accordance with BS 1924 (1975) specification. Also, it was found that the percentage of weight loss in W-D tests was well within the durability limits recommended by the ASTM D 559 test method. It has been deduced that the strength criterion alone is adequate in determining the potential of cement-stabilized soil for roadbase.

In another laboratory study, Viklander (1997) investigated the permeability and volume changes in till due to F-T cycles. In this study, a frequently used fine-grained nonplastic till was compacted in three types of rigid wall permeameters having different volumes. Then, the specimens were exposed to 18 F-T cycles and vertical permeability was measured at the end of each cycle. It was found that vertical permeability slightly decreased with an increase in the number of F-T cycles. It was also reported that the initial void ratio and the degree of compaction have significant impact on the microstructural changes in soil when exposed to F-T cycles.

At the Royal Institute of Technology in Sweden, Simonsen and Isacsson (1999) studied soil behavior during freezing and thawing using variable and constant confining pressure triaxial tests. In this study, two subgrade sands and one subbase gravel were investigated with regard to resilient behavior during F-T cycles. The specimens were compacted using a vibrating hammer for lower densities and a gyratory compactor for higher densities. Each specimen was tested at five different temperatures namely, 68, 32, 30.2, 23, and 14^{o}F (i.e., 20, 1, -1, -5, and -10^{o}C). The aim of this study was to compare the resilient performance in Constant Confining Pressure (CCP) and Variable Confining Pressure (VCP) conditions during freezing and thawing. It was found that at non freezing temperatures, the VCP moduli are about 45-55% lower than the CCP moduli, while at freezing temperatures the difference decreases to 20%. It was also observed that the influence of confining pressure was more significant in the CCP than in the VCP test. Also, shear strains at non freezing and subfreezing were comparable for both tests while volumetric strain values were not comparable. No conclusive effect of F-T on resilient behavior could be established. Some samples showed a significant reduction in M_r after F-T whereas other samples remained unaffected.

In a study on wood ash-modified Black Cotton soil, Rao et al. (2000) evaluated the impact of W-D cycles on the swelling behavior of stabilized expansive soils. Specimens were prepared by stabilizing with different percentages of hydrated lime namely, 2%, 4%, and 7%. Then, the specimens were cured in a desiccator for 10 days followed by four W-D cycles. Each wetting cycle consisted of subjecting the specimens in consolidated rings to wetting by allowing them to absorb moisture from a wet sand bath for about 48 hours. Then, the specimens were dried by subjecting them to a temperature of 104^{o}F (40^{o}C) using a hot air circulator. The influence of cyclic wetting and drying on the swelling behavior of the stabilized soils was examined. It was found that cyclic wetting and drying caused the specimens to become more porous and less saturated and it also caused the specimens to collapse at flooding pressures. The beneficial effect of the lime stabilization was partially lost during this experiment. Also, it was observed that the clay content in the specimens increased with the cyclic wetting and drying which in turn affected the Atterberg limits and swell shrink potentials.

In a combined laboratory and field study from Oklahoma, Miller and Zaman (2000) investigated the durability of CKD-stabilized soil by performing UCS on samples subjected to F-T and W-D cycles separately. Tests were conducted on 7-day cured three combinations of soil and additives, namely, CKD with sand, CKD with shale, and quicklime with shale. One

W-D cycle consisted of immersing samples in water for 5 hours, followed by oven drying for 24 hours at 160^{o}F (71^{o}C). Samples that survived were subjected to UCS after 0, 1, 3, 7, and 12 W-D cycles. The UCS tests were conducted after the drying cycle so that moisture conditions would be uniform for each sample tested. The same procedure was used to prepare and cure samples during F-T testing. One F-T cycle consisted of placing samples in a freezer at -9^{o}F (-23^{o}C) for 24 hour and then pacing in a moisture chamber under controlled humidity of 95% and temperature of about 73^{o}F (23^{o}C). UCS tests were conducted after 0, 1, 3, 7, and 12 cycles. Specimens were tested at the end of thawing period. CKD-stabilized shale specimens showed an increase in UCS values for the first three W-D cycles, beyond which the samples did not survive immersion in water. On the other hand, specimens stabilized with quicklime survived only one W-D cycle. Sand specimens stabilized with CKD showed an increase in UCS values over the full 12 cycles of W-D. Contrary to W-D cycles, all the specimens survived 12 F-T cycles.

Guettala et al. (2002) examined both F-T and W-D durability of earth blocks with the increase of sand content. Specimens were subjected to F-T and W-D cycles in accordance with the ASTM D 560 and 559 test methods, respectively. F-T tests were carried out by placing the soil specimens on an absorbent water saturated pad at a temperature of -9.4^{o}F (-23^{o}C) for a period of 24 hours and then thawed in a moist environment at 70^{o}F (21^{o}C). It was observed that by increasing the sand content to 30%, the weight loss reaches a plateau and stops decreasing. Each W-D cycles consisted of immersing the specimens in water for 5 hours and then drying at a temperature of 160^{o}F (71^{o}C) for 42 hours. The procedure was repeated for 12 cycles and the specimens were brushed after each cycle before weight loss was recorded. Results showed that weight loss decreases by 65% when the sand content is increased by 30%.

In a comparative study by Parsons and Milburn (2003), the durability of soils treated with different additives, namely, lime, CFA, Portland cement and enzymatic stabilizer were evaluated. After compaction of the soil-additive mix, the samples were cured for 7 days in a humidity room and then subjected to a series of F-T and W-D cycles. The cement-treated soils had the least weight loss in F-T testing, while CFA-treated soils had lower weight losses in F-T testing than the lime-treated soils. The relative performance in the W-D cycles was mixed; lime generally performed better on fine-grained materials and Portland cement on coarse-grained soils, although Portland cement performed relatively well with the CH clays. Additionally, CFA performed well only on the SM soil, where it survived the full 12 cycles.

In another study by Parsons and Kneebone (2004), eight different soils with classifications of CH, CL, ML, SM and SP were tested for F-T and W-D durability to evaluate the relative performance of CKD as a stabilizing agent. Results were compared with previous findings for the same soils stabilized with lime, cement, and fly ash. It was reported that the CKD treated soil samples' performance in W-D testing was similar to that for lime, fly ash and cement treated soils. However, CKD-stabilized samples were not as durable in F-T testing as lime, fly ash and cement treated soil samples.

Arora and Aydilek (2005) conducted F-T tests on silty sand (SM) stabilized with 40% class F fly ash in combination with cement or lime. It was found that the strength of specimens stabilized with class F fly ash and cement increased with an increasing number of F-T cycles. The increase in strength was more enhanced for mixtures that contained 7%

cement than for mixtures with 4 and 5% cement. Also, lime-stabilized specimens survived during F-T cycles but their strengths decreased with an increasing number of F-T cycles.

Guney et al. (2005) investigated the impact of W-D cycles on the swelling behavior of lime-stabilized clayey soils. A total of three types of clays were stabilized by adding 3% and 6% lime by weight of soil. Then, the specimens were subjected to 4 W-D cycles. Each W-D cycle consisted of inundating the specimen in tap water for 60 hours followed by air drying at room temperature to its initial water content. The results showed that the initial beneficiary effect of lime stabilization was lost after the first W-D cycle and the swelling potential increased during the subsequent cycles. On the other hand, the swelling potential and the swelling pressure of the raw clay samples started decreasing after the first cycle and they reached equilibrium after the fourth cycle.

In a study from Malaysia, Deboucha and Hashim (2009) investigated the effect of additives namely, binder (5, 10 and 15%), 85% cement and 15% bentonite, and different percentages of sand (5 to 25%), on the durability of tropical peat soils. Durability was evaluated by stabilized sample for unconfined compressive strength after inundating in water. It was found that the increase in the percentage of binder from 5 to 15% enhances the durability of samples. It was also found that the durability of stabilized specimens is dependent on the level of strength gained due to pozzolanic reaction before testing.

In a recent study, Chen et al. (2010) investigated the influence of F-T cycles on soils stabilized with lime and liquid stabilizer. It was found that the compressive strength of stabilized soils decreases with an increase in the number of F-T cycles. Also, results demonstrated that the stabilized soils have better impermeability and F-T resistance compared to raw soils which helps by preventing settlement, frost boil and other damages in seasonally frozen regions.

2.3 Vacuum Saturation

The vacuum saturation method was proposed by Dempsey and Thompson (1973) as a rapid and economical method for predicting the durability of stabilized materials. Currently, the vacuum saturation test is outlined in ASTM C 593 as a durability test for Class C fly ash, lime-fly ash, and lime-stabilized soils. This method consists of mixing soil and additive at optimum moisture content and compacting with standard effort in a 4-in. diameter Proctor mold. After compaction, the specimens are cured for 7 days and placed in a vacuum chamber that is subsequently evacuated to a pressure of 11.8 psi (24-in. Hg). After 30 minutes, the chamber is flooded with de-ionized water, and the vacuum is removed. The specimens are allowed to soak for 1 hour and are then tested for UCS. Only a few studies (e.g., McManis and Arman, 1989; Guthrie et al., 2008; Parker, 2008) are available in the literature.

McManis and Arman (1989) evaluated the durability of two CFA-stabilized sands, namely, A-3 and A-2-4 in accordance with the ASTM C 593 specifications. The specimens were conditioned in a vacuum saturation chamber and tested for UCS with the exception of being cured in a humidity room at $73^{o}\pm3^{o}$F ($22.7^{o}\pm1^{o}$C) rather than at 100^{o}F (38^{o}C), as specified in the ASTM procedure. A comparison of the differences in strength between the specimens subjected to this procedure and those not subjected to this procedure provided a relative measure of durability of the sand mixtures. The strength loss in the A-3 specimens was inconsistent, but the A-2-4 specimens demonstrated a consistent loss in strength.

In a recent study, Parker (2008) conducted vacuum saturation tests on silty sand and lean clay stabilized with different additives, namely, class C fly ash, lime-fly ash, lime or

Type I/II Portland cement. It was found that the silty sand specimens stabilized with lime-fly ash had significantly higher UCS after vacuum saturation than specimens stabilized with CFA, lime or cement. Also, clay specimens stabilized with CFA or lime-fly ash had significantly higher UCS values than the specimens stabilized with cement or lime. This study also proposed strong correlation between residual UCS values after F-T cycling and vacuum saturation.

2.4 Tube Suction Test

The Tube Suction Test (TST) was developed by the Finnish National Road Administration and the Texas Transportation Institute to evaluate the moisture susceptibility or the amount of “free” water present within a soil system (Syed et al., 1999; Guthrie et al., 2001). The TST involves measurement of the surface dielectric values (DV) of the test specimens. During the test, the increase of moisture in the specimen is monitored with a dielectric probe, which measures the dielectric properties at the surface of the specimen. The DV is a measure of the unbound or “free” moisture within the specimen. High surface dielectric readings indicate suction of water by capillary forces and can be an indicator of a non-durable material that will not perform well under saturated or freeze-thaw cycling conditions (Scullion and Saarenketo, 1997). Guthrie and Scullion (2003) suggested that aggregate base specimens having final dielectric readings of less than 10 are characterized as satisfactory with respect to moisture and/or frost susceptibility, while specimens with final readings above 16 are considered unsatisfactory. Aggregate base specimens with final dielectric values between 10 and 16 are expected to exhibit marginal long-term durability. To the author’s knowledge, there are no recommended lower and upper DV values for stabilized soil specimens. Hence, in the present study DV values will be used to evaluate comparative moisture susceptibility of the stabilized soil specimens.

In recent years, TST results have been correlated with bearing capacity, frost heave, and several other parameters (PCA, 1992; Saarenketo and Scullion, 1996; Scullion and Saarenketo, 1997; Little, 2000; Syed et al., 2000; Guthrie and Scullion, 2000; Saarenketo et al., 2001; Guthrie and Scullion, 2003; Saeed et al., 2003; Syed et al., 2003; Barbu et al., 2004; Zhang and Tao, 2008). Little (2000) evaluated moisture susceptibility of low, moderate, and high plasticity soils using the TST. Moisture susceptibility was determined indirectly by measuring the DV of stabilized specimens using a Percometer^{TM}. Tests were performed on three versions of each soil: untreated, lime-treated with unsealed curing, and lime-treated with controlled curing (seal-cured). It was found that for low-plasticity soils, lime acted as a fine filler and increased the water content after capillary soaking. No significant difference was seen on the DV over that of the untreated soil. For moderate plasticity and high plasticity soils, lime treatment, with seal-curing, resulted in slightly lower moisture contents and substantial and statistically significant reductions in DVs.

Barbu et al. (2004) studied only the moisture susceptibility of 28 day cured silty sand specimens stabilized with 3.5% of cement. Different conditions for conducting the TST were evaluated, such as specimen size, compaction energy and size of clods. The two different cylindrical specimen sizes used were 12-in. (305 mm) by 6-in. (152 mm) diameter and 7-in. (180 mm) by 4-in. (101.6 mm) diameter. DV readings were taken for 500 hours using a Percometer^{TM}. It was concluded that the difference in final result due to different dimensions of the specimen, compaction energy or clod size is not significant. Zhang and Tao (2006) conducted wetting-drying tests, along with the TST and 7-day UCS to determine the efficiency of cement stabilization on low plastic soils, which is frequently encountered in Louisiana. This study confirmed the equivalence among wetting-drying, TST, and 7-day UCS tests as an alternative to traditional durability tests.

Zhang and Tao (2006) conducted TST for evaluating durability of cement-stabilized low plasticity soils. A series of specimens were molded at six different cement contents (2.5, 4.5, 6.5, 8.5, 10.5 and 12.5%) and four different molding moisture contents (15.4, 18.5, 21.5, and 24.5%). It was found that the final stable DV values of stabilized specimens were all above the value of 30. The maximum DVs generally decreased with an increase in cement content. With an increase in the molding moisture content, it was less effective for cement to reduce the maximum DV. Also, it was reported that at the low cement dosages, specimens molded on the dry side of compaction curve can suck in free water faster than those compacted on the wet side until enough amount of cement is used. Furthermore, the test results indicated that the water-cement ratio of cement-stabilized soil had the dominant influence on the maximum DV.

In a recent study, Parker (2008) evaluated the moisture susceptibility of 7-day cured stabilized silty sand and lean clay specimens. Five additives, namely, class C fly ash, lime-fly ash, lime, and type I/II Portland cement were used in this study. DV values measured in the tube suction test were lowest for specimens treated with lime-fly ash and cement with respect to the sand and for specimens treated with class C fly ash and cement with respect to the clay. The lime-fly ash and cement successfully reduced the DV values of sand specimens to a marginal rating, while no stabilizer reduced the moisture susceptibility of the clay to a satisfactory level.

In another recent study, Guthrie and Shambaugh (2009) investigated the reproducibility of the TST procedure. Overall, 7 different factors namely, air temperature, mixing and soaking water salinity, dielectric probe seating force, number of days for drying before start of capillary soaking, aggregate fines content, water bath height, and specimen compaction energy were investigated. Two different aggregates (caliche and limestone) were used for preparing the specimens and tested with specific combinations of the aforementioned factors. Results showed that air temperature, drying time, fines content, water bath height, and compaction energy were significant for the caliche aggregate. On the other hand, only air temperature showed to be significant for limestone aggregates. It was also found that small variations in mixing and soaking water salinity and dielectric probe seating force didn't exert significant influence on the final dielectric values in the TST.

It is also worth mentioning here that there is no standardized procedure for conducting the TST on stabilized materials. A summary of TST procedure used by different researchers is presented in Table 2.1. Hence, one of the objectives of this study is to develop TST procedure for stabilized soils, as will be discussed later.

2.5 Other Methods

Several researchers (see e.g., Kenai et al., 2006; Zhang and Tao, 2006; Osinubi et al., 2010) and agencies use 7-day UCS values as an indicator of the durability for the soil stabilization mix design. For example, Zhang and Tao (2008) established equivalency of 7-day UCS and W-D durability. In a recent study, Osinubi et al. (2010) evaluated the durability of soil-lime-slag mixtures by determining the strength of moisture conditioned specimens. The resistance to loss in strength was determined as a ratio of the UCS of specimens wax-cured for 7 days, de-waxed top and bottom and later moisture conditioned in water for another

7 days to the UCS of specimens wax-cured for 14 days. It was found that the resistance to loss in strength decreased with a higher slag content. For 8% lime-stabilized specimen, a peak value of 80% with the highest durability was observed. However, soil-lime-slag mixtures containing 6 – 8% lime showed resistance to loss in strength values in the range between 50 – 70%.

Some researchers (e.g., Prusinski and Bhattacharja, 1999; Parsons and Milburn, 2003; Parsons and Kneebone, 2004) used the leaching test for evaluating the durability of stabilized soil specimens. The leaching durability test involves leaching de-ionized water through a Proctor specimen of soil for 28 days. Leachate samples are collected for determining flow rate, calcium concentration, and pH at different intervals of 1, 3, 7, 14, 21, and 28 days. Only limited information is available on leaching of CFA- or CKD-stabilized soil specimens. However, extensive leaching investigations were performed on lime-stabilized specimens by McCallister and Petry (1990; 1991; 1992). According to McCallister and Petry (1990; 1991; 1992), lime-addition levels in soils are defined at two levels: lime modification optimum (LMO) as determined by pH test (ASTM D 6276) and lime stabilization optimum (LSO) as determined by the lime addition percentage which provides the maximum UCS. For the soils tested by McCallister and Petry (1990; 1991; 1992), the lime levels for LMO and LSO were 3 – 4% and 7 – 8%, respectively.

Table 2.1: Summary of Literature Review of Tube Suction Test on Stabilized Materials

Reference	Type of Soil /Aggregate (Additive)	Curing period	Specimen Size	Drying Period	Duration of reading	Experimental Details
Little (2000)	Silty soil (L)	7 days	152.4 mm x 152.4 mm (6.0 in) x 6.0 in)	4 days (40^o C)	311 hours (13 days)	Specimen was placed in a tray with a porous plate at the bottom of the specimen (No mold was used)
Syed et al. (2000)	Aggregates (CLS)	NA	152.4 mm x 203.2 mm (6.0 in x 8.0 in)	--	240 hours (10 days)	Specimen was compacted in cylindrical plastic molds. These molds were having 1.0mm diameter holes around the circumference(at height of 6 mm from the bottom) of the mold at a horizontal spacing of 12.5 mm
Guthrie and Scullion (2003)	Hanson Aggregates	NA	152.4 mm x 203.2 mm (6.0 in x 8.0 in)	2 days (60 ± 5^o C)	240 hours (10 days)	Specimen was compacted in cylindrical plastic molds. These molds were having 1.5mm diameter holes around the circumference(at height of 6 mm from the bottom) of the mold at a horizontal spacing of 12.5 mm
Saeed et al. (2003)	NA	NA	152.4 mm x 203.2 mm (6.0 in x 8.0 in)	3 days (38^o C)	--	Specimens were compacted in cylindrical plastic molds. These molds were having 1/16 in diameter holes (¼ in above the outside bottom of the mold)around the circumference of the mold at a horizontal spacing of 0.5 in. This equates to 38 or 39 holes around the cylinder base. In addition it also consisted of one 1/16 in diameter hole in each quadrant of the circular bottom of the mold, with each hole about 2 in from the center
Syed et al. (2003)	Aggregates (C)	0 day	101.6 mm x 116.8 mm (4.0 in x 4.6 in)	3-4 days (40^o C)	240 hours (10 days)	Specimen was placed in a tray with a porous plate at the bottom of the specimen (No mold was used)
Barbu et al. (2004)	Silty sand (C)	28 days	152.4 mm x 304.8 mm, 101.6 mm x 177.8 mm (6.0 in x 12.0 in, 4.0 in x 7.0 in)	2 days (50^o C)	500 hours (21 days)	The bottom of the tube was cut and replaced with aluminum foil pierced with a 1.mm nail, to form 3 concentric circles and with a distance between holes of approximately 4 cm
Zhang and Tao (2008)	Lean clay (C)	1 day	101.6 mm x 177.8 mm (4.0 in x 7.0 in)	14 days (40^o C)	240 hours (10 days)	Specimens were placed in plastic tube with holes at their bottoms, and then plastic tubes were placed in a large plastic container with a porous stone underneath and 20 mm water above the bottom= of the samples

L-Lime; C-Cement; CLS-Concentrated liquid stabilizer; NA-Not Applicable

CHAPTER 3 MATERIAL PROPERTIES AND LABORATORY TESTING

3.1 General

This chapter is devoted to presenting the sources of materials that were used in this study. The subgrade soils were collected from different counties in Oklahoma, and the stabilizing agents were shipped to our laboratory by different agencies. Soil and additive properties including moisture-density relationships of raw and stabilized soils are discussed in this chapter. An overview of different durability test methods used in this study is also presented.

3.2 Collection of Soils

As noted earlier, five different soils were used in this study: (1) Port series; (2) Kingfisher series; (3) Carnasaw series; (4) Dennis series; and (5) Lomill series. Bulk soil samples were collected from three different counties in Oklahoma: Cleveland, Latimer, and Muskogee. Figure 3.1 shows the location of these counties on the Oklahoma state map. Figures 3.2 (a), (b), and (c) photographically depict the field sampling of soil from Cleveland, Latimer, and Muskogee Counties, respectively. It is clear that the University of Oklahoma (OU) research team used different methods (e.g., shovels/picks, backhoe, hand augers, and rotary drilling method) for collecting soils in cooperation and guidance from the Oklahoma Department of Transportation (ODOT). It is also worth noting that all soils were sampled from composite B and/or C horizons in order to collect clean and organic free samples. More than 40 plastic bags, each having a weight of approximately 40 lbs, were transported to the Broce Laboratory (Figure 3.2 d) and stored for processing and testing. After collection, these soils were air dried in the laboratory and processed by passing through the U.S. Standard Sieve #4.

The first soil used in this study belongs to the Port series. Bulk samples were collected from Cleveland County (near Norman), located in Central Oklahoma. Port soil is found in 33 counties throughout Oklahoma and it covers about one million acres of Central Oklahoma. Kingfisher series soil was sampled from East Lindsey Street in Norman, which is located in Cleveland County. Carnasaw series soil was sampled from Latimer County, located in the Southeast Oklahoma (Figure 3.1). The samples for Carnasaw series soils were collected from on-ramp junction at SH 52 and Northeast 1130th Avenue, as shown in Figure 3.2 (b). Dennis series soil was sampled from the Northwest intersection of Gibson Street and U.S. 165. This site is located near Muskogee in Muskogee County, as shown in Figure 3.2 (c). Lomill series soil was collected from the corner of Robinson Street and Northwest 60th Street in Norman (Figure 3.2 a).

3.3 Soil Properties Testing

This section presents a brief description of the tests performed on the collected soils. Most of the tests were performed following a standardized procedure. A summary of soil properties is presented in Table 3.1.

3.3.1 Atterberg Limits

Atterberg limits namely, Plastic Limit (PL) and Liquid Limit (LL) were determined by conducting tests in accordance with the ASTM D 4318 test method. A summary of the Atterberg limits for the selected soil types, Port, Kingfisher, Carnasaw, Dennis and Lomill is presented in Table 3.1. It is clear from Table 3.1 that Port soil has the lowest PI of 7 with a LL and PL of approximately 26 and 19, respectively. Lomill series soil showed the highest PI value of approximately 35, with a LL of 54 and a PL of 19. Carnasaw, Dennis and Lomill series soils produced LL values of greater than 50 (Table 3.1). Thus, Carnasaw, Dennis, and Lomill series soils were classified as Fat Clays, as discussed later.

3.3.2 Grain Size Analysis

In this study, sieve analysis was performed on all the collected soils in accordance with the ASTM D 6913 test method. To determine the gradation of soil portion with a size smaller than 75 μm, hydrometer tests were conducted in accordance with the ASTM D 422 test method. For this 55 – 60 gm of soil passing U.S. Standard Sieve #10 was used. To disperse the soil particles, the soil sample was soaked overnight in a sodium hexametaphosphate solution having a concentration of 40 gm/l. A calibrated hydrometer of type 152 H was used to conduct the test. After this test the portion coarser than U.S. Standard Sieve #200 was oven dried and sieve analysis was performed in accordance with the ASTM D 1140 test method. The gradation curves are presented in Figure 3.3. It is clear from Figure 3.3 and Table 3.1 that Port soil contained the lowest percent passing U.S. Standard Sieve #200. This soil series contained more than 84% sand particles; this concentration is higher than the other soils. Kingfisher, Carnasaw, Dennis and Lomill series soils showed a percent passing U.S. Standard Sieve #200 of 95%, 92%, 97%, and 93%, respectively (Table 3.1).

3.3.3 Soil Classification

Based on the Atterberg limits tests and gradation test results, all soil series were classified using the Unified Soil Classification System (USCS) in accordance with the ASTM D 2487 test method. Additionally, soils were classified by using the AASHTO classification system in accordance with the AASHTO M 145 test method. A summary of both USCS and AASHTO soil classifications of all the soils is presented in Table 3.1. Port soil is classified as CL-ML (silty clay with sand) in accordance with the USCS classification system, and A-4 soil in accordance with the AASHTO M 145 test method. Kingfisher series soil is classified as CL (lean clay) and A-6, in accordance with the USCS and the AASHTO classification systems, respectively. On the other hand, Carnasaw, Dennis, and Lomill soils are classified as CH (fat clay) in accordance with the USCS classification system. According to the AASHTO soil classification system, Carnasaw is classified as A-7-5 whereas both Dennis and Lomill soils are classified as A-7-6.

3.3.4 Specific Gravity Tests

Specific gravity tests were performed on Port, Dennis, Carnasaw, Kingfisher, and Lomill series soils in accordance with the ASTM D 854 test method. Specific gravity values of all five soils are presented in Table 3.4. It is clear from Table 3.4 that Port soil showed a specific gravity value of 2.65. Both Kingfisher and Lomill soils exhibited a specific gravity value of approximately 2.68, while Carnasaw and Dennis soils showed the lowest (2.62) and the highest (2.69) specific gravity values, respectively.

3.3.5 pH and pH Response

An elevated pH level of soil-lime mixture is important because it provides an adequate alkaline environment for ion-exchange reactions (Little, 2000). In the laboratory, pH is determined using the method recommended by ASTM D 6276 for lime-stabilization, which involves mixing the solids with de-ionized (DI) water, periodically shaking the samples, and then testing with a pH meter after 1 hour. The ASTM D6276 procedure specifies that enough lime must be added to a soil-water system to maintain a pH of 12.4 after 1 hour. This ensures that adequate lime is provided to sustain the saturation during the 1 hour period (Prusinski and Bhattacharja, 1999). Figure 3.4 shows a photographic view of the setup used for determining pH values.

Several researchers (e.g., Haston and Wohlgemuth, 1985; Prusinski and Bhattacharja, 1999; IRC, 2000; Little, 2000; Qubain et al., 2000; Mallela et al., 2004; Puppala et al., 2006; Consoli et al., 2009) have used pH values of soil-lime mixture as an indicator of the reactivity of lime. However, only limited studies (see e.g., Miller and Azad, 2000; Parsons et al., 2004; Peethamparan and Olek, 2008; Gomez, 2009; Solanki, 2010) evaluated the pH response of soil-CFA or soil-CKD mixtures. Hence, the pH values of soil-additive mixtures were determined to investigate whether the pH would reflect the effectiveness of soil stabilization with lime, CFA, or CKD.

The pH results of raw soil, raw additive, and soil-additive mixtures are presented in Table 3.2 and are used as the primary guide in determining the amount of additive required to stabilize each soil. It is clear that raw Port, Kingfisher, Dennis, and Lomill soils are alkaline with a pH value greater than 8.0 (Figures 3.5 – 3.9). In contrast, Carnasaw soil is acidic with a pH value of approximately 4.17. Also, it was found that raw lime, CFA, and CKD had pH values of 12.58, 11.83, and 12.55. The pH values of raw CFA and CKD are consistent with the results reported by other researchers (e.g., Miller and Azad, 2000; Sear, 2001; Parsons et al., 2004; Peethamparan and Olek, 2008; Gomez, 2009). The pH trend of raw additives is similar to the trend of available free-lime content in additives, as shown in Table 3.3.

For all the soil-additive mixtures, the pH values increase with an increase in the percentage of additive and show an asymptotic behavior after a certain percentage (Figures

3.5 – 3.9). In the current study, an increase of less than 1% in pH with respect to raw soil is assumed to be the starting point of asymptotic behavior. As evident from Table 3.2 and Figures 3.5 through 3.9, the pH values started showing asymptotic behavior with 3% lime for Port, Kingfisher, and Dennis and 5% lime for Carnasaw and Lomill. With CFA and CKD, Port, Kingfisher, and Dennis showed asymptotic behavior at an additive content of 10%. On the other hand, Lomill soil showed an asymptotic behavior with 10% CFA and 12.5% CKD. However, Carnasaw soil never attained asymptotic behavior with CFA and CKD contents up to 17.5% (Figure 3.7). This can be attributed to the acidic behavior of Carnasaw soil, which requires higher amount of moderately basic CFA and CKD for neutralization. Based on the aforementioned observations and recommendations made by OHD L-50 (Soil Stabilization Mix Design Procedure, 2006), it was decided to select 6% lime, 10% CFA and 10% CKD for laboratory performance evaluation. It is also important to note that a similar additive content was used for stabilizing all the soils used in the study for better comparisons.

3.4 Additive Types and Properties

In this study, hydrated lime, class C fly ash (CFA), and cement kiln dust (CKD) were the main additives, also called stabilizers or stabilizing agents. Hydrated lime was supplied by the Texas Lime Company in Cleburne, Texas. It is a dry powder manufactured by treating quicklime (calcium oxide) with sufficient water to satisfy its chemical affinity with water, thereby converting the oxides to hydroxides. CFA from Lafarge North America (Tulsa, Oklahoma) was brought in well-sealed plastic buckets. The CFA was produced in a coal-fired electric utility plant, American Electric Power (AEP), located in Muskogee, Oklahoma. CKD used was provided by Lafarge North America, in Tulsa, Oklahoma. Sealed buckets were shipped to our laboratory from Tulsa. CKD is an industrial waste collected during the production of Portland cement. The chemical properties of the stabilizing agents are presented in Table 3.3. From the aforementioned chemical properties (Table 3.3), the differences between the chemical composition and physical properties among the selected additives are clearly evident. These differences will lead to different performances of stabilized soil specimens, as reported by Chang (1995), Parsons and Milburn (2003), Kim and Siddiki (2004), Khoury and Zaman (2007), and Solanki (2010).

3.5 Moisture-Density Test

In the laboratory, the soil was mixed manually with a stabilizer in order to determine the moisture-density relationship of soil-additive mixtures. The procedure consists of adding a specific amount of additive, namely, 6% lime or 10% CFA or 10% CKD to the processed soil. The amount of additive added was based on the dry weight of soil. The additive and the soil were mixed manually to uniformity and tested for moisture-density relationships by conducting standard Proctor test in accordance with the ASTM D 698 test method. The moisture content was determined by oven-drying the soil-additive mixture. A summary of the optimum moisture contents (OMCs) and maximum dry densities (MDDs) for different soil-additive mixtures is presented in Table 3.4.

3.5.1 Port Soil and Additive Mixture

The OMC and MDD of raw soils were found to be 13.1% and 113.4 pcf, respectively. Results showed that with the addition of 6% lime there was an increase in OMC (+2.8%) and a decrease in MDD (-6.2 pcf). The same behavior was observed with 10% CKD with an OMC of 15.2% and MDD of 109.3 pcf. Other researchers (e.g., Haston and Wohlegemuth, 1985; Zaman et al., 1992; Miller and Azad, 2000; Sreekrishnavilasam et al., 2007) also observed effects similar to those in the current study. One of the reasons for such behavior can be attributed to the increased number of fines in the mix due to the addition of lime and CKD. According to Little (1996), OMC increases with increasing lime content because more water is needed for the soil-lime chemical reactions. Nagaraj (1964) suggested that a reduction in MDD of the lime-treated soil is reflective of the increased resistance offered by the flocculated soil structure against the compactive effort.

A decrease in OMC (-0.3%) and an increase in the MDD (+1.5 pcf) were observed by the addition of 10% CFA. These observations were similar to those reported by McManis and Arman (1989) for sandy silty soil and by Misra (1998) for clays.

3.5.2 Kingfisher Soil and Additive Mixture

The moisture-density results performed on Kingfisher series soil-additive mixtures are presented in Table 3.4. Raw Kingfisher soil presented an OMC value of 16.5% and a MDD value of 110.6 pcf. It is clear from the laboratory study performed on Kingfisher series soil that OMC remained the same (16.5%) with the addition of 6% lime. However, a decrease (-4.0 pcf) in the MDD values was observed with the addition of 6% lime. Similar observations were reported by Nagaraj (1964), Haston and Wohlegemuth (1985), Ali (1992), and Little (1996). Similar reasons as presented in Section 3.5.1 could be used for rationalizing this behavior.

The addition of 10% CFA decreased the OMC (-1.2%) and increased the MDD (-0.4 pcf). Similar behavior was observed by McManis and Arman (1989), Misra (1998), and Solanki et al. (2007a). For example, Misra (1998) reported that the increase in MDD can be attributed to the packing of finer fly ash particles (smaller than U.S. Standard Sieve #200) in voids between larger soil particles.

The stabilization of Kingfisher soil with 10% CKD showed moisture-density behavior similar to that of the 6% lime. The OMC presented an increase (+0.8%) and a decrease in the MDD (-2.0 pcf) with the addition of 10% CKD. Similar observations were reported by other researchers (see e.g., Zaman et al., 1992; Miller and Azad, 2000; Solanki et al., 2007b, Solanki, 2010).

3.5.3 Carnasaw Soil and Additive Mixture

The raw Carnasaw series soil presented an OMC value of 20.3% at a MDD value of 103.7 pcf. The addition of 6% hydrated lime and 10% CKD to the mix initiated an increase in OMC by 2.4% and 1.4%, respectively. A decrease in MDD of 4.7 pcf and 1.9 pcf was observed due to the addition of 6% hydrated lime and 10% CKD. This behavior is similar to the trend of moisture-density test results noted in Sections 3.5.1 and 3.5.2. Hence, similar reasons as discussed in Sections 3.5.1 and 3.5.2 could be used for rationalizing this behavior. For CFA stabilization, the results showed that the MDD increased (+1.6 pcf) with the addition of 10% CFA. Similar to Port and Kingfisher, the OMC values in Carnasaw decreased (-1.7%) by adding 10% CFA.

3.5.4 Dennis Soil and Additive Mixture

The OMC and MDD of raw soil were found to be 22.7% and 98.5 pcf, respectively. The addition of 6% lime in the raw soil increased the OMC by 0.9%. In contrast, a decrease (approximately 2.1 pcf) in the MDD with 6% lime is observed. The addition of 10% CFA resulted in a decrease in OMC values by approximately 3.5% and an increase in MDD values by 3.6 pcf, as compared to the raw soil. The soil-CKD mixture resulted in an OMC of 21.5%

(a 1.2% increase) and a MDD of 99.8 pcf (a 1.3 pcf decrease). Similar reasons, as discussed in previous sections, could be used for rationalizing this behavior.

3.5.5 Lomill Soil and Additive Mixture

The OMC and MDD of raw soil were found to be 24.7% and 96.25 pcf. The addition of 6% lime in the raw soil increased the OMC by 0.2%. In comparison, a decrease (approximately 2.9 pcf) in the MDD was observed due to the addition of 6% lime. The OMC and MDD of the soil-CFA mixture was found to be 21.3% and 97.6 pcf, respectively. This shows a decrease in OMC by approximately 3.4% and an increase in MDD by 1.35 pcf, compared to the raw soil. The soil-CKD mixture resulted in an OMC of 22.0% and a MDD of 98.0 pcf, a decrease in OMC by 2.7% and an increase in MDD by 1.75 pcf, compared to the raw soil values.

3.6 Durability Tests

3.6.1 Conventional Freeze-Thaw and Wet-Dry Test (Unconfined Compressive Strength)

The freeze-thaw (F-T) and wet-dry (W-D) test were performed in accordance with the procedures outlined in the ASTM D 560 and ASTM D 559 test methods. The specimens were prepared by mixing raw soil with a specific amount of additive. The amount of additive (6% for lime and 10% for CFA and CKD) added was based on the dry weight of the soil. The specimens were molded with a Harvard miniature device (diameter = 1.3 in and height = 2.8 in). The Harvard miniature procedure was calibrated in accordance with the ASTM D 4609 test method using each soil and additive mixture so that at the standard Proctor optimum moisture content (OMC) and the Harvard miniature procedure produced a specimen having the standard Proctor maximum dry density (MDD). All the specimens were compacted at the

OMC and MDD of the soil-additive mixture, which is presented in Table 3.4. After compaction, the specimens were cured for 7 days at a temperature of 23.0 ± 1.7^{o}C (73.4 ± 3.1^{o}F) and a relative humidity of approximately 96%, as recommended by the ASTM D 1632 test method. A total of two replicates were prepared for each combination and then subjected to 0, 1, 4, 8 and 12 F-T or W-D cycles after 7 days of curing. Each F-T cycle consisted of freezing for 24 hours at a temperature not warmer than -23.3^{o}C (-10^{o}F) and thawing for 23 hours at 21.1^{o}C (70^{o}F) and 100% relative humidity (Figure 3.10 a, and b). Free potable water was made available to the porous plates under the specimens to permit the specimens to absorb water through capillary action during the thawing period. Each W-D cycle consisted of placing a 7-day cured specimen in a water bath at room temperature for five hours, followed by oven drying at a temperature of 71^{o}C (160^{o}F) for 42 hours (Figure 3.10 c and d). After the completion of appropriate F-T or W-D cycle, unconfined compressive strength (UCS) tests were conducted by loading the specimens in a displacement control mode at a strain rate of 1% per minute.

3.6.2 Conventional Freeze-Thaw and Wet-Dry Test (Resilient Modulus)

The new Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO, 2004) recommends the evaluation of resilient modulus (M_r) for a critical performance prediction of the stabilized subgrade layer. Thus, in this study it was decided to evaluate the effect of F-T and W-D cycles on the M_r values of the stabilized soil specimens.

The specimens were prepared according to the method described by Solanki et al. (2009a, and 2009b). The mixture for each specimen consists of raw soil mixed with specific amount of additive. The amount of additive (6% for lime and 10% for CFA and CKD) was added based on the dry weight of the soil. The additive and soil were mixed manually for uniformity. After the blending process, a desired amount of water added was based on the OMC. Then the mixture was compacted in a mold having a diameter of 4.0 in and a height of 8.0 in to reach a dry density between 95%-100% of the maximum dry density (MDD) (Table 3.4). After compaction, the specimens were cured for 7 days at a temperature of 23.0 ± 1.7^{o}C (73.4 ± 3.1^{o}F) and a relative humidity of approximately 96%. Then, the specimens were subjected to either F-T cycles or W-D cycles by using similar procedures as described in Section 3.6.1.

After the completion of the appropriate F-T or W-D cycle, the resilient modulus (M_r) tests were performed in accordance with the AASHTO T 307 test method. The sample was loaded following the sequences shown in Table 3.5. A complete setup of M_r testing on stabilized subgrade soil specimen is shown in Figures 3.11 and 3.12. Figure 3.11 shows the MTS digital control system and signal conditioning unit. Figure 3.12 shows the sample inside the triaxial chamber for M_r testing.

To generate the desired haversine-shaped load and to read the load and displacement signals, a program was written using Material Testing System (MTS) Flex Test SE Automation software. The load-deformation response was recorded for the last 5 cycles of each stress sequence by using a computer-controlled Flex Test SE Test Controller (see Figure 3.11). The Flex Test SE digital servo-controller from MTS is made up of a powerful array of reliable, flexible, and easy-to-use controllers designed to address the full spectrum of material and component testing needs. Basic capabilities include station configuration, auto-zeroing, control mode switching with hydraulics on, and adaptive control. The controller provides a self-contained single-channel control and can be linked to other controllers for multi-channel testing. All the data was collected and stored in an MS Excel file; a macro program was written in Excel to process these data and evaluate the resilient modulus. The M_r for each sequence was calculated from the average recoverable strain and average load from the last five cycles by using the following expression:

$$M_r = \frac{\sigma_d}{\varepsilon_r} \tag{3.1}$$

where, σ_d = repeated cyclic deviatoric stress, and ε_r = recoverable strain (or resilient strain). Further, details of the apparatus and the noise reduction method used are given by Solanki et al. (2009b).

Figures 3.13 (a) and (b) show photographic view of specimens under freezing and thawing inside a ESPEC freeze-thaw chamber (Model Number: ESL-3CA). Formation of ice crystals during freezing cycle is clearly evident from Figure 3.13 (a). Also, it is evident from Figure 3.13 (b) that specimens absorb moisture and swell during the thawing cycle. Figures 3.14 (a) and (b) show photographic view of the specimens subjected to the first wetting and drying cycle, respectively. The specimens were subjected to wetting by submerging the specimens inside an ice chest filled with water (Figure 3.14 a). Specimens were subjected to drying in an oven (Figure 3.14 b).

3.7 Moisture Susceptibility Test

The moisture susceptibility of the 7-day cured specimens was evaluated by moisture conditioning of Harvard miniature specimens in water for 5 hours. This was achieved by immersing each specimen in 250-ml glass bottle filled with 200 ml of DI water. During the moisture conditioning, the swelling behavior of the samples was monitored by visual observation. After 5 hours of immersion, the specimens were weighted and measured for height to the nearest 0.001 inch in 3 places that are approximately 120^{o} apart. Additionally, the diameter was measured to the nearest 0.001 inch near the top, in the middle, and near the base of each sample. The three height and diameter measurements were averaged and the volume was calculated. Both weight and volume were used for determining the degree of saturation. Then, the specimens were tested for UCS by loading them in a displacement control mode at a strain rate of 1% per min. Figure 3.15 shows a photographic view of specimens at the end of 5 hours of moisture conditioning.

3.8 Vacuum Saturation Test

The vacuum saturation test was performed in accordance with the ASTM C 593 test method, with slight modifications. This method consists of mixing soil with 6% lime or 10% CFA, or 10% CKD, and compacting with standard effort in a Proctor mold (diameter = 4 in and height = 4.6 in). After compaction, the specimens were cured in a humidity room at 23.0 ± 1.7^{o}C (73.4 ± 3.1^{o}F) rather than at 37.8^{o}C (100^{o}F), as specified in the ASTM procedure. Following curing, the specimens were placed in a vacuum chamber subjected to a vacuum pressure of 11.8 psi (24 in Hg). After 30 minutes, vacuum was removed and the chamber was flooded with water and the specimens were allowed to soak for 1 hour. After the saturation period, the water was drained and the specimens were immediately tested for UCS by loading them in a displacement control mode at a strain rate of 1% per min. A comparison of the differences in UCS values between specimens subjected to this procedure (UCS after vacuum saturation) and those not subjected to this procedure (UCS before vacuum saturation) provided a relative measure of durability of the stabilized specimens. Figure 3.16 shows a photographic view of the setup used for the vacuum saturation test. The vacuum chamber consists of a 1 in thick Plexiglas lid. As shown in Figure 3.16, the specimens were placed in an upright position on a perforated steel plate so that water could enter the soil from all surfaces.

3.9 Tube Suction Test

Since there is no standard protocol for conducting tube suction tests, the durability of the specimens was evaluated by preparing specimens using the following three different methods:

1. *Method-1*

   Compaction: Standard Proctor compaction (five layers/lifts) at the OMC and a target dry density of 95-100% of MDD.

   Cylindrical specimen size: diameter = 4 in., height = 8 in.

2. *Method-2*

   Compaction: Superpave gyratory compactor (single layer/lift) at the OMC and a target dry density of 95-100% of MDD.

   Cylindrical specimen size: diameter = 4 in., height = 4 in.

3. *Method-3*

   Compaction: Superpave gyratory compactor (single layer/lift) at the OMC and a target dry density of 95-100% of MDD.

   Cylindrical specimen size: diameter = 6 in, height = 6 in.

Method-2 and Method-3 are similar to the method of compaction used by Harris et al. (2006). According to Harris et al. (2006), the specimens should be molded in one lift because molding specimens in multiple lifts with a drop hammer generates permeability barriers. The permeability barriers do not allow the water to rise up through the sample beyond the bottom lift (Harris et al., 2006). It is also important to note that for reducing permeability barriers the new lift was placed after first scarifying the top surface of the previous lift to a depth of approximately ¼ inch in accordance with AASHTO T 307 test method. In the present study, the specimen size compacted using the Superpave gyratory compactor was restricted to 6 in. (Method-3) due to the constraint of molding in one lift.

After compaction, the specimens were cured for 7 days in a controlled environment involving a temperature of 23.0 ± 1.7°C (73.4 ± 3.1°F) and a relative humidity of approximately 96%. Then, the specimens were dried in an oven at 40 ± 5°C (104 ± 9°F) for two days. After oven drying, the specimens were allowed to cool down at room temperature for 30 minutes, and then coated with a thin layer of grease around the lateral surface and placed on a porous stone in an open dish containing approximately 0.4 in of de-ionized (DI) water. Since the quality of the porous stones has an important influence on the final DV (Barbu and Scullion, 2005), clean porous stones were used. Further, the top surface of the specimens was covered with a plastic sheet and plate for preventing loss of moisture due to evaporation. During the wetting of specimens in DI water, the increase in dielectric value (DV) with time due to capillary rise of water was measured. Four measurements were taken along the circumference on the top surface of the specimens in separate quadrants and the fifth reading was taken at the center on the top surface of specimens and an average of all five readings was calculated. Measurements were taken daily for 10 days using a dielectric probe (or Percometer™) and the final, 10th day reading was reported. A photographic view of the TST setup is shown in Figure 3.17. To ensure adequate contact of probe on the top of the surface of the specimens, a surcharge of 4.86 lb was applied (Figure 3.17). After 10 days of TST, the specimens prepared using Method-1 and Method-2 were cut into five and three equal layers, respectively, and oven dried for moisture content.

Table 3.1: Testing Designation and Soil Properties

Methods	Parameter/Units	Port	Kingfisher	Carnasaw	Dennis	Lomill
ASTM D 2487	USCS Symbol	CL-ML	CL	CH	CH	CH
AASHTO M 145	AASHTO Designation	A-4	A-6	A-7-5	A-7-6	A-7-6
ASTM D 2487	USCS Name	Silty clay with sand	Lean clay	Fat clay	Fat clay	Fat clay
ASTM D 2487	% finer than 0.075 mm	84	95	92	97	93
ASTM D 4318	Liquid limit	26	39	58	51	54
ASTM D 4318	Plastic limit	19	18	29	19	19
ASTM D 4318	Plasticity index	7	21	29	32	35
ASTM D 854	Specific Gravity	2.65	2.68	2.62	2.69	2.68

Table 3.2: Variation of pH Values with Soil and Additive Type

Type of Additive	Additive Content (%)	Port		Kingfisher		Carnasaw		Dennis		Lomill	
		pH value	% Increase[a]	pH value	% Increase[a]	pH value	% Increase[a]	pH value	% Increase[a]	pH value	% Increase[a]
Lime	0	8.91	---	8.82	---	4.17	---	7.26	---	8.35	---
	1	12.24	37.4	12.04	36.5	9.22	121.1	11.82	62.8	10.98	31.5
	3[b]	**12.43**	**39.5**	**12.49**	**41.6**	12.23	193.3	**12.72**	**75.2**	12.14	45.4
	5	12.45	39.7	12.50	41.7	**12.54**	**200.7**	12.78	76.0	**12.43**	**48.9**
	6	12.45	39.7	12.54	42.2	12.55	201.0	12.81	76.4	12.55	50.3
	7	12.46	39.8	12.57	42.5	12.55	201.0	12.82	76.6	12.59	50.8
	9	12.47	40.0	12.57	42.5	12.57	201.4	12.9	77.7	12.68	51.9
	100	12.58	41.2	12.58	42.6	12.58	201.7	12.58	73.3	12.58	50.7
CFA	0	8.91	---	8.82	---	4.17	---	7.26	---	8.35	---
	2.5	10.97	23.1	10.03	13.7	5.19	24.5	9.87	36.0	10.29	23.2
	5	11.30	26.8	10.83	22.8	5.93	42.2	10.43	43.7	10.79	29.2
	7.5	11.39	27.9	11.28	27.9	6.55	57.1	10.81	48.9	11.19	34.0
	10[b]	**11.50**	**29.1**	**11.42**	**29.5**	7.79	86.8	**11.16**	**53.7**	**11.36**	**36.0**
	12.5	11.59	30.0	11.50	30.4	8.32	99.5	11.25	55.0	11.47	37.4
	15	11.6	30.2	11.57	31.2	8.86	112.5	11.32	55.9	11.59	38.8
	17.5	11.62	30.4	11.61	31.6	9.47	127.1	11.34	56.2	11.67	39.8
	100	11.83	32.8	11.83	34.1	11.83	183.7	11.83	62.9	11.83	41.7
CKD	0	8.91	---	8.82	---	4.17	---	7.26	---	8.35	---
	2.5	11.35	27.4	11.11	26.0	7.05	69.1	9.33	28.5	10.47	25.4
	5	11.88	33.3	11.73	33.0	8.8	111.0	10.5	44.6	11.14	33.4
	7.5	12.09	35.7	12	36.1	10.11	142.4	11.18	54.0	11.62	39.2
	10[b]	**12.22**	**37.1**	**12.15**	**37.8**	10.88	160.9	**11.39**	**56.9**	11.83	41.7
	12.5	12.3	38.0	12.23	38.7	11.28	170.5	11.54	59.0	**12.03**	**44.1**
	15	12.36	38.7	12.3	39.5	11.62	178.7	11.67	60.7	12.12	45.1
	17.5	12.38	38.9	12.36	40.1	11.98	187.3	11.76	62.0	12.23	46.5
	100	12.55	40.9	12.55	42.3	12.55	201.0	12.55	72.9	12.55	50.3

[a]Increase in pH w.r.t. pH value of raw soil; [b]Bold values represent minimum additive content providing asymptotic behavior (<1%increase)

Table 3.3: Chemical Properties of Stabilizers

Chemical compound/Property	Percentage by weight, (%)		
	Lime	CFA	CKD
Silica (SiO_2)[a]	0.6	37.7	14.1
Alumina (Al_2O_3)[a]	0.4	17.3	3.1
Ferric oxide (Fe_2O_3)[a]	0.3	5.8	1.4
Silica/Sesquioxide ratio (SSR) $SiO_2/(Al_2O_3+Fe_2O_3)$	1.9	3.0	6.0
Calcium oxide (CaO)[a]	68.6	24.4	47
Calcium hydroxide ($Ca(OH)_2$)[a]	95.9**	…	…
Magnesium oxide (MgO)[a]	0.7	5.1	1.7
Sulfur trioxide (SO_3)[a]	0.1	1.2	4.4
Alkali content ($Na_2O + K_2O$)[a]	0.1	2.2	1.7
Loss on ignition[b]	31.8*	1.2	27
Free lime[b]	46.1	0.2	6.7
Percentage passing No. 325[c]	98.4	85.8	94.2
pH (pure material)[d]	12.58	11.83	12.55
Specific surface area (m^2/gm)[e]	17.0	6.0	12.0
28-day UCS (kPa)	…	708	17

[a]X-ray Fluorescence analysis; [b]ASTM C 114; [c]ASTM C 430; [d]ASTM D 6276; [e]Ethylene glycol monoethyl ether method (Cerato and Lutenegger 2001); UCS: Unconfined compressive strength; *$Ca(OH)_2$ decomposes at 512°C; **Before ignition

Table 3.4: A Summary of OMC-MDD of Soil-Additive Mixtures

Type of Soil	Type of additive	Percentage of additive	OMC (%)	Maximum dry density	
				kN/m^3	pcf
Port	None	0	13.1	17.8	113.4
Kingfisher		0	16.5	17.4	110.6
Carnasaw		0	20.3	16.3	103.7
Dennis		0	22.7	15.5	98.5
Lomill		0	24.7	15.1	96.25
Port	Lime	6	15.9	16.9	107.2
Kingfisher		6	16.5	16.8	106.6
Carnasaw		6	22.7	15.6	99.0
Dennis		6	23.6	15.2	96.4
Lomill		6	24.9	14.7	93.3
Port	CFA	10	12.8	18.1	114.9
Kingfisher		10	15.3	17.4	111.0
Carnasaw		10	18.6	16.6	105.3
Dennis		10	19.2	16.1	102.1
Lomill		10	21.3	15.4	97.6
Port	CKD	10	15.2	17.2	109.3
Kingfisher		10	17.3	17.1	108.6
Carnasaw		10	21.7	16.0	101.8
Dennis		10	21.5	15.7	99.8
Lomill		10	22.0	15.4	98.0

1 pcf = 0.1572 kN/m^3; OMC: optimum moisture content; MDD: maximum dry density; CFA: class C fly ash; CKD: cement kiln dust

Table 3.5: Testing Sequence used for Resilient Modulus Test

Sequence Number	Confining Pressure (psi)	Maximum Axial Stress (psi)	Cyclic Stress (psi)	Constant Stress (psi)	No. of Load Applications
Conditioning	6	4	3.6	0.4	500
1	6	2	1.7	0.1	100
2	6	4	3.6	0.4	100
3	6	6	5.4	0.6	100
4	6	8	7.3	0.9	100
5	6	10	9.0	1.0	100
6	4	2	1.7	0.1	100
7	4	4	3.6	0.4	100
8	4	6	5.4	0.6	100
9	4	8	7.3	0.9	100
10	4	10	9.0	1	100
11	2	2	1.7	0.1	100
12	2	4	3.6	0.4	100
13	2	6	5.4	0.6	100
14	2	8	7.3	0.9	100
15	2	10	9.0	1	100

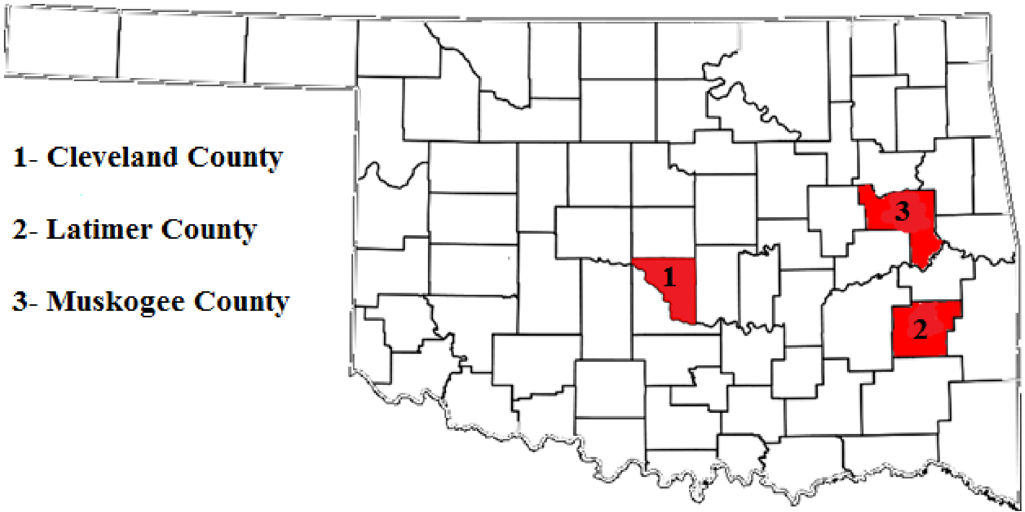


Figure 3.1: Soil Locations on Oklahoma County Map

Figure 3.2: Soil Collection from (a) Cleveland County (b) Latimer County (c) Muskogee County and (d) Soils Samples in Plastic Bags.

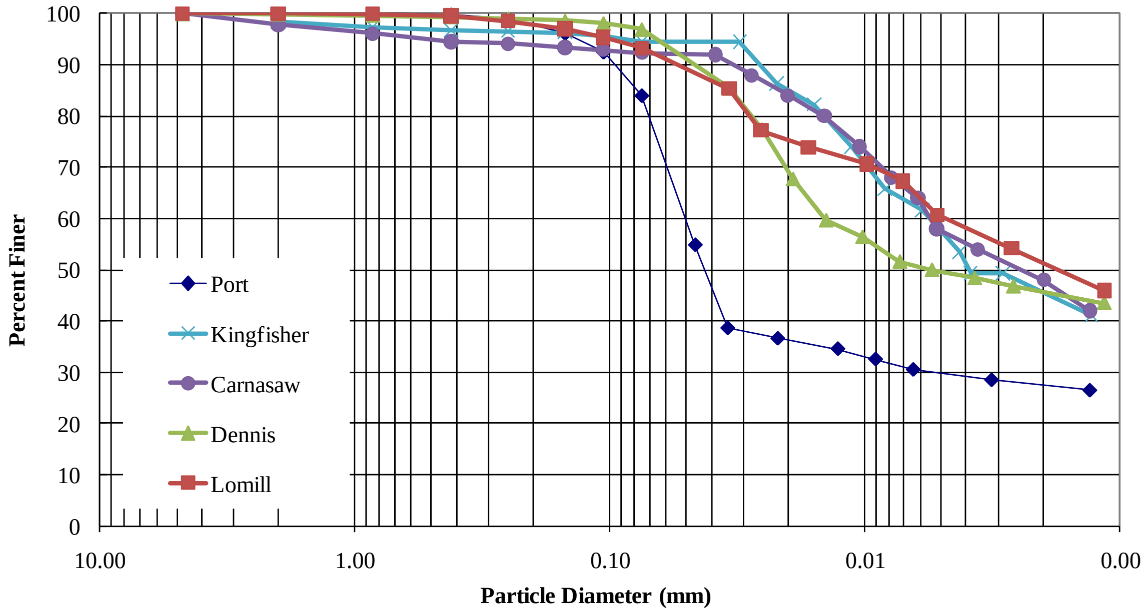


Figure 3.3: Gradation Plot for all Five Soils

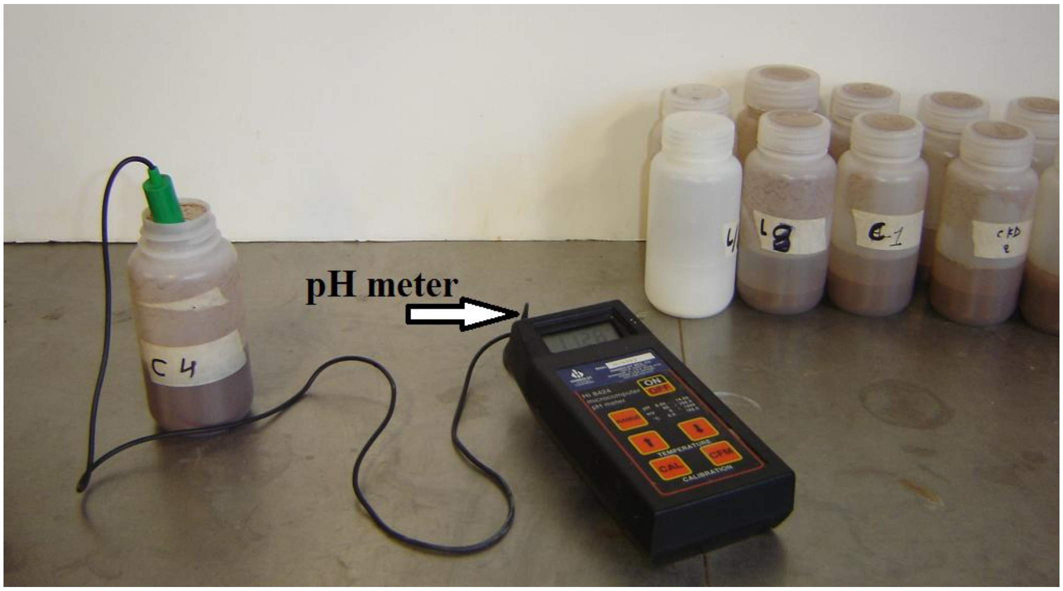


Figure 3.4: pH test in Progress

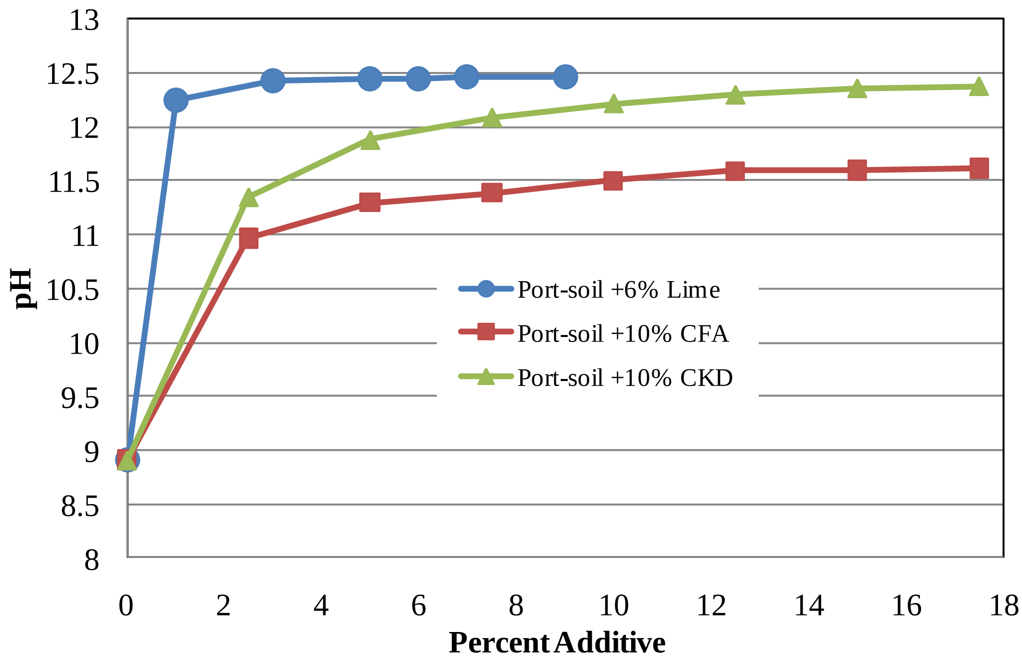


Figure 3.5: pH Results for Stabilized Port Soil

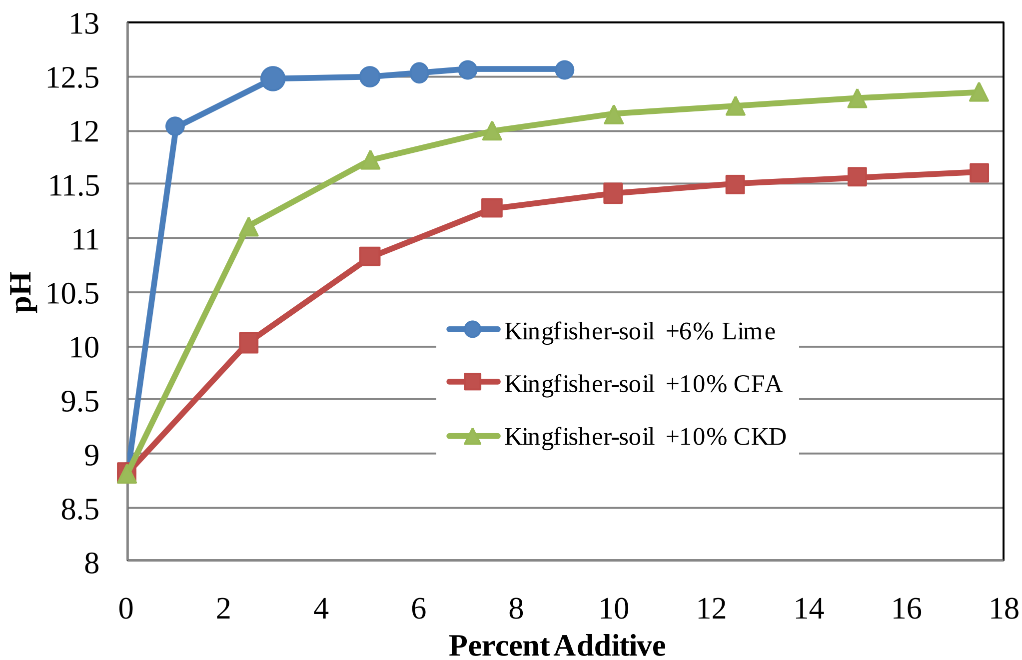


Figure 3.6: pH Results for Stabilized Kingfisher Soil

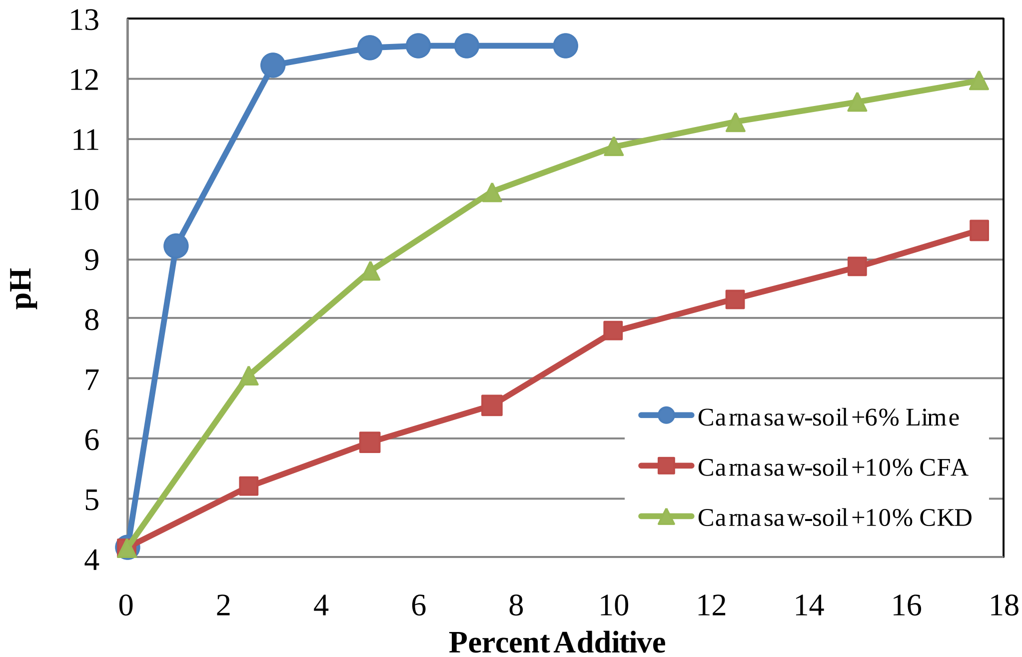


Figure 3.7: pH Results for Stabilized Carnasaw Soil

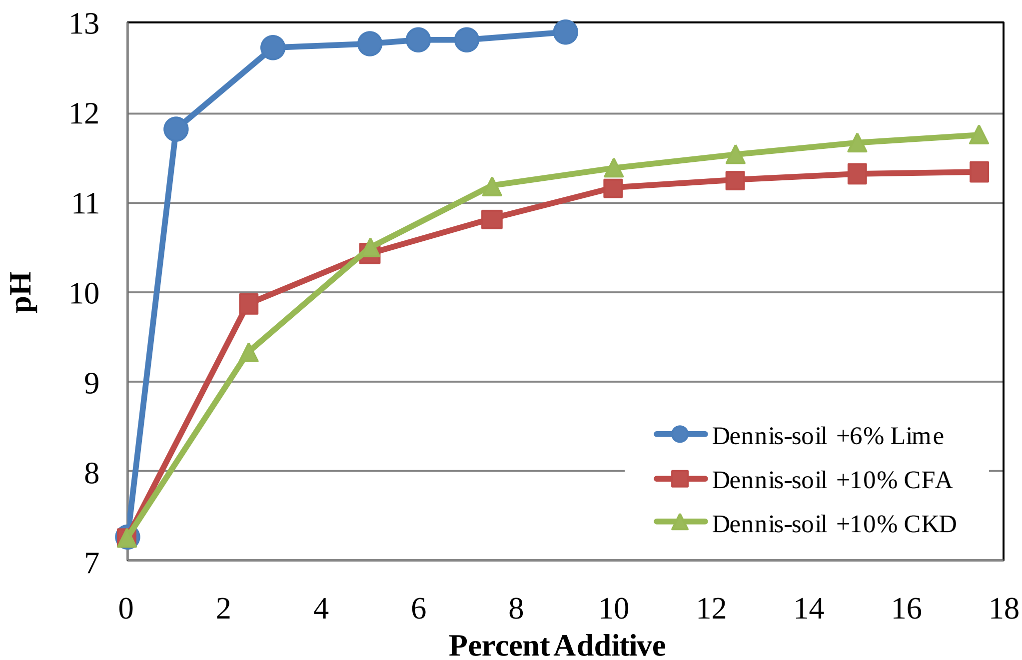


Figure 3.8: pH Results for Stabilized Dennis Soil

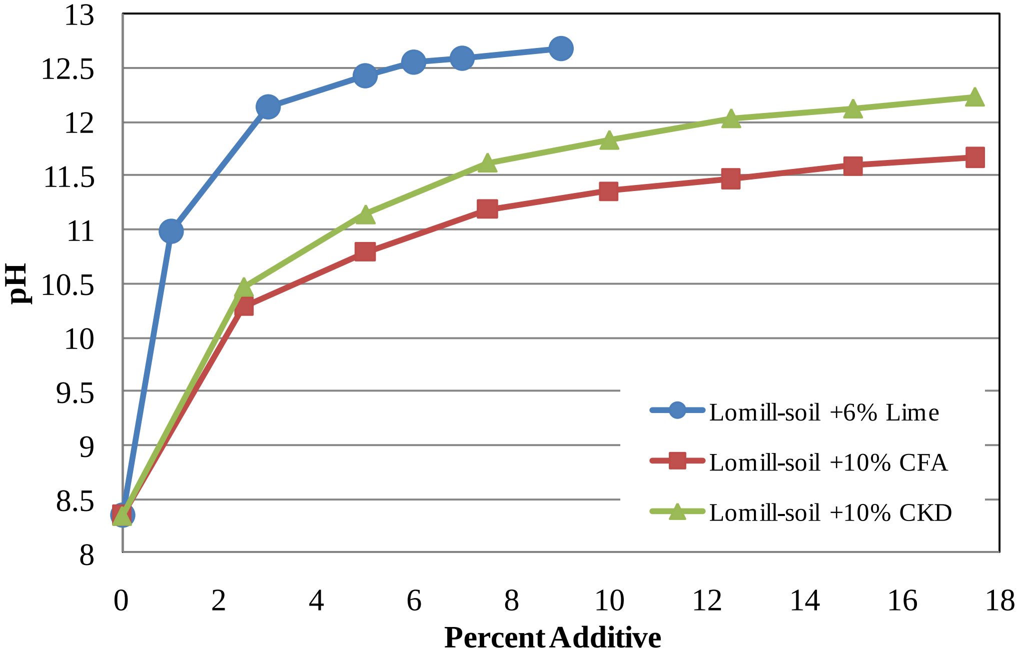


Figure 3.9: pH Results for Stabilized Lomill Soil

(a) (b)

(c) (d)

Figure 3.10: Setup for (a) Freezing, (b) Thawing, Wetting (c) and Drying (d) Tests.

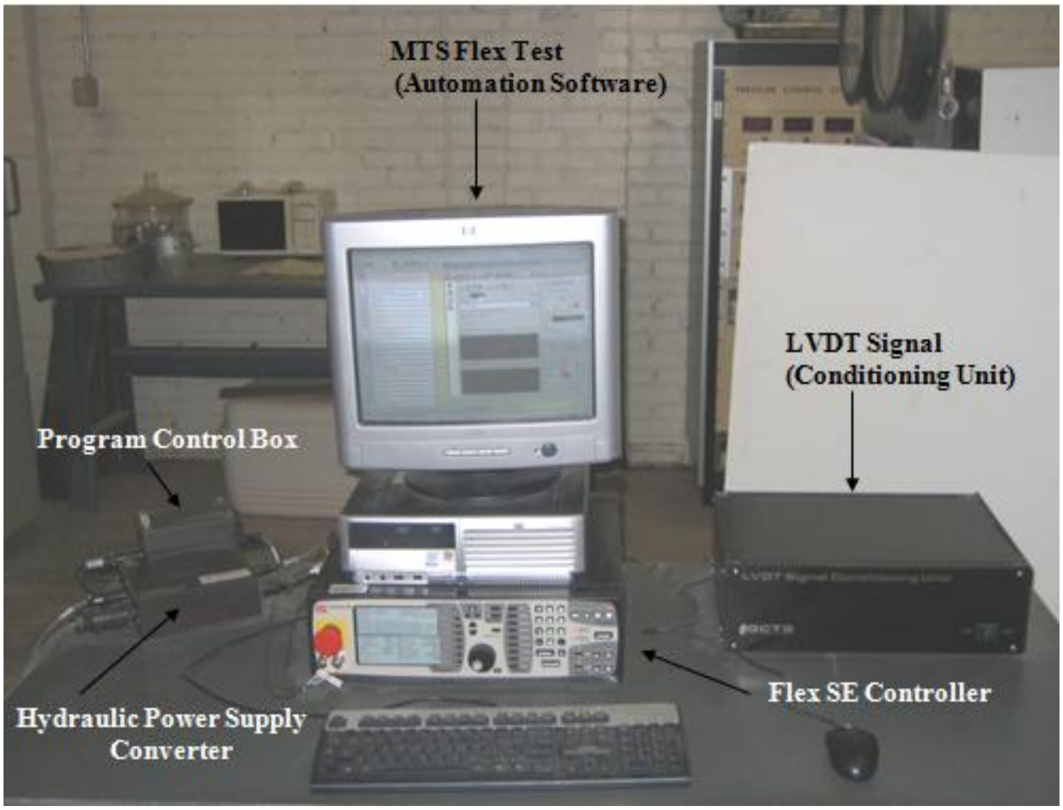


Figure 3.11: MTS Digital Control System and Computer

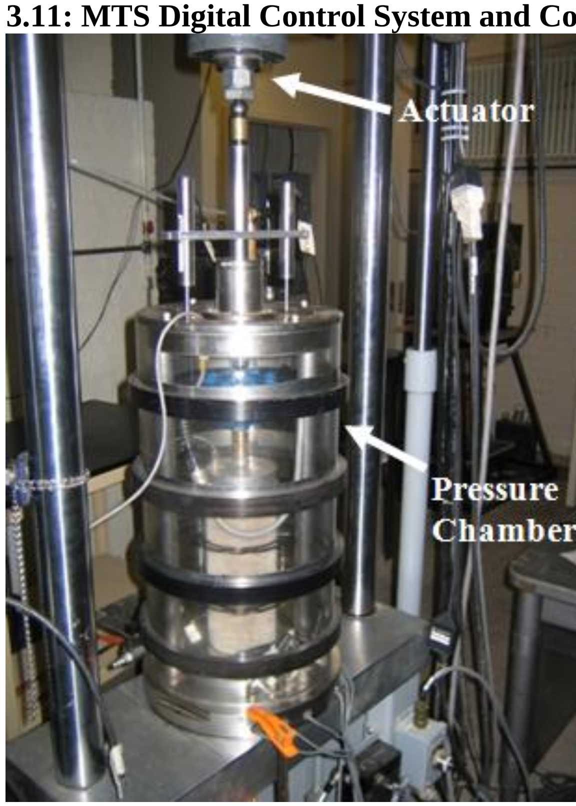


Figure 3.12: Setup for Resilient Modulus Test (With Pressure Chamber)

(a) (b)

Figure 3.13: Resilient Modulus Specimens under (a) Freezing and (b) Thawing

(a) (b)

Figure 3.14: Specimens under Wetting Cycle at 0 hours (a) and During 42 hours Oven Drying (b)

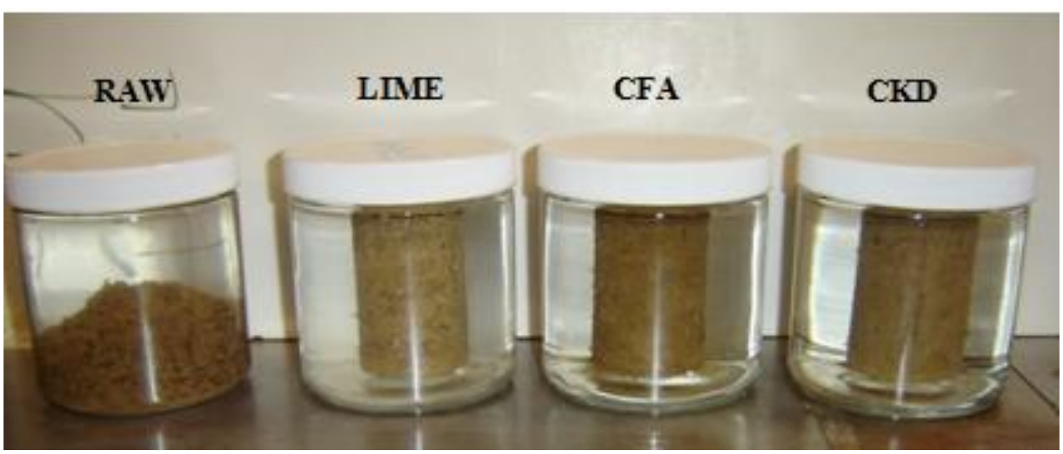


Figure 3.15: Specimens during Wetting Process

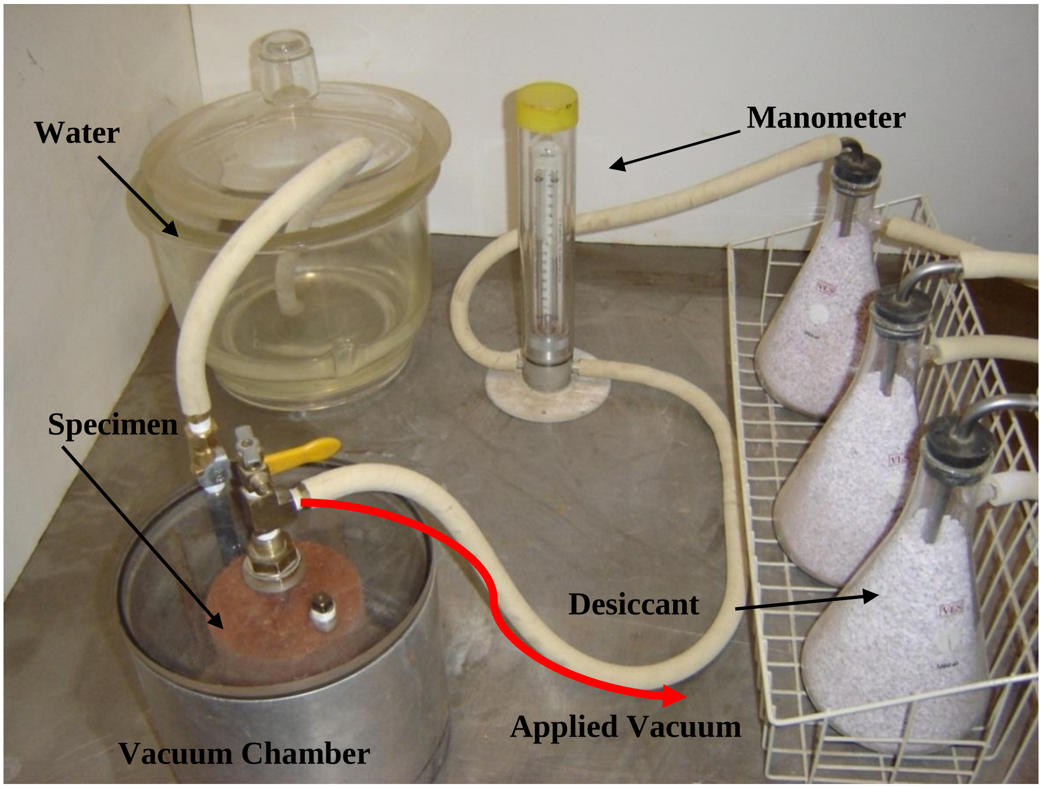


Figure 3.16: Setup for Vacuum Saturation Test

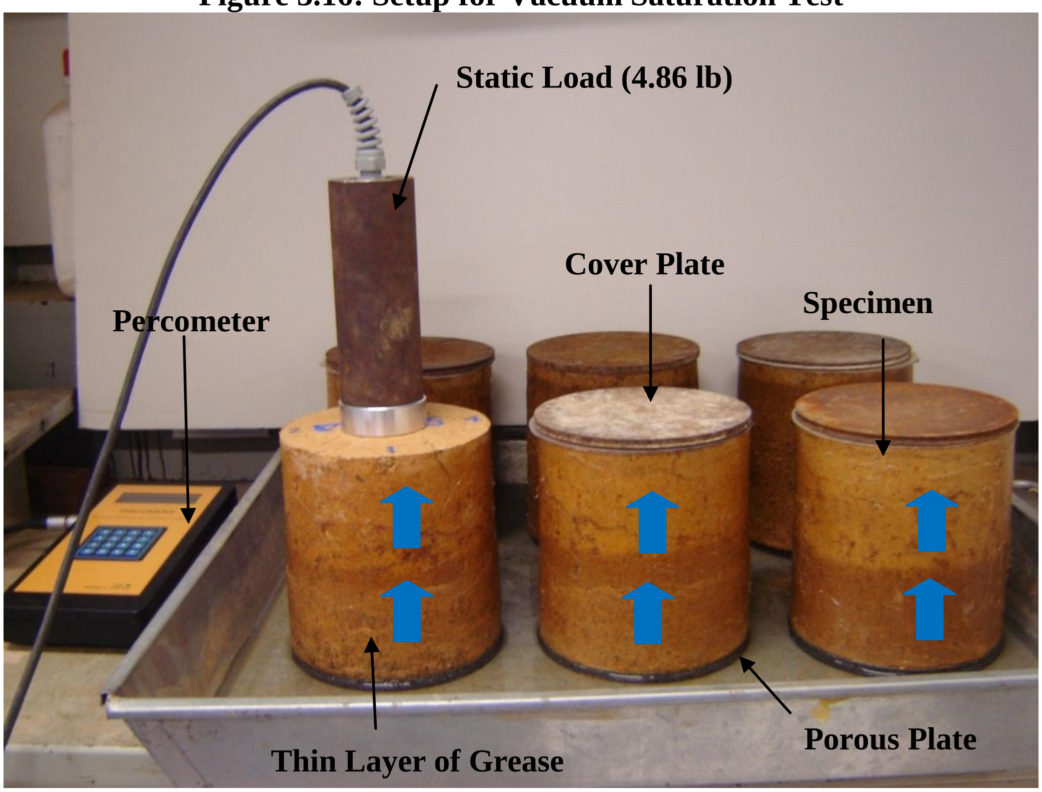


Figure 3.17: Setup for Tube Suction Test

4.1 General

This chapter is devoted to presenting and discussing the results of unconfined compressive strength (UCS) and resilient modulus (M_r) tests conducted at the end of freeze-thaw (F-T) and wet-dry (W-D) cycles. Experimental results for UCS before and after vacuum saturation, moisture susceptibility, and tube suction test are also presented.

4.2 Effect of F-T Cycles on UCS

4.2.1 Effect of soil type

The individual results of the UCS tests after 0, 1, 4, 8, and 12 F-T cycles are graphically illustrated in Figures 4.1, 4.2, 4.3, 4.4, and 4.5 for Port, Kingfisher, Carnasaw, Dennis, and Lomill series soil specimens, respectively. All the specimens tested in this study generally showed a reduction in the UCS values with an increase in the number of F-T cycles. For example, the UCS value of raw, 6% lime-, 10% CFA-, and 10% CKD-stabilized Port series soil specimens after 12 F-T cycles are approximately 97.1%, 85.2%, 87.0%, and 82.8% lower than a comparable specimen with no F-T cycle. A similar qualitative trend was observed for the Kingfisher, Carnasaw, Dennis, and Lomill specimens, where the UCS values exhibited a decrease as the number of F-T cycles increased up to 12. The decrease in UCS values can be explained by a combined effect of pore structure and the increase in moisture content (Figures 4.6-4.10 for Port, Kingfisher, Carnasaw, Dennis, and Lomill soil specimens) during the thawing portion of the cycle. An increase in moisture content during the thawing phase results in the formation of ice lenses within the void space of the specimens in the freezing phase; formation of ice lenses distorts the structure of raw and stabilized specimens

(Solanki, 2010). On the other hand, a higher density of stabilized soil specimens indicates a fine pore structure. The capillary force exerted on a pore wall depends on the pore size: the smaller the pore, the higher the suction force. As water enters and exits the pores, it can generate considerable pressure and degrade the surrounding material (Prusinski and Bhattacharja, 1999). Although lime-stabilized specimens had a higher moisture content after 8 F-T cycles than the corresponding CFA-stabilized specimens (Figure 4.6-4.8) for most of the soils tested, those specimens also had a lower density, indicating an open pore structure which reduces the F-T damage effects (12.9 psi for Kingfisher-soil-lime versus 11.7 psi for Kingfisher-soil-CFA mixtures). It is also clear from Figures 4.1 through 4.5 that the decrease in UCS from F-T cycle 0 to 1 is higher than the decrease in UCS between the other F-T cycles. For example, UCS values of 6% lime-stabilized Kingfisher soil specimens decreased by approximately 40% between F-T cycles 0 and 1, and 38% between F-T cycles 1 and 4. It is speculated that initial freezing and thawing actions opened up the pores, reducing the damaging effects of later F-T cycles.

It is also interesting to note that raw and stabilized Carnasaw soil specimens showed the highest visual degradation and the lowest UCS values at the end of the F-T cycles (Figure 4.3) as compared to the corresponding raw and stabilized specimens of Port, Kingfisher, Dennis, and Lomill soils. One of the explanations could be the acidic behavior of Carnasaw soil (pH = 4.17), which will result in a lower rate of cementitious reactions (Table 3.2).

4.2.2 Effect of additive type

The effect of F-T action on UCS values varies from one soil-additive mixture to another, as shown in Figures 4.1 through 4.5. Table 4.1 shows the average percentage decrease in UCS values of raw and stabilized Port, Kingfisher, Carnasaw, Dennis, and Lomill soil specimens due to F-T action. It is evident that for Port soil specimens, a silty clay with sand, the percentage decrease in UCS values of 10% CKD-stabilized specimens is lower than the corresponding 6% lime-stabilized specimens, followed by 10% CFA-stabilized specimens. For example, the UCS values of CKD-stabilized specimens subjected to 4 F-T cycles are approximately 65% lower than the corresponding UCS values of stabilized specimens with no such cycles. The corresponding percentage decrease is 75% and 82% for lime- and CFA-stabilized specimens. Although the percentage decrease in UCS values for lime-stabilized specimens subjected to 1 F-T cycle is higher than the corresponding CKD-stabilized specimens, the UCS values for CKD-stabilized specimens were higher than the corresponding UCS values of the lime-stabilized specimens. Specifically, the UCS values of CKD-stabilized specimens is 87.8 psi, which is approximately 91% higher than the corresponding UCS values of lime-stabilized specimens after 1 F-T cycle (Figure 4.1). Figure 4.11 shows a photographic view of the raw, 6% lime-, 10% CFA-, and 10% CKD-stabilized specimens of Port soil at the end of 12 F-T cycles. Consequently, CKD-stabilization provided better resistance than lime- and CFA-stabilization towards F-T durability of Port soil specimens.

Contrary to the behavior of stabilized Port soil specimens, F-T tests on Kingfisher soil (lean clay), Carnasaw, Dennis, and Lomill soils (fat clays) stabilized with 6% lime showed the lowest percentage decrease in UCS values followed by 10% CKD and 10% CFA (Table 4.1). For example, the average UCS value of 6% lime-stabilized Carnasaw soil specimens subjected to 1 F-T cycles is 23 psi, as compared to 9.4 psi, and 3 psi for 10% CKD- and 10% CFA-stabilized specimens, respectively. Although Kingfisher series soil specimens showed the lowest percentage decrease in UCS values with the addition of 6% lime, the average UCS value of CKD-stabilized specimens was the highest at the end of the F-T cycles. Furthermore, the percentage decrease in UCS values from Table 4.1 supports the fact that the 6% lime stabilized specimens are more durable against F-T cycles when compared to specimens stabilized with 10% CKD and 10% CFA. It is believed that the presence of higher calcium content in lime, among all additives used in this study (Table 3.3), will produce a higher amount of cementitious products (e.g., calcium silicate hydrate, calcium aluminate hydrate) after combining with pozzolana (silicious and aluminacious material). Since Kingfisher, Carnasaw, Dennis, and Lomill soil have a very high clay content indicating a higher amount of pozzolana as compared to Port soil (Table 3.1), more cementitious compounds are expected in Kingfisher, Carnasaw, and Lomill soil after stabilization with lime. Figures 4.12, 4.13, 4.14, and 4.15 show photographic views of raw and stabilized specimens of Kingfisher, Carnasaw, Dennis and Lomill soil, respectively. It is clear from Figures 4.12, 4.13, 4.14, and 4.15 that raw soil specimens show more degradation than the corresponding stabilized Kingfisher, Carnasaw, Dennis, and Lomill soil specimens. Additional photographic views of specimens at the end of different F-T cycles are presented in Appendix A. From these figures, it can be concluded that durability of Kingfisher, Carnasaw, Dennis, and Lomill soil specimens against F-T cycles is higher with lime as compared to CFA and CKD.

4.3 Effect of W-D Cycles on UCS

4.3.1 Effect of Soil Type

The UCS test results after 0 and 1 W-D cycles are graphically illustrated in Figures 4.16, 4.17, 4.18, and 4.19 for Kingfisher, Carnasaw, Dennis, and Lomill series soil specimens. No specimen survived beyond 1 W-D cycle. All the specimens tested in this study, in general, showed an increase in the UCS values at the end of 1 W-D cycle. For example, the UCS value of 6% lime-, 10% CFA-, and 10% CKD-stabilized Lomill series soil specimens after 1 W-D cycle is approximately 4.0, 3.7, and 3.4 times greater than a comparable specimen with a zero W-D cycle. A similar qualitative trend was observed for all other tested soils, namely Kingfisher, Carnasaw, and Dennis, where the UCS values exhibited an increase after subjecting the specimens to 1 W-D cycle. The increase in UCS values can be explained by the drying phase, where the moisture content in the specimen is decreased to levels below 1% eliminating the effect of pore water in the specimens. The failure of specimens during subsequent W-D cycles, however, can be due to the presence of open cracks in the specimens from the drying phase, which can facilitate the penetration of water. Water enters and exits the pores which can generate considerable pressure and degrade the surrounding material (Prusinski and Bhattacharja, 1999). Figures 4.20 through 4.23 show deterioration of Kingfisher, Carnasaw, Dennis, and Lomill soil specimens, due to the application of W-D cycles. All raw soil specimens collapsed during the wetting phase of 1 W-D cycle.

4.3.2 Effect of Additive Type

The effect of W-D action on the UCS values varies from one soil-additive mixture to another, as shown in Figures 4.16 through 4.19. It is evident from Figure 4.16 that for the Kingfisher soil specimens (lean clay), the percentage increase in UCS values of 10% CKD-stabilized specimens is higher than the corresponding 10% CFA-stabilized specimens, followed by 6% lime-stabilized specimens. For example, the UCS value of 10% CKD-stabilized specimens subjected to 1 W-D cycle is approximately 238% higher than the corresponding UCS value of stabilized specimens with no such cycle. Similar behavior was reported by other researchers (e.g., Miller and Zaman, 2000; Rahman, 2002). Specifically, the UCS value of CKD-stabilized specimens is 694 psi, which is approximately 38% higher than the corresponding UCS values of lime-stabilized specimens after 1 W-D cycle (Figure 4.16).

Similar to the behavior of stabilized Kingfisher soil specimens, W-D tests on Carnasaw soil projected 10% CKD-stabilized specimens showed the highest increase in UCS values (Figure 4.17). Both 6% lime- and 10% CFA-stabilized specimens disintegrated during the wetting phase of 1 W-D cycle (Figure 4.21). On the other hand, Dennis and Lomill soil specimens stabilized with 6% lime showed the highest UCS values, followed by 10% CKD- and 10% CFA-stabilized specimen (Figures 4.18 and 4.19). Additional photographic views of specimens at the end of different W-D cycles are presented in Appendix B.

4.4 Effect of F-T Cycles on M_r

4.4.1 Effect of Soil Type

Resilient modulus tests were conducted on the soil specimens at the end of 0, 1, 4, 8, and 12 F-T cycles, as discussed in Section 3.6.2. The M_r test results for raw and stabilized Port, Kingfisher, Carnasaw, Dennis, and Lomill series soil specimens are presented in Tables 4.2 through 4.6, respectively. For comparison, M_r values at a particular stress level (σ_d = 5.4 psi, σ_3= 4 psi) are graphically presented in Figures 4.24 through 4.28 for Port, Kingfisher, Carnasaw, Dennis and Lomill series soils. In general, it is clear that both raw and stabilized specimens of Port, Kingfisher, Carnasaw, Dennis, and Lomill soils showed a reduction in M_r values due to the application of F-T cycles. For example, the application of 1 F-T cycle decreased the M_r values of raw, 6% lime-, 10% CFA-, and 10% CKD-stabilized Port series soil specimens by approximately 67%, 82%, 75%, and 88%, respectively. Such reductions in M_r values could be explained by using similar reasons as discussed in Section 4.2. It is also clear from Figures 4.24 through 4.28 that a reduction in M_r values from F-T cycle 0 to 1 is higher than the reduction in M_r values between the other F-T cycles. For example, the M_r values of 6% lime-stabilized Kingfisher soil specimens decreased by approximately 87%

between F-T cycles 0 and 1, and by 21% between F-T cycles 1 and 4. It is speculated that freezing and thawing opened up the pores, which reduced the damaging effects of later F-T cycles.

4.4.2 Effect of Additive Type

It is evident from Table 4.2 and Figure 4.24 that the Port series soil provided the highest M_r values with 10% CKD after 1 F-T cycle. For example, 6% lime, 10% CFA, and 10% CKD provided M_r values of Port soil ranging between 14,072 - 20,885 psi, 11,599 - 18,114 psi, and 26,123 - 34,016 psi at the end of 1 F-T cycle. The Kingfisher series soil provided a similar range of M_r values at the end of 1 F-T cycle with 6% lime (12,664 – 18,482 psi) and 10% CKD (12,944 – 23,737 psi), followed by 10% CFA (11,373 – 16,272 psi) which are the lowest M_r values. Carnasaw, Dennis, and Lomill series soil exhibited the highest M_r values with 6% lime followed by 10% CKD and 10% CFA at the end of 1 F-T cycle. For example, the application of 1 F-T cycle reduced the M_r values of Lomill series soil, with the M_r values after reduction ranging between 13,824 - 20,857 psi, 9,074 - 13,420 psi, and 10,657 - 15,542 psi with 6% lime, 10% CFA, and 10% CKD, respectively. Similar reductions in M_r values due to the application of F-T cycles were reported by Khoury (2007) for base course materials stabilized with CKD and CFA. To the author's knowledge, no study is available in the open literature indicating the effect of F-T cycles on M_r values of stabilized subgrade soils. Additional photographic views of M_r specimens at the end of different F-T cycles are presented in Appendix C.

4.5 Effect of W-D Cycles on M_r

4.5.1 Effect of Soil Type

Resilient modulus tests were conducted on the soil specimens at the end of 0 and 1 W-D cycles, as discussed in Section 3.6.2. All of the specimens failed during the application of 2 W-D cycle. The M_r test results for raw and stabilized Kingfisher, Carnasaw, Dennis, and Lomill soil specimens are presented in Tables 4.7 through 4.10. For comparison, the M_r values at a particular stress level (σ_d = 5.4 psi, σ_3= 4 psi) are graphically presented in Figures 4.29 through 4.32 for Kingfisher, Carnasaw, Dennis, and Lomill series soil specimens, respectively. In general, it is clear that both the raw and stabilized specimens of Kingfisher, Carnasaw, Dennis, and Lomill soils showed a reduction in M_r values due to the application of W-D cycles. For example, the application of 1 W-D cycle decreased the M_r value of raw, 6% lime-, 10% CFA-, and 10% CKD-stabilized Kingfisher series soil specimens by approximately 100%, 70%, 53%, and 76%, respectively. The decrease in M_r values could be explained by using similar reasons as discussed in Section 4.2. It is also clear from Figures 4.29 through 4.32 that the decrease in M_r values due to an increase in W-D cycles from 0 to 1 is most dominant where most of the loss in strength happened.

4.5.2 Effect of Additive Type

It is clear from Table 4.7 and Figure 4.29 that the Kingfisher series soil provided similar magnitude of M_r values with 6% lime and 10% CKD. For example, 6% lime, 10% CFA, and 10% CKD provided M_r values of the Kingfisher soil specimens ranging between 27,251 - 45,733 psi, 23,059 - 38,697 psi, and 25,784 - 43,271 psi, at the end of 1 W-D cycle. The Dennis and Lomill series soil provided the highest M_r values with 6% lime followed by

10% CKD and 10% CFA at the end of 1 F-T cycle. For example, at the end of 1 F-T cycle, Dennis series soil specimens stabilized with 6% lime, 10% CFA, and 10% CKD provided M_r values ranging between 27,867 – 33,434 psi, 15,227 – 20,398 psi, and 1,929 – 24,803 psi, respectively. For Lomill series soil, these ranges are between 29,705 – 47,561 psi, 17,269 – 25,714 psi, and 20,423 – 30,313 psi for specimens stabilized 6% lime, 10% CFA, and 10% CKD, respectively. On the other hand, the Carnasaw series showed the highest M_r values with 10% CKD, followed by 6% lime. For example, application of 1 F-T cycle reduced the M_r values of Carnasaw series soil ranging between 27,375 - 54,253 psi, and 28,642 - 35,894 psi for 10% CKD- and 6% lime-stabilization, respectively. Additional photographic views of M_r specimens during W-D cycles are presented in Appendix D.

4.6 Moisture Susceptibility Test

Figures 4.33 through 4.37 show UCS values of Port, Kingfisher, Carnasaw, Dennis and Lomill series soils, respectively, tested before and after a 5-hour soaking period. It is clear from Figures 4.33 through 4.37 that all of the soil specimens showed a reduction in UCS values due to soaking in water for 5-hour. Port soil specimens stabilized with 10% CKD showed the highest resistance towards moisture damage with a retained UCS value of 83.8 psi, followed by 60.5 psi for 10% CKD and 43.9 psi for 10% CFA. Similarly, Kingfisher series soil specimens showed the highest retained UCS value of 76.9 psi with 10% CKD, followed by 52.0 psi for 6% lime and 48.1 psi for 10% CFA. Kingfisher, Dennis, and Lomill soils exhibited a similar trend with 6% lime presenting the highest resistance towards moisture followed by 10% CKD and 10% CFA. For example, Dennis series soil specimens showed a retained UCS value of 48.3 psi, 19.7 psi, and 28.3 psi with 6% lime, 10% CFA, and 10% CKD, respectively. In the case of Carnasaw series soil, all of the raw and stabilized specimens collapsed during the 5-hour soaking period. However, visual observations indicated that the raw soil specimens collapsed first, followed by 10% CFA and 10% CKD. Carnasaw series soil specimens stabilized with 6% lime showed the highest resistance towards moisture and disintegrated at the end.

As noted in Section 3.7, the degree of saturation was measured before and after soaking, and the results are presented in Figures 4.38 through 4.41 for Port, Kingfisher, Dennis and Lomill soils. It is clear, that generally the degree of saturation of stabilized soil specimens increases due to the 5-hour soaking period. For example, Port soil specimens stabilized with 6% lime, 10% CFA, and 10% CKD presented an increase in degree of saturation by 5.7%, 4.5%, and 7.3%, respectively, due to the 5-hour soaking period (Figure 4.38). The degree of saturation of Kingfisher series soil specimens increased by 13.7%, 8.3%, and 4.9% with 6% lime, 10% CFA, and 10% CKD, respectively, due to 5-hour soaking period. Dennis series soil (fat clay) stabilized with 6% lime exhibited an increase in degree of saturation by 6.5%, which is lower than the increase in degree of saturation of specimens stabilized with 10% CKD (10.4%) and 10% CFA (10.6%). Similar to the trend in behavior of Dennis soil, the specimens of Lomill soil stabilized with 6% lime presented the lowest increase in degree of saturation (2.4%). Figures 4.42 through 4.46 show photographic view of Port, Kingfisher, Carnasaw, Dennis and Lomill specimens at the end of the 5-hour of soaking period. Additional photographic views of the specimens at during soaking are presented in Appendix E.

Figure 4.47 shows the relationship between the degree of saturation and the moisture content of the specimens before and after the 5-hour soaking period. A moderate level of relationship with a R^2 value of 0.56 and 0.64 (Figure 4.47) is clearly evident between the degree of saturation and the moisture content. It is important to note that in this study the degree of saturation was calculated by assuming specific gravity of the stabilized specimen is same as that of raw soil. However, in reality the specific gravity of stabilized soil may be different than that of the raw soil specimens due to the formation of cementitious compounds (this topic is beyond the scope of the current study). Thus, to evaluate the effect of specific gravity on the degree of saturation, a parametric study was performed by calculating the degree of saturation at different specific gravity values for Dennis series soil specimens (Table 1). It is clear from Table 1 that the degree of saturation is dependent on the specific gravity values and decreases with increase in specific gravity value. For example, an increase in specific gravity value from 2.60 to 2.75 decreased the degree of saturation value by approximately 6.9%, 8.1%, and 7.8% for 6% lime-, 10% CFA-, and 10% CKD-stabilized specimens, respectively.

4.7 Effect of Vacuum Saturation on UCS

4.7.1 Effect of Soil Type

The individual results of the UCS tests before and after vacuum saturation are graphically illustrated in Figures 4.48, 4.49, 4.50, 4.51, and 4.52 for Port, Kingfisher, Carnasaw, Dennis and Lomill series soil specimens, respectively. Similar to the F-T testing, all the specimens tested in this study showed a reduction in the UCS values after being subjected to vacuum saturation. However, the percentage reduction in the UCS values is dependent on the type of soil. For example, the UCS values of raw, 6% lime-, 10% CFA-, and 10% CKD-stabilized Port series soil specimens after vacuum saturation are approximately 100%, 45%, 53%, and 55% lower than a comparable specimen tested without vacuum saturation. On the other hand, the percentage decrease in UCS values is approximately 100%, 35%, 84%, and 65% for raw, 6% lime-, 10% CFA-, and 10% CKD-stabilized specimens of Dennis soil. A similar qualitative trend was observed for the Kingfisher, Carnasaw, and Lomill specimens, in which the UCS values exhibited a decrease in strength after being subjected to vacuum saturation. The decrease in UCS values can be explained by a combined effect of pore structure and the increase in moisture content during the soaking portion of the test after the application of vacuum to the specimens. An increase in moisture content in the specimens results in water filling the void space of the specimens and therefore, increases the pore water pressure in the specimens, which can distort the specimens internal structure. According to Dempsey and Thompson (1973), an increase in vacuum pressure leads to a reduction in UCS values and an increase in moisture content. The capillary force exerted on a pore wall depends on the pore size; as water enters and exits the pores, it can generate considerable pressure and degrade the surrounding material (Prusinski and Bhattacharja, 1999). It is clear from Figures 4.48 through 4.52 that no raw soil specimen was able to withstand the 1-hour soaking period after subjecting to vacuum and it failed in the vacuum chamber without being tested for UCS.

4.7.2 Effect of Additive Type

The average UCS value of the CKD-stabilized Port (38.0 psi) and Kingfisher (62.9 psi) specimens were the highest after vacuum saturation. Similar to the trends of UCS values after the F-T cycles, the 6% lime-stabilized specimens of Kingfisher, Carnasaw, Dennis, and Lomill soil specimens showed the lowest percentage decrease in UCS values after vacuum saturation. For example, the Kingfisher soil specimens stabilized with 6% lime, 10% CFA, and 10% CKD showed a percentage decrease in UCS values of approximately 51%, 66%, and 71%, respectively. Also, it is evident from Figures 4.50, 4.51, and 4.52 that for Carnasaw, Dennis, and Lomill soil specimens, the UCS values after vacuum saturation of 6% lime-stabilized specimens are higher than the corresponding the 10% CKD-stabilized specimens, followed by the 10% CFA-stabilized specimens. On the other hand, 10% CKD showed higher strengths in Port (silty clay with sand) and Kingfisher (lean clay) soil specimens. Since UCS values of stabilized Port, Kingfisher, Carnasaw, Dennis and Lomill series soil specimens after vacuum saturation showed similar trends as seen for UCS values after F-T cycling, similar reasons as mentioned in the preceding section (Section 4.2.2) can be used to rationalize the observed trends. Figures 4.53, 4.54, 4.55 and 4.56 show photographic views of the visual degradation of stabilized Kingfisher, Carnasaw, Dennis, and Lomill soil specimens at the end of the vacuum saturation test. Additional photographic views of specimens taken during the vacuum saturation test are presented in Appendix F.

4.8 Tube Suction Test

As noted in Section 3.9, the tube suction test was conducted on Port, Kingfisher, and Carnasaw series soil by using three methods, namely Method-1, Method-2, and Method-3. A summary of the final 10th day dielectric constant values (DVs) for the raw and stabilized Port, Kingfisher, and Carnasaw soil specimens evaluated by using Method-1 through Method-3 is given in Figures 4.57, 4.58 and 4.59, respectively.

4.8.1 Effect of Method of Specimen Preparation

It is clear from Figures 4.57 through 4.59 that the specimens prepared using Method-1 showed a lower DV as compared to specimens prepared using Method-2 and Method-3; Method-2 and Method-3 provided similar DVs. For example, raw Kingfisher soil specimens provided a DV of 18.1, 40.2, and 39.9 when specimens were prepared in accordance with

Method-1, Method-2 and Method-3, respectively. The differences in DV values between the specimens prepared by using Method-1 and Method-2 or Method-3 could be attributed to the variation of the moisture content values along the height of the specimens, as shown in Figures 4.60 through 4.62, for Port, Kingfisher, and Carnasaw soil specimens. For specimens prepared using Method-1, it is observed that the moisture content of the bottom layer is very high compared to the moisture content of the top layer. This difference in moisture content between bottom and top layers varies between 1.3 and 3.9%, 1.3 and 6.9%, and 1.0 and 6.7% for Port, Kingfisher, and Carnasaw soil specimens, respectively. Comparatively, all of the Port, Kingfisher, and Carnasaw soil specimens prepared using Method-2 showed a difference in moisture content of less than 0.5% between the bottom and top layers. Since the measured signal using a Percometer^{TM} depends only on the dielectric properties of the top 0.8 – 1.2 in. of material (Saarenketo, 2006; Adek, 2007), it is expected that the specimen having a uniform moisture content will provide the representative behavior. Also, it is important to note that the specimens compacted in a single layer (Method-2 and Method-3) are more representative of the field conditions where stabilized subgrade layer is generally compacted in one lift. Figures 4.63 (a) and (b) show a photographic view of 10% CKD-stabilized Carnasaw soil specimens prepared by using Method-1 and Method-2, respectively. It is evident from Figures 4.63 (a) and (b) that the specimen prepared using Method-1 is dry at top, while specimen prepared by using Method-2 is uniformly wet, which resulted in lower (28.9) and higher (41.1) DVs, respectively, as shown in Figure 4.59.

4.8.2 Effect of Soil and Additive Type

Since Method-2 and Method-3 provided similar and representative DVs of stabilized soil specimens, the DVs obtained by using Method-2 were used for further evaluation of the effect of soil and additive type on durability. Furthermore, the DVs of Dennis and Lomill soil specimens were also evaluated by using Method-2. A summary of the final dielectric constant value of Dennis and Lomill series soil specimens along with the average moisture content is provided in Figures 4.64 and 4.65. The raw Port, Kingfisher, Carnasaw, Dennis, and Lomill series soil specimens showed an average DV of approximately 35.3, 40.2, 39.2, 42.1, and 49.5, respectively. Stabilization with 10% CFA is more effective in reducing the DV of Port soil specimens, followed by 6% lime. For example, the DV values reduced by 18% and 17% by treating Port soil specimens with 10% CFA and 6% lime, respectively. Similar to the qualitative trend noticed in the preceding sections, Kingfisher, Carnasaw, Dennis, and Lomill soil specimens showed more effectiveness with 6% lime by decreasing the DVs of corresponding raw soil specimens by 20%, 15%, 12%, and 9%, respectively. These results are consistent with the observations made by Little (2000), and Barbu and McManis (2004). The percentage decrease in DV due to 10% CFA was found to be approximately 7%, 4%, 0.4%, and 8% for Kingfisher, Carnasaw, Dennis, and Lomill soil specimens, respectively, which is consistent with the observations reported by Guthrie et al. (2008) and Parker (2008). It is an indication that lime and CFA stabilization has more or less the same degree of effectiveness in reducing the DV for Lomill soil specimens.

Moreover, CKD was found to show no significant improvement in DVs for the Port, Carnasaw, Kingfisher, Dennis, and Lomill series soil specimens. For example, Port, Kingfisher, Carnasaw, and Dennis series soil specimens prepared with 10% CKD showed an average increase of approximately 5%, 4%, 5%, and 4% in DVs as compared to corresponding raw specimens. Similar behavior of an increase in DV with the addition of 2% CKD in limestone base material was reported by Si and Herrera (2007). This behavior of an increase in DV of CKD-stabilized specimens may be attributed to the presence of extra CKD in the specimen which is not reacting with the host material; hence, it absorbs water which increases the moisture content (Figures 4.60 – 4.63, 4.64 – 4.65) and dielectric constant. Furthermore, the results presented in Figures 4.64 and 4.65 indicate that the standard deviation of DVs of specimens ranges between 0.14 – 2.76 and 0.28 – 1.18 for Dennis and Lomill series soil specimens, respectively. The variation of DVs with time for Dennis and Lomill series soil specimens are presented in Figures 4.66 and 4.67, respectively.

Figure 4.68 shows that the final DV is affected by the moisture content of specimens (R^2 = 0.70). However, it is worth noting that the final DV is dependent on the material type and is influenced by properties such as clay content, saturation history, degree of bonding of water molecules around soil particle, optimum moisture content, and plastic limit (Saarenketo, 2006).

4.9 Size Effect

To study the effect of size on the durability of the specimens, selected Carnasaw series soil specimens were tested for UCS at the end of the F-T cycles. A total of eight cylindrical specimens having a diameter of 4.0 in and a height of 8.0 in were prepared in this study in accordance with method discussed in Section 3.6.2. These eight specimens included two replicates for each soil-additive mix, namely raw Carnasaw soil, Carnasaw soil with 6% lime, Carnasaw soil with 10% CFA, and Carnasaw soil with 10% CKD. After 7 days of curing, one replicate was tested for UCS before any F-T cycle, whereas the other replicate was tested for UCS after 1 F-T cycle in accordance with method discussed in Section 3.6.1. A summary of UCS values before and after 1 F-T cycle of raw soil, 6% lime-, 10% CFA-, and 10% CKD-stabilized specimens is presented in Figures 4.69, 4.70, 4.71, and 4.72, respectively. For comparison purpose, the UCS values of corresponding Harvard miniature specimens are also presented in same figures.

It is clear from Figures 4.69 through 4.72 that the UCS values of specimens having a bigger size (4.0 in x 8.0 in) is lower than the UCS values of corresponding specimens having a smaller size (Harvard miniature specimens, 1.3 in x 2.8 in). For example, the UCS values of 4.0 in x 8.0 in specimens is approximately 22%, 83%, 13%, and 61% lower than the UCS values of corresponding smaller specimens of Carnasaw soil stabilized with 0%, 6% lime-, 10% CFA-, and 10% CKD, respectively.

4.10 Effect of Molding Moisture Content

To study the effect of different molding moisture contents on durability, selected specimens of Dennis series soil were prepared and tested at the end of F-T cycles. A total of four M_r specimens (4.0 in x 8.0 in) and eight UCS specimens (1.3 in x 2.8 in) were prepared at a moisture content of OMC+4% in accordance with methods discussed in Sections 3.6.1 and 3.6.2, respectively.

Each set of four M_r specimens included one specimen for each soil-additive mix namely, raw Dennis soil, Dennis soil with 6% lime, Dennis soil with 10% CFA, and Dennis soil with 10% CKD. After 7 days of curing, the specimens were tested for M_r and then subjected to 1 F-T cycle followed by M_r testing. A summary of resilient modulus test results is presented in Table 4.12. For comparison purpose, M_r values at a specific stress level (σ_3 = 4.0 psi, σ_d = 5.4 psi) are presented in Figures 4.73 through 4.76 for raw, 6% lime-, 10% CFA-, and 10% CKD-stabilized specimens. It is clear that the M_r values at OMC+4% is lower than the M_r values of corresponding specimens at OMC, as expected. For example, an increase in moisture content by 4% decreased the M_r values (σ_3 = 4.0 psi, σ_d = 5.4 psi) by approximately

73% and 62% for 6% lime-stabilized specimens tested at the end of 0 and 1 F-T cycles, respectively.

The eight specimens prepared at OMC+4% for UCS testing included two replicates for each soil-additive mix namely, raw Dennis soil, Dennis soil with 6% lime, Dennis soil with 10% CFA, and Dennis soil with 10% CKD. After 7 days of curing, one replicate was tested for UCS before any F-T cycle, whereas the other replicate was tested for UCS after the application of 1 F-T cycle in accordance with method discussed in Section 3.6.1 and the results are presented in Figures 4.77 through 4.80. It is clear from Figures 4.77 through 4.80 that the UCS values of specimens compacted at OMC showed higher UCS values than the UCS values of the corresponding specimens compacted at OMC+4% and tested without any application of F-T cycles. For example, an increase in moisture content by 4% decreased the UCS values by approximately 31%, 57%, 48%, and 35% in raw, 6% lime-, 10% CFA- and 10% CKD-stabilized specimens, respectively, tested at the end of 0 F-T cycle. Similar behavior of higher UCS values at OMC than OMC+4% is evident for the specimens tested at the end of 1 F-T cycle. However, the percentage difference in UCS values between specimens at OMC and OMC+4% is comparatively lower for specimens tested at the end of 1 F-T cycle than the specimens tested without any F-T cycle. For example, an increase in moisture content by 4% decreased the UCS values by approximately 0%, 24%, 34%, and 7% in raw, 6% lime-, 10% CFA-, and 10% CKD-stabilized specimens, respectively, tested at the end of 1 F-T cycle. This difference in behavior could be explained by the differences in the degree of saturation of the specimens before and after the application of F-T cycles (Figures 4.81 – 4.84). It is clear from Figures 4.81 through 4.84 that the specimens compacted at OMC+4% had a higher degree of saturation (1.7% – 3.0%) than the corresponding specimens compacted at OMC and tested without any application of F-T cycle. On the other hand, specimens compacted at OMC had higher (0.7% – 1.5%) degrees of saturation than the corresponding specimens compacted at OMC+4% and tested at the end of 1 F-T cycle.

4.11 Discussion

Based on the aforementioned different durability test results, Port series soil specimens, a silty clay with sand, clearly showed better performance with 10% CKD in F-T (UCS), W-D (UCS), F-T (M_r), W-D (M_r), moisture susceptibility, and vacuum saturation tests. Kingfisher series soil specimens, a lean clay, showed no clear trend with any one particular additive. For example, the F-T (M_r) results showed that the lime-stabilized specimens are on top with highest M_r values at the end of F-T cycles. The moisture susceptibility and vacuum saturation test results showed that the CKD-stabilized specimens are on top with the highest retained UCS values. All three fat clays used in this study (Carnasaw, Dennis, and Lomill) showed better durability with lime, as compared to CKD and CFA. This fact is evident from the retained UCS/M_r values at the end of F-T (UCS), W-D (UCS), F-T (M_r), W-D (M_r), moisture susceptibility and vacuum saturation tests.

According to OHD L-50 (ODOT, 2006), percentage of CFA/CKD that gives a minimum strength of 50 psi but not more than 150 psi should be selected. For lime-stabilized soil specimens, OHD L-50 recommends amount of lime providing a minimum pH of 12.3 in accordance with ASTM D 6276 requirements. Following OHD L-50 recommendations, it appears that for Port soil (A-4), 6% lime and 10% CKD are suitable additives. For Kingfisher soil (A-6), only 6% lime and 10% CFA appears to be suitable additives. For Carnasaw soil (A-7-5), only 6% lime appears as a suitable additive. For Dennis (A-7-6) and Lomill (A-7-6) soils, all 6% lime, 10% CFA and 10% CKD appears suitable additives.

Furthermore, the results obtained from tube suction, vacuum saturation, and moisture susceptibility tests were compared with results obtained from F-T (UCS), W-D (UCS), and F-T (M_r) for identifying the test method that could be used as an inexpensive and time efficient procedure for measuring durability of stabilized specimens.

The relationship between DVs and retained UCS at the end of 1/12 F-T and 1 W-D cycle are presented in Figures 4.85 and 4.86, respectively. Figure 4.87 shows a relationship between DVs and the retained M_r values at the end of 1 F-T cycle. A weak correlation ($R^2 < 0.2$) between the DV and other durability indicators (UCS after 1 F-T cycle, UCS after 1 W-D cycle, and M_r after 1 F-T cycle) is clearly evident from Figures 4.85 through 4.87. Also, it is important to note that the final DVs of all the raw and stabilized specimens tested in this study were above the value of 16. Guthrie and Scullion (2003) suggested the following interpretation of DV for aggregate base material:

Lower DV	**Upper DV**	**Interpretation of Aggregate Base Durability**
NA	10	Good
10	16	Marginal
16	NA	Poor

NA: Not Applicable

Referring to the maximum DV criterion proposed by Guthrie and Scullion (2003), which was mainly for coarse soils or aggregates, the soils tested in this study were moisture susceptible with its maximum DV above 16. However, based on the increase of 7-day UCS by 50 psi over raw specimens criterion, as recommended by several highway agencies (Table 1.1) for the selection of additive content, 10% CKD-stabilized Port soil, 6% lime-/10% CFA-/10% CKD-stabilized Kingfisher, Dennis, and Lomill soil specimens should be durable. Thus, the maximum DV criterion seems more conservative since no specimen satisfied the maximum DV criterion, which is consistent with the observations reported by Zhang and Tao (2008). Also, no correlation was observed between the final DV after tube suction test and durability evaluated by using other durability indicators. For example, Port soil specimens stabilized with 10% CKD showed the best acceptable performance against F-T cycles among all the additives used in this study. On the other hand, the tube suction test results projected 10% CKD-stabilized specimens showing the worst performance with a very high DV of approximately 37.2 (Figure 4.57).

Figures 4.88, 4.89, and 4.90 show plots of UCS after vacuum saturation versus UCS after 1 F-T cycle, UCS after 1 W-D cycle, and M_r after 1 F-T cycle, respectively. The R^2 value associated with these correlations is comparatively moderate (0.40 – 0.50). Furthermore, Figures 4.91 through 4.93 show a relationship between UCS values after 5-hour soaking (moisture susceptibility test) and other durability indicators, namely UCS after 1 F-T cycle, UCS after 1 W-D cycle, and M_r after 1 F-T cycle. The R^2 values associated with these correlations is comparatively high and ranges between 0.70 – 0.86. Thus, a strong correlation exists between UCS values retained after moisture susceptibility tests and UCS/M_r values retained after F-T/W-D cycles. It is also interesting to note that moisture susceptibility is most inexpensive test among all the durability tests evaluated in this study.

Table 4.1: Percentage Decrease in UCS Values of Raw and Stabilized Soil Specimens Due to F-T Cycles

Additive Type	Number of F-T Cycles			
	1	4	8	12
	Port Soil			
None	95.8	96.4	96.7	97.1
6% Lime	32.5	75.4	82.2	85.2
10% CFA	56.9	82.3	86.6	87.0
10% CKD	48.3	65.3	78.0	82.8
	Kingfisher Soil			
None	94.8	95.3	95.6	97.2
6% Lime	40.3	78.8	86.0	89.4
10% CFA	69.2	90.8	92.0	92.6
10% CKD	66.4	83.1	88.2	89.6
	Carnasaw Soil			
None	95.2	95.5	96.5	100.0
6% Lime	62.3	91.0	95.2	98.0
10% CFA	96.9	97.5	98.0	99.0
10% CKD	88.2	93.7	97.6	99.0
	Dennis Soil			
None	95.6	98.2	98.6	98.7
6% Lime	73.5	90.8	90.9	94.7
10% CFA	89.1	94.8	94.9	95.7
10% CKD	84.9	91.6	92.3	92.5
	Lomill Soil			
None	93.8	97.1	100.0	100.0
6% Lime	44.7	84.5	88.0	90.5
10% CFA	91.5	95.8	95.2	96.4
10% CKD	87.4	93.9	94.5	94.3

Table 4.2: M_r Values of Stabilized Port Soil at the End of 0, 1, 4, 8 and 12 Freeze-Thaw Cycles

σ_3 (psi)	σ_d (psi)	Port Series Soil																	
		Raw			**6% Lime**					**10% CFA**					**10% CKD**				
		Cycle 0	Cycle 1	Cycle 4	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12
6	1.8	26,205	7,675	*	231,549	20,885	18,116	17,323	*	117,295	18,114	13,100	*	-	478,822	34,016	24,608	18,916	19,001
6	3.6	22,193	6,910	*	162,853	18,802	16,309	15,595	*	76,285	16,307	11,794	*	-	235,356	30,622	22,153	17,029	17,630
6	5.4	19,834	6,551	*	130,687	18,125	15,716	14,617	*	50,769	16,100	10,901	*	-	204,779	30,907	21,639	16,558	16,857
6	7.2	18,404	6,610	*	110,560	17,678	15,566	14,365	*	59,520	15,500	10,641	*	-	196,910	30,425	21,321	16,189	16,618
6	9.0	17,482	6,851	*	96,095	17,582	15,737	14,473	*	59,659	15,195	10,599	*	-	191,601	30,358	21,113	16,120	16,695
4	1.8	23,392	6,443	*	172,284	17,518	15,798	14,534	*	100,650	15,831	11,572	*	-	410,037	27,896	20,520	15,298	16,643
4	3.6	19,298	5,983	*	118,014	16,980	15,310	13,835	*	64,242	15,098	10,677	*	-	257,637	29,018	20,980	15,504	15,950
4	5.4	17,447	5,778	*	88,800	16,424	14,686	13,294	*	56,314	14,249	9,889	*	-	232,374	28,996	20,419	15,164	15,308
4	7.2	16,483	5,794	*	87,024	16,216	14,420	13,007	*	57,658	13,835	9,516	*	-	203,654	28,821	20,072	14,904	15,184
4	9.0	15,912	5,858	*	85,279	16,182	14,260	12,857	*	54,722	13,683	9,350	*	-	193,464	28,754	19,853	14,826	15,172
2	1.8	21,146	4,780	*	255,837	15,136	13,220	11,735	*	83,498	13,408	9,430	*	-	325,990	24,919	18,425	13,528	13,751
2	3.6	16,888	4,354	*	106,077	14,429	12,330	10,783	*	63,172	12,338	8,215	*	-	252,375	25,615	18,045	13,026	13,006
2	5.4	15,210	4,233	*	82,785	14,027	11,920	10,450	*	53,004	11,723	7,656	*	-	227,159	25,795	17,668	12,757	12,647
2	7.2	14,400	4,303	*	78,017	13,928	11,938	10,481	*	48,365	11,603	7,546	*	-	197,560	25,918	17,506	12,703	12,649
2	9.0	13,946	4,388	*	80,052	14,072	11,884	10,437	*	48,535	11,599	7,420	*	-	193,301	26,123	17,518	12,799	12,799

1 psi= 6.89 kPa; 1 ksi= 6.89 MPa; CFA: class C fly ash; CKD: cement kiln dust

σ_d: cyclic axial stress; σ_3: confining pressure; M_r: resilient modulus; *Specimen failed before the end of this cycle

Table 4.3: M_r Values of Stabilized Kingfisher Soil at the End of 0, 1, 4, 8 and 12 Freeze-Thaw Cycles

σ_3 (psi)	σ_d (psi)	Kingfisher Series Soil																			
		Raw			**6% Lime**					**10% CFA**					**10% CKD**						
		Cycle 0	Cycle 1	Cycle 4	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12		
6	1.8	14,150	2,258	*	142,230	18,482	14,800	13,566	13,147	86,853	16,272	10,403	*	-	188,270	23,737	14,339	*	-		
6	3.6	12,093	2,094	*	134,879	17,527	14,035	12,865	12,467	4,653	14,361	9,865	*	-	136,568	17,219	10,402	*	-		
6	5.4	9,875	1,802	*	127,828	16,733	13,174	11,976	11,588	29,817	15,205	8,905	*	-	141,408	16,330	9,816	*	-		
6	7.2	8,322	1,689	*	120,408	16,176	12,809	11,551	11,249	65,779	14,538	8,454	*	-	142,588	15,689	9,349	*	-		
6	9.0	7,321	1,653	*	116,139	15,921	12,695	11,356	11,100	74,789	14,022	8,124	*	-	139,908	15,166	9,072	*	-		
4	1.8	13,371	2,178	*	123,173	16,161	12,925	12,048	11,630	3,451	14,723	9,308	*	-	136,348	16,212	10,168	*	-		
4	3.6	11,235	1,626	*	124,949	15,476	12,315	11,433	11,030	27,891	14,481	8,328	*	-	144,711	15,522	9,529	*	-		
4	5.4	9,420	1,591	*	118,466	14,960	11,766	10,822	10,432	57,733	13,773	7,656	*	-	138,559	14,952	8,899	*	-		
4	7.2	8,204	1,587	*	115,979	14,608	11,487	10,405	10,090	62,437	13,229	7,281	*	-	136,056	14,592	8,488	*	-		
4	9.0	7,338	1,587	*	113,095	14,548	11,379	10,149	9,864	65,947	12,936	7,053	*	-	135,122	14,260	8,253	*	-		
2	1.8	13,052	1,938	*	127,180	14,083	10,852	9,967	9,482	34,566	13,239	7,547	*	-	148,588	14,663	8,880	*	-		
2	3.6	10,901	1,473	*	119,331	13,299	9,991	9,135	8,621	49,652	12,441	6,468	*	-	136,775	13,970	7,970	*	-		
2	5.4	9,134	1,462	*	120,169	12,854	9,564	8,630	8,229	50,327	11,807	6,001	*	-	135,308	13,470	7,425	*	-		
2	7.2	7,985	1,488	*	115,910	12,642	9,461	8,447	8,117	51,795	11,490	5,822	*	-	137,576	13,110	7,134	*	-		
2	9.0	7,195	1,514	*	111,209	12,664	9,461	8,248	8,022	54,098	11,373	5,767	*	-	133,500	12,944	6,978	*	-		

1 psi= 6.89 kPa; 1 ksi= 6.89 MPa; CFA: class C fly ash; CKD: cement kiln dust

σ_d: cyclic axial stress; σ_3: confining pressure; M_r: resilient modulus; *Specimen failed before the end of this cycle

Table 4.4: M_r Values of Stabilized Carnasaw Soil at the End of 0 and 1Freeze-Thaw Cycles

σ_3 (psi)	σ_d (psi)	Carnasaw Series Soil																	
		Raw			6% Lime					10% CFA					10% CKD				
		Cycle 0	Cycle 1	Cycle 4	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12
6	1.8	19,944	7,288	*	88,009	18,642	*	-	-	48,619	11,024	*	-	-	67,580	12,348	*	-	-
6	3.6	18,787	5,748	*	83,620	17,749	*	-	-	43,417	9,583	*	-	-	67,004	11,155	*	-	-
6	5.4	16,981	4,349	*	80,039	16,365	*	-	-	39,176	8,198	*	-	-	62,448	9,779	*	-	-
6	7.2	15,395	3,504	*	74,116	15,616	*	-	-	36,639	7,434	*	-	-	59,434	9,055	*	-	-
6	9.0	13,966	3,270	*	71,545	15,388	*	-	-	34,359	6,990	*	-	-	55,866	8,524	*	-	-
4	1.8	18,822	6,328	*	81,482	16,795	*	-	-	42,770	9,381	*	-	-	66,278	11,164	*	-	-
4	3.6	17,884	4,535	*	79,044	15,467	*	-	-	38,499	7,670	*	-	-	60,815	9,589	*	-	-
4	5.4	16,651	3,625	*	77,102	14,503	*	-	-	35,130	6,594	*	-	-	58,564	8,449	*	-	-
4	7.2	15,158	3,298	*	73,351	13,859	*	-	-	32,934	6,060	*	-	-	56,547	7,768	*	-	-
4	9.0	13,887	*	*	70,849	13,640	*	-	-	31,745	5,664	*	-	-	55,230	7,413	*	-	-
2	1.8	16,976	*	*	85,840	13,540	*	-	-	39,358	6,798	*	-	-	69,200	8,918	*	-	-
2	3.6	16,475	*	*	79,796	12,374	*	-	-	35,729	5,324	*	-	-	61,386	7,456	*	-	-
2	5.4	15,455	*	*	74,136	11,632	*	-	-	31,774	4,676	*	-	-	57,491	6,595	*	-	-
2	7.2	14,305	*	*	72,429	11,269	*	-	-	29,644	4,485	*	-	-	55,837	6,141	*	-	-
2	9.0	13,241	*	*	70,738	11,198	*	-	-	28,642	4,346	*	-	-	54,161	5,910	*	-	-

1 psi= 6.89 kPa; 1 ksi= 6.89 MPa; CFA: class C fly ash; CKD: cement kiln dust

σ_d: cyclic axial stress; σ_3: confining pressure; M_r: resilient modulus; *Specimen failed before the end of this cycle

Table 4.5: M_r Values of Stabilized Dennis Soil at the End of 0, 1, 4 and 8 Freeze-Thaw Cycles

σ_3 (psi)	σ_d (psi)	Dennis Series Soil																	
		Raw			6% Lime					10% CFA					10% CKD				
		Cycle 0	Cycle 1	Cycle 4	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12
6	1.8	9,278	1,471	-	241,262	24,005	17,912	15,015	*	42,855	11,085	7,766	6,747	*	63,672	13,716	*	-	-
6	3.6	8,605	1,364	-	223,749	22,262	16,612	13,925	*	39,744	10,280	7,202	6,368	*	63,258	12,720	*	-	-
6	5.4	7,432	*	-	155,958	21,951	15,659	13,138	*	36,406	9,734	6,774	5,538	*	60,034	12,211	*	-	-
6	7.2	6,519	*	-	137,790	21,809	15,280	12,856	*	34,082	9,399	6,299	5,028	*	57,120	11,871	*	-	-
6	9.0	5,795	*	-	128,821	21,786	15,188	12,788	*	32,329	9,291	5,941	4,743	*	55,165	11,447	*	-	-
4	1.8	9,009	*	-	185,454	20,424	14,932	13,226	*	35,353	9,290	7,137	6,506	*	61,175	12,262	*	-	-
4	3.6	8,622	*	-	189,455	20,287	14,305	12,356	*	32,926	8,683	6,927	5,455	*	59,133	11,803	*	-	-
4	5.4	7,772	*	-	144,352	20,021	13,814	11,788	*	31,014	8,310	6,201	4,786	*	56,571	11,251	*	-	-
4	7.2	6,867	*	-	135,482	20,171	13,692	11,572	*	30,099	8,217	5,770	4,460	*	55,347	10,848	*	-	-
4	9.0	6,004	*	-	130,625	20,280	13,711	11,546	*	29,879	8,186	5,379	4,204	*	54,161	10,702	*	-	-
2	1.8	8,874	*	-	193,425	18,186	12,494	11,113	*	33,187	7,516	6,483	5,132	*	61,008	11,107	*	-	-
2	3.6	8,355	*	-	192,299	17,898	11,712	9,966	*	30,581	6,910	5,460	4,064	*	58,003	10,536	*	-	-
2	5.4	7,537	*	-	144,409	17,730	11,317	9,576	*	28,645	6,700	4,925	3,633	*	55,315	10,044	*	-	-
2	7.2	6,695	*	-	133,122	17,817	11,345	9,553	*	27,653	6,774	4,661	3,480	*	54,322	9,748	*	-	-
2	9.0	5,928	*	-	128,231	18,057	11,544	9,633	*	27,255	6,904	4,400	3,339	*	53,569	9,626	*	-	-

1 psi= 6.89 kPa; 1 ksi= 6.89 MPa; CFA: class C fly ash; CKD: cement kiln dust

σ_d: cyclic axial stress; σ_3: confining pressure; M_r: resilient modulus; *Specimen failed before the end of this cycle

Table 4.6: M_r Values of Stabilized Lomill Soil at the End of 0, 1 and 4 Freeze-Thaw Cycles

σ_3 (psi)	σ_d (psi)	Lomill Series Soil																	
		Raw			6% Lime					10% CFA					10% CKD				
		Cycle 0	Cycle 1	Cycle 4	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12	Cycle 0	Cycle 1	Cycle 4	Cycle 8	Cycle 12
6	1.8	12,086	3,354	-	138,149	20,857	16,527	*	-	60,155	13,420	7,993	*	-	216,786	15,542	*	-	-
6	3.6	10,664	2,077	-	137,781	20,097	15,381	*	-	59,614	13,076	7,527	*	-	86,633	15,171	*	-	-
6	5.4	9,058	1,740	-	135,534	18,811	14,107	*	-	57,004	12,312	6,699	*	-	68,756	14,156	*	-	-
6	7.2	7,440	*	-	135,116	18,170	13,546	*	-	54,625	11,746	6,274	*	-	60,214	13,538	*	-	-
6	9.0	6,293	*	-	133,193	19,622	13,442	*	-	53,609	11,588	6,046	*	-	55,731	13,178	*	-	-
4	1.8	11,539	*	-	146,497	19,338	14,053	*	-	58,017	12,089	6,928	*	-	168,779	14,055	*	-	-
4	3.6	10,305	*	-	136,270	17,503	12,965	*	-	55,256	11,408	6,191	*	-	76,677	13,410	*	-	-
4	5.4	8,927	*	-	132,714	16,764	12,070	*	-	53,670	10,780	5,622	*	-	59,546	12,650	*	-	-
4	7.2	7,687	*	-	131,191	16,297	11,760	*	-	53,422	10,522	5,358	*	-	54,310	12,305	*	-	-
4	9.0	6,671	*	-	130,454	16,139	11,699	*	-	52,223	10,425	5,290	*	-	52,209	12,193	*	-	-
2	1.8	12,086	*	-	124,386	15,683	11,099	*	-	52,893	10,125	5,287	*	-	137,852	11,789	*	-	-
2	3.6	10,799	*	-	131,202	14,638	10,025	*	-	54,748	10,190	4,590	*	-	66,659	11,191	*	-	-
2	5.4	9,350	*	-	132,936	13,949	9,427	*	-	53,221	9,326	4,275	*	-	54,366	10,781	*	-	-
2	7.2	8,042	*	-	129,947	13,741	9,366	*	-	52,024	9,559	4,208	*	-	49,497	10,670	*	-	-
2	9.0	6,992	*	-	129,094	13,824	9,517	*	-	49,247	9,074	4,195	*	-	48,321	10,657	*	-	-

1 psi= 6.89 kPa; 1 ksi= 6.89 MPa; CFA: class C fly ash; CKD: cement kiln dust

σ_d: cyclic axial stress; σ_3: confining pressure; M_r: resilient modulus; *Specimen failed before the end of this cycle

Table 4.7: M_r Values of Stabilized Kingfisher Soil after Different Wet-Dry Cycles

σ_3 (psi)	σ_d (psi)	Kingfisher Series Soil							
		Raw		6% Lime		10% CFA		10% CKD	
		Cycle 0	Cycle 1	Cycle 0	Cycle 1	Cycle 0	Cycle 1	Cycle 0	Cycle 1
6	1.8	14,150	*	142,230	45,733	86,853	38,697	188,270	43,271
6	3.6	12,093	*	134,879	42,414	63,002	35,888	136,568	40,130
6	5.4	9,875	*	127,828	36,842	65,234	31,174	141,408	34,858
6	7.2	8,322	*	120,408	32,329	65,779	27,355	142,588	30,588
6	9.0	7,321	*	116,139	29,203	64,543	24,711	139,908	27,631
4	1.8	13,371	*	123,173	43,521	62,900	36,825	136,348	41,177
4	3.6	11,235	*	124,949	40,693	66,758	34,433	144,711	38,502
4	5.4	9,420	*	118,466	35,558	63,920	30,087	138,559	33,643
4	7.2	8,204	*	115,979	31,503	62,765	26,656	136,056	29,807
4	9.0	7,338	*	113,095	28,455	62,335	24,077	135,122	26,922
2	1.8	13,052	*	127,180	42,435	68,547	35,906	148,588	40,150
2	3.6	10,901	*	119,331	38,583	63,097	32,647	136,775	36,506
2	5.4	9,134	*	120,169	33,463	62,420	28,315	135,308	31,661
2	7.2	7,985	*	115,910	29,837	63,467	25,247	137,576	28,231
2	9.0	7,195	*	111,209	27,251	61,586	23,059	133,500	25,784

1 psi= 6.89 kPa; 1 ksi= 6.89 Mpa; CFA: class C fly ash; CKD: cement kiln dust

σ_d: cyclic axial stress; σ_3: confining pressure; M_r: resilient modulus;

*Specimen failed; all specimens failed in W-D Cycle 2

Table 4.8: M_r Values of Stabilized Carnasaw Soil after Different Wet-Dry Cycles

σ_3 (psi)	σ_d (psi)	Carnasaw Series Soil							
		Raw		6% Lime		10% CFA		10% CKD	
		Cycle 0	Cycle 1	Cycle 0	Cycle 1	Cycle 0	Cycle 1	Cycle 0	Cycle 1
6	1.8	19,944	*	88,009	35,894	48,619	*	67,580	54,253
6	3.6	18,787	*	83,620	35,773	43,417	*	67,004	43,889
6	5.4	16,981	*	80,039	34,205	39,176	*	62,448	39,792
6	7.2	15,395	*	74,116	34,589	36,639	*	59,434	38,814
6	9.0	13,966	*	71,545	32,025	34,359	*	55,866	38,444
4	1.8	18,822	*	81,482	28,901	42,770	*	66,278	40,008
4	3.6	17,884	*	79,044	27,832	38,499	*	60,815	34,150
4	5.4	16,651	*	77,102	28,663	35,130	*	58,564	32,945
4	7.2	15,158	*	73,351	28,415	32,934	*	56,547	32,699
4	9.0	13,887	*	70,849	30,544	31,745	*	55,230	33,790
2	1.8	16,976	*	85,840	26,346	39,358	*	69,200	30,444
2	3.6	16,475	*	79,796	24,282	35,729	*	61,386	26,878
2	5.4	15,455	*	74,136	25,160	31,774	*	57,491	25,944
2	7.2	14,305	*	72,429	26,589	29,644	*	55,837	26,413
2	9.0	13,241	*	70,738	28,788	28,642	*	54,161	27,375

1 psi= 6.89 kPa; 1 ksi= 6.89 Mpa; CFA: class C fly ash; CKD: cement kiln dust

σ_d: cyclic axial stress; σ_3: confining pressure; M_r: resilient modulus;

*Specimen failed; all specimens failed in W-D Cycle 2

Table 4.9: M_r Values of Stabilized Dennis Soil after Different Wet-Dry Cycles

σ_3 (psi)	σ_d (psi)	**Dennis Series Soil**							
		Raw		**6% Lime**		**10% CFA**		**10% CKD**	
		Cycle 0	Cycle 1	Cycle 0	Cycle 1	Cycle 0	Cycle 1	Cycle 0	Cycle 1
6	1.8	9,278	*	241,262	33,434	42,855	20,398	63,672	24,803
6	3.6	8,605	*	223,749	31,842	39,744	19,427	63,258	23,849
6	5.4	7,432	*	155,958	33,437	36,406	19,937	60,034	25,052
6	7.2	6,519	*	137,790	34,438	34,082	20,711	57,120	26,096
6	9.0	5,795	*	128,821	35,103	32,329	21,415	55,165	27,017
4	1.8	9,009	*	185,454	23,018	35,353	14,386	61,175	17,349
4	3.6	8,622	*	189,455	26,246	32,926	15,564	59,133	19,510
4	5.4	7,772	*	144,352	28,171	31,014	16,514	56,571	20,929
4	7.2	6,867	*	135,482	30,250	30,099	17,546	55,347	22,466
4	9.0	6,004	*	130,625	32,049	29,879	18,620	54,161	23,891
2	1.8	8,874	*	193,425	20,303	33,187	11,250	61,008	14,295
2	3.6	8,355	*	192,299	22,532	30,581	12,080	58,003	15,453
2	5.4	7,537	*	144,409	24,329	28,645	12,998	55,315	16,775
2	7.2	6,695	*	133,122	26,025	27,653	14,040	54,322	18,266
2	9.0	5,928	*	128,231	27,867	27,255	15,227	53,569	19,929

1 psi= 6.89 kPa; 1 ksi= 6.89 Mpa; CFA: class C fly ash; CKD: cement kiln dust

σ_d: cyclic axial stress; σ_3: confining pressure; M_r: resilient modulus;

*Specimen failed; all specimens failed in W-D Cycle 2

Table 4.10: M_r Values of Stabilized Lomill Soil after Different Wet-Dry Cycles

σ_3 (psi)	σ_d (psi)	Lomill Series Soil							
		Raw		6% Lime		10% CFA		10% CKD	
		Cycle 0	Cycle 1	Cycle 0	Cycle 1	Cycle 0	Cycle 1	Cycle 0	Cycle 1
6	1.8	12,086	*	138,149	47,561	60,155	25,714	216,786	30,313
6	3.6	10,799	*	137,781	47,525	59,614	25,142	86,633	29,418
6	5.4	9,350	*	135,534	45,751	57,004	23,879	68,756	29,965
6	7.2	8,042	*	135,116	45,747	54,625	24,600	60,214	30,973
6	9.0	6,992	*	133,193	46,441	53,609	25,252	55,731	32,315
4	1.8	11,689	*	146,497	35,850	58,017	20,699	168,779	23,187
4	3.6	10,664	*	136,270	34,474	55,256	19,989	76,677	22,813
4	5.4	9,058	*	132,714	34,195	53,670	20,280	59,546	23,500
4	7.2	7,440	*	131,191	35,953	53,422	20,629	54,310	24,813
4	9.0	6,293	*	130,454	38,633	52,223	21,759	52,209	26,602
2	1.8	11,539	*	124,386	25,989	52,893	15,917	137,852	15,317
2	3.6	10,305	*	131,202	24,674	54,748	15,054	66,659	15,526
2	5.4	8,927	*	132,936	25,208	53,221	15,389	54,366	16,833
2	7.2	7,687	*	129,947	27,056	52,024	16,131	49,497	18,532
2	9.0	6,171	*	129,094	29,705	49,247	17,269	48,321	20,423

1 psi= 6.89 kPa; 1 ksi= 6.89 Mpa; CFA: class C fly ash; CKD: cement kiln dust

σ_d: cyclic axial stress; σ_3: confining pressure; M_r: resilient modulus;

*Specimen failed; all specimens failed in W-D Cycle 2

Table 4.11: Relationship between Specific Gravity and Degree of Saturation of Stabilized Dennis Soil

Specific Gravity G_s	Degree of Saturation S_r		
	6% Lime	10% CFA	10% CKD
2.60	94.9	95.8	97.4
2.65	92.4	92.8	94.6
2.69*	90.6	90.7	92.5
2.70	90.1	90.2	92.0
2.75	88.0	87.7	89.6

* Original Raw Dennis Soil G_s Value

Table 4.12: M_r Values of Stabilized Dennis Soil (Compacted at OMC+4%) at the End of 0 and 1 Freeze-Thaw Cycles

σ_3 (psi)	σ_d (psi)	**Dennis Series Soil**							
		Raw		**6% Lime**		**10% CFA**		**10% CKD**	
		Cycle 0	Cycle 1	Cycle 0	Cycle 1	Cycle 0	Cycle 1	Cycle 0	Cycle 1
6	1.8	8,096	*	47,561	9,993	39,634	8,959	43,448	9,528
6	3.6	6,936	*	47,112	9,771	39,260	8,451	41,077	8,053
6	5.4	5,454	*	45,191	8,968	35,659	7,644	39,826	7,288
6	7.2	4,339	*	42,003	8,531	34,002	7,276	37,766	6,855
6	9.0	3,703	*	38,879	8,222	31,399	7,103	35,778	6,540
4	1.8	7,420	*	45,361	9,249	34,801	8,088	39,559	7,523
4	3.6	6,299	*	42,093	8,207	32,078	6,998	38,164	6,832
4	5.4	5,222	*	39,343	7,668	30,786	6,413	37,258	6,320
4	7.2	4,368	*	38,014	7,456	30,079	6,297	36,123	6,050
4	9.0	3,763	*	36,294	7,316	29,245	6,099	35,329	5,847
2	1.8	7,237	*	43,123	7,482	32,936	6,025	38,884	6,379
2	3.6	6,177	*	40,074	6,475	30,395	5,234	37,713	5,517
2	5.4	5,121	*	38,372	6,105	27,976	4,942	36,472	5,136
2	7.2	4,299	*	36,311	6,054	26,259	4,985	35,498	4,970
2	9.0	3,728	*	35,574	6,056	25,645	4,989	34,856	4,862

1 psi= 6.89 kPa; 1 ksi= 6.89 Mpa; CFA: class C fly ash; CKD: cement kiln dust

σ_d: cyclic axial stress; σ_3: confining pressure; M_r: resilient modulus;

*Specimen failed; all specimens failed in W-D Cycle 2

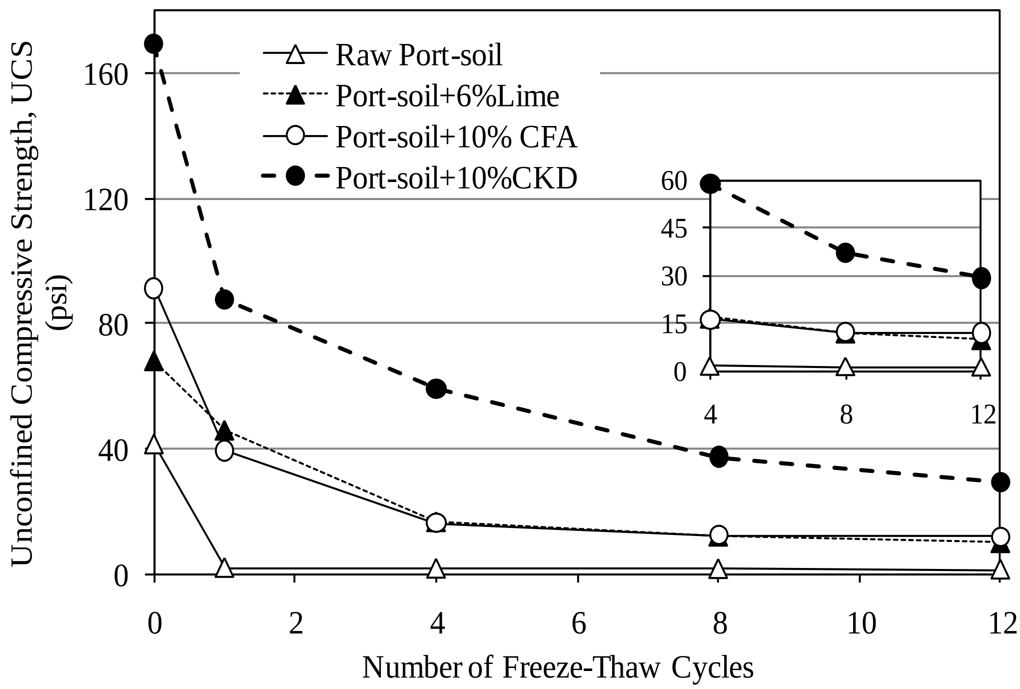


Figure 4.1: UCS Values of Stabilized Port Soil After F-T Cycles

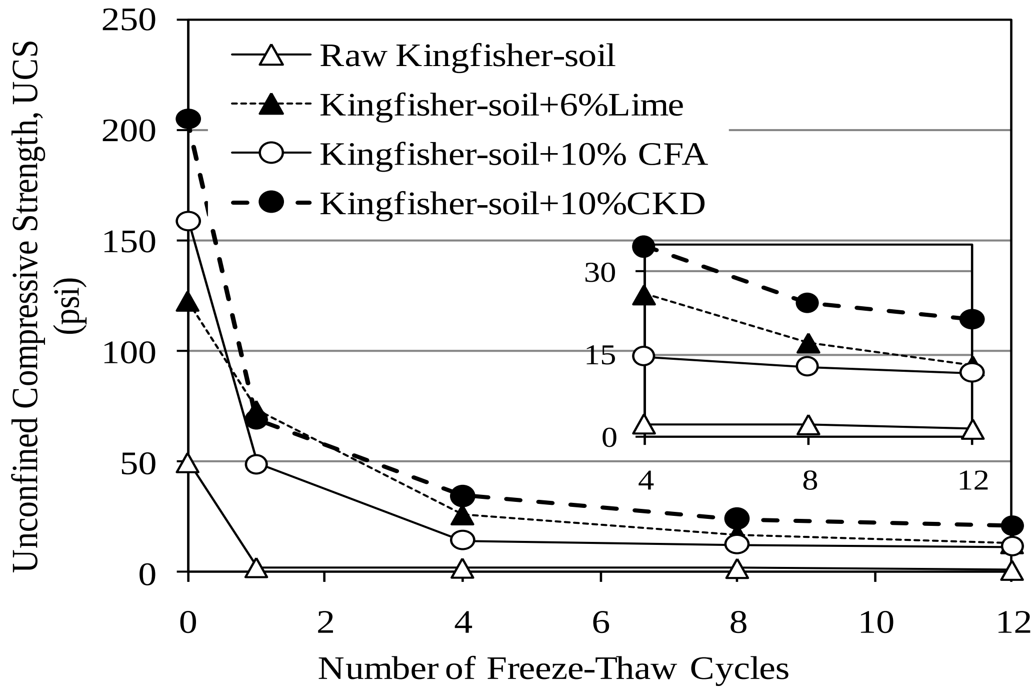


Figure 4.2: UCS Values of Stabilized Kingfisher Soil After F-T Cycles

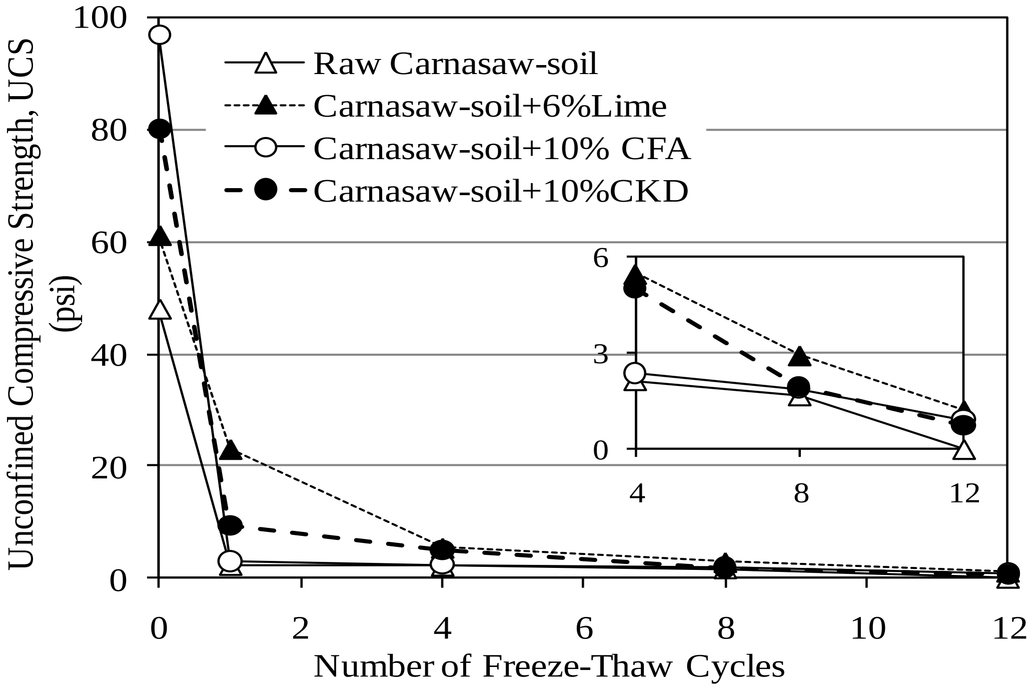


Figure 4.3: UCS Values of Stabilized Carnasaw Soil After F-T Cycles

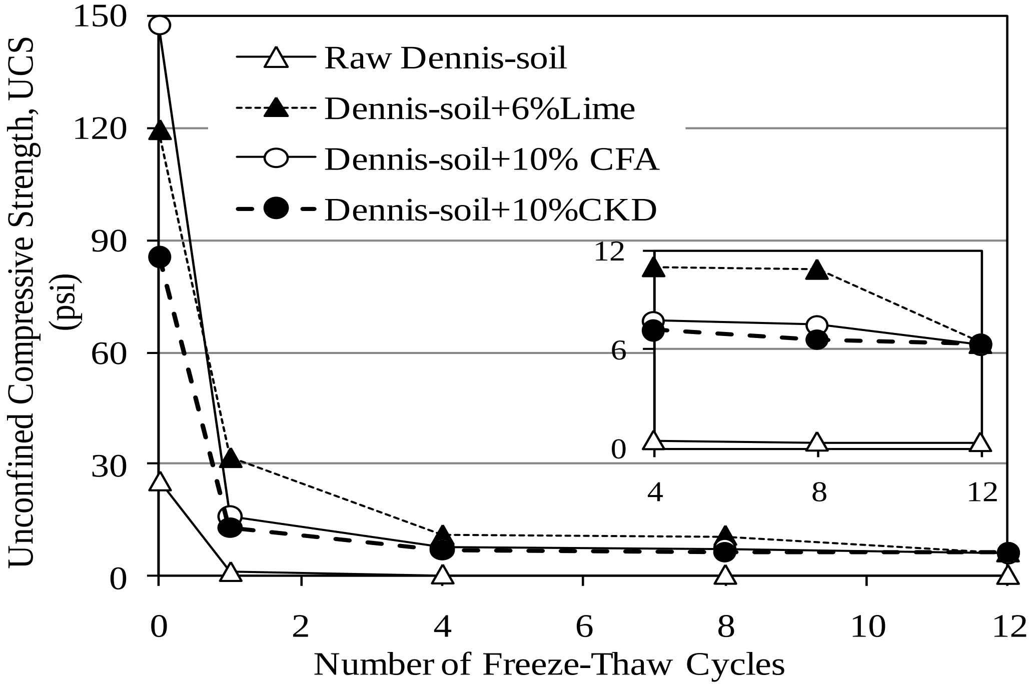


Figure 4.4: UCS Values of Stabilized Dennis Soil After F-T Cycles

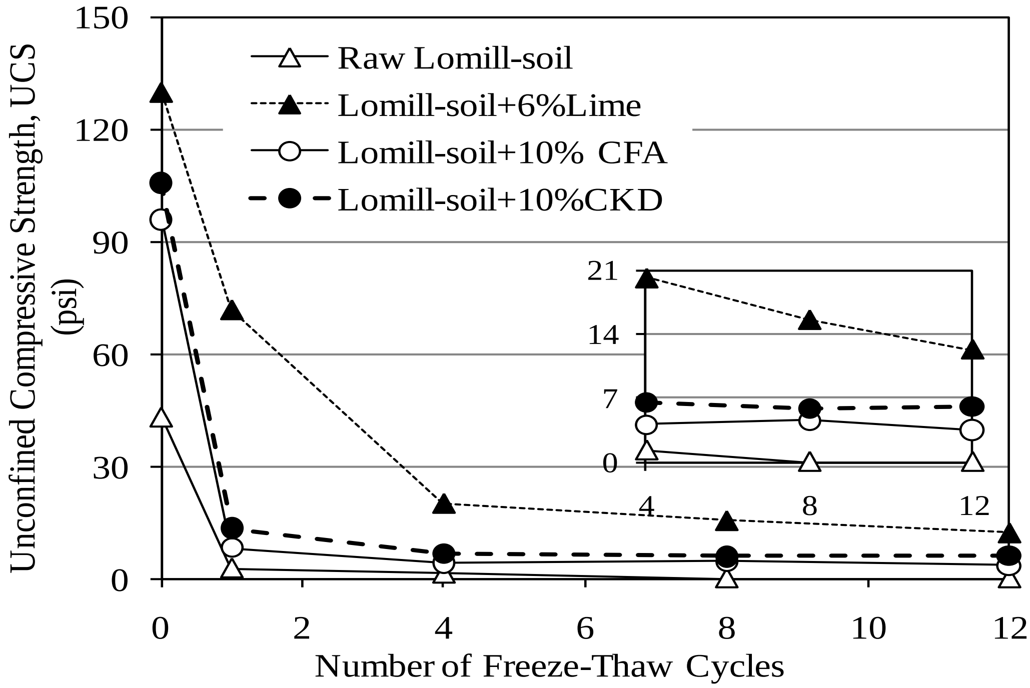


Figure 4.5: UCS Values of Stabilized Lomill Soil After F-T Cycles

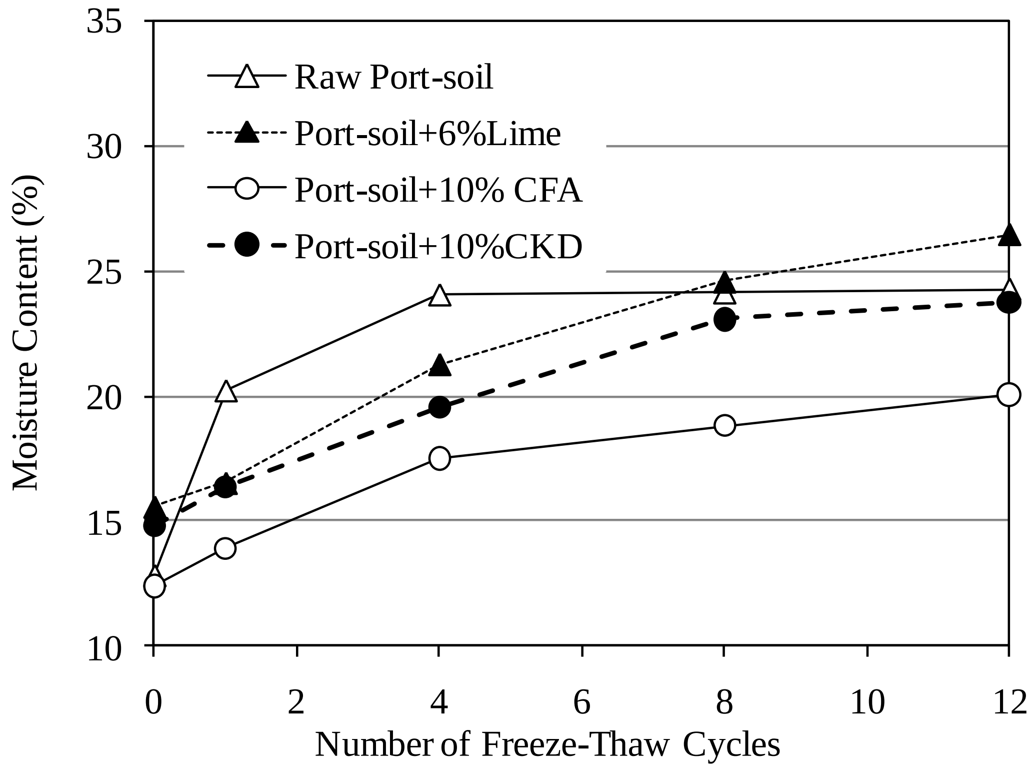


Figure 4.6: Moisture Content of Raw and Stabilized Port Soil Specimens at the End of 0, 1, 4, 8 and 12 Freeze-Thaw Cycles

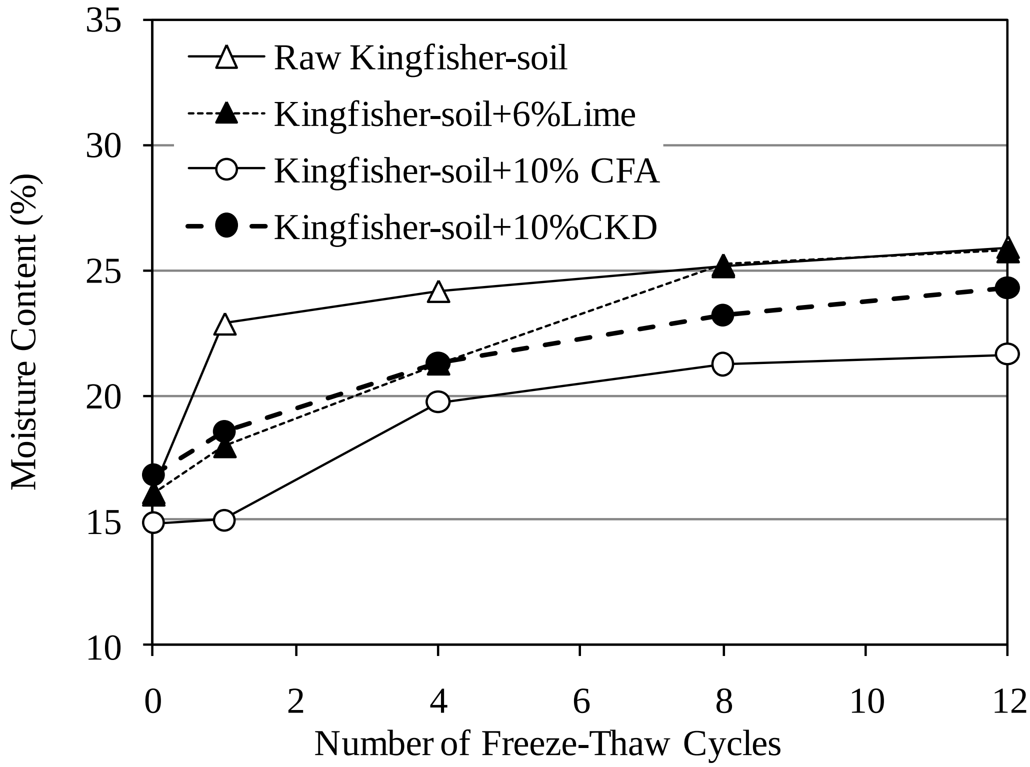


Figure 4.7: Moisture Content of Raw and Stabilized Kingfisher Soil Specimens at the End of 0, 1, 4, 8 and 12 Freeze-Thaw Cycles

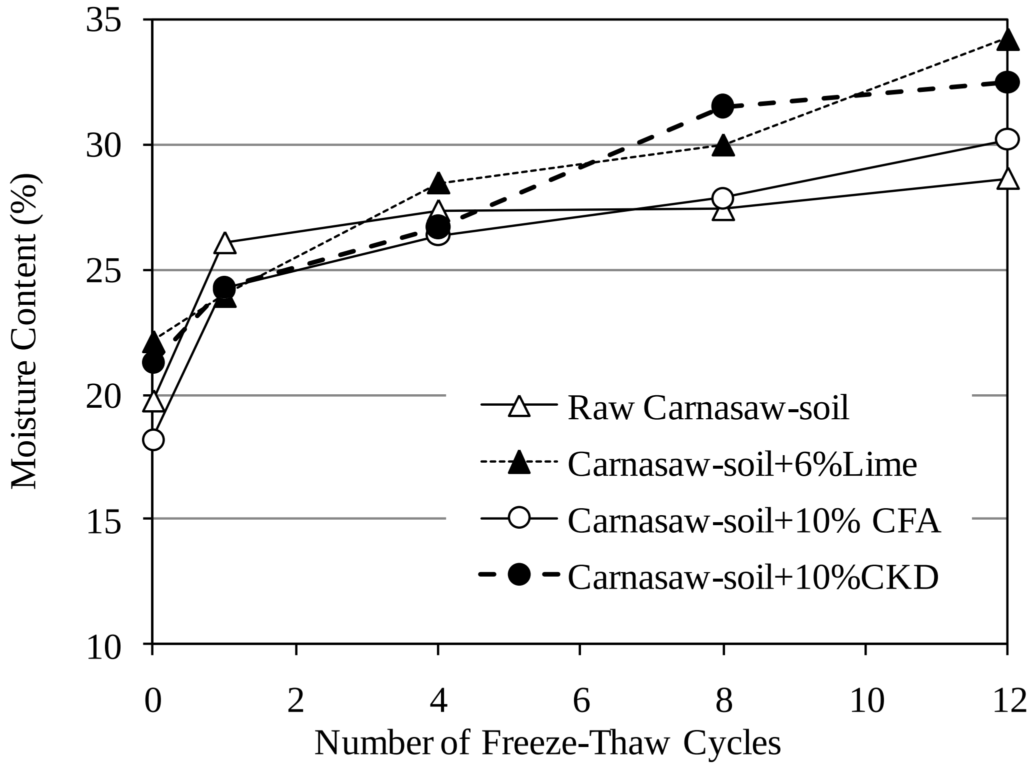


Figure 4.8: Moisture Content of Raw and Stabilized Carnasaw Soil Specimens at the End of 0, 1, 4, 8 and 12 Freeze-Thaw Cycles

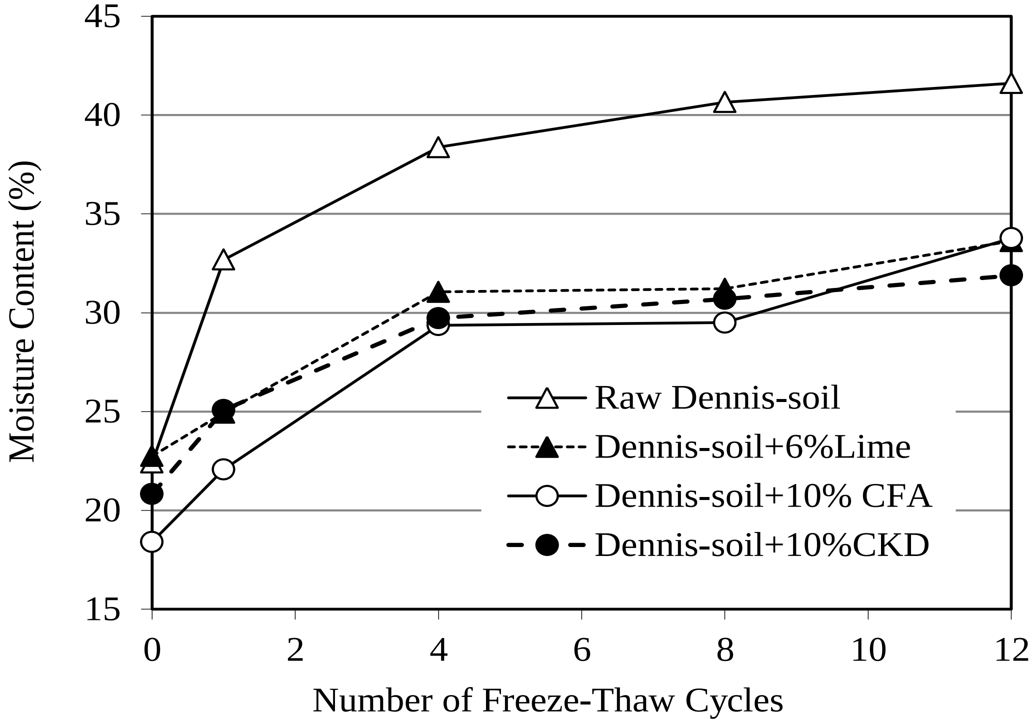


Figure 4.9: Moisture Content of Raw and Stabilized Dennis Soil Specimens at the End of 0, 1, 4, 8 and 12 Freeze-Thaw Cycles

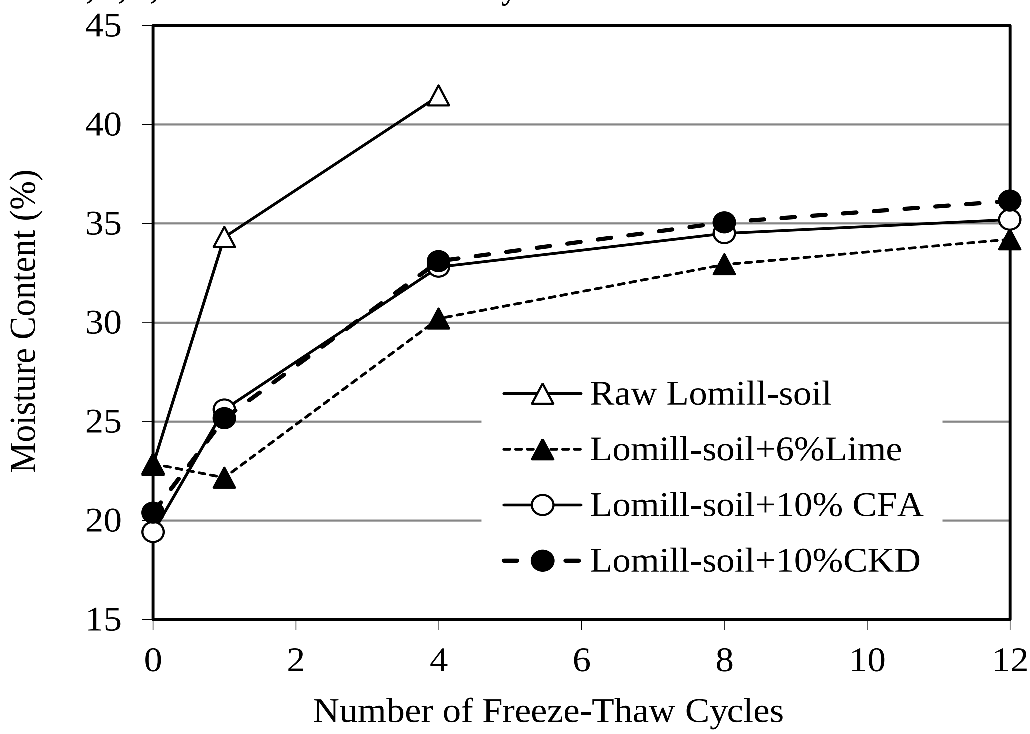


Figure 4.10: Moisture Content of Raw and Stabilized Lomill Soil Specimens at the End of 0, 1, 4, 8 and 12 Freeze-Thaw Cycles

Figure 4.11: Harvard Miniature Port Specimens at the End of 12 Freeze-Thaw Cycles After UCS Test (From Left to Right: Raw, Lime, CFA, CKD)

Figure 4.12: Harvard Miniature Kingfisher Specimens at the End of 12 Freeze-Thaw Cycles After UCS Test (From Left to Right: Raw, Lime, CFA, CKD)

Figure 4.13: Harvard Miniature Carnasaw Specimens at the End of 12 Freeze-Thaw Cycles After UCS Test (From Left to Right: Raw, Lime, CFA, CKD)

Figure 4.14: Harvard Miniature Dennis Specimens at the End of 12 Freeze-Thaw Cycles After UCS Test (From Left to Right: Raw, Lime, CFA, CKD)

Figure 4.15: Harvard Miniature Lomill Specimens at the End of 12 Freeze-Thaw Cycles After UCS Test (From Left to Right: Lime, CFA, CKD)

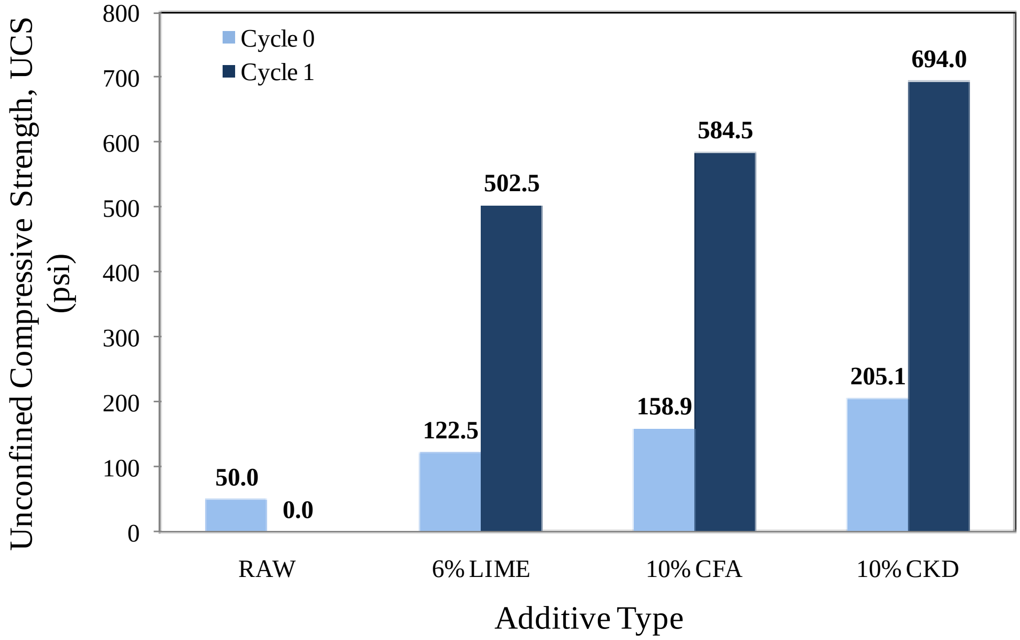


Figure 4.16: UCS Values of Stabilized Kingfisher Soil After Wet-Dry Cycles

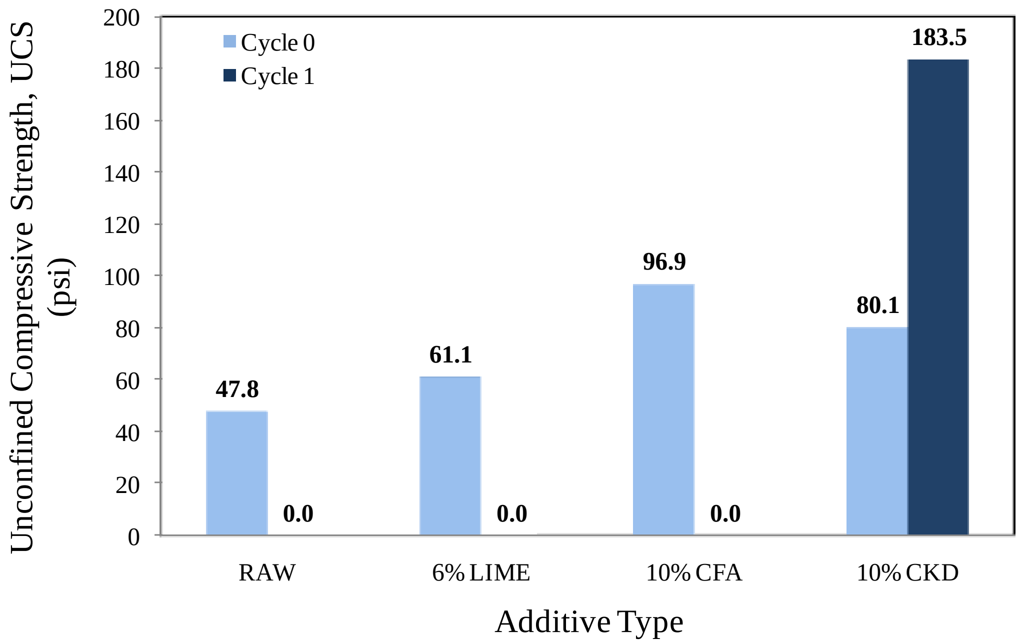


Figure 4.17: UCS Values of Stabilized Carnasaw Soil After Wet-Dry Cycles

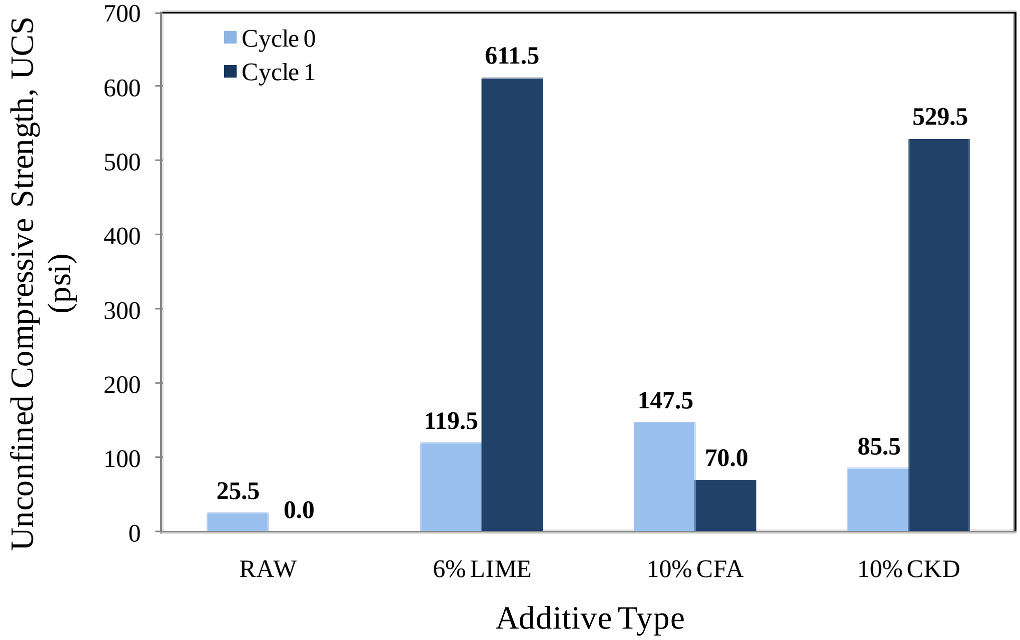


Figure 4.18: UCS Values of Stabilized Dennis Soil After Wet-Dry Cycles

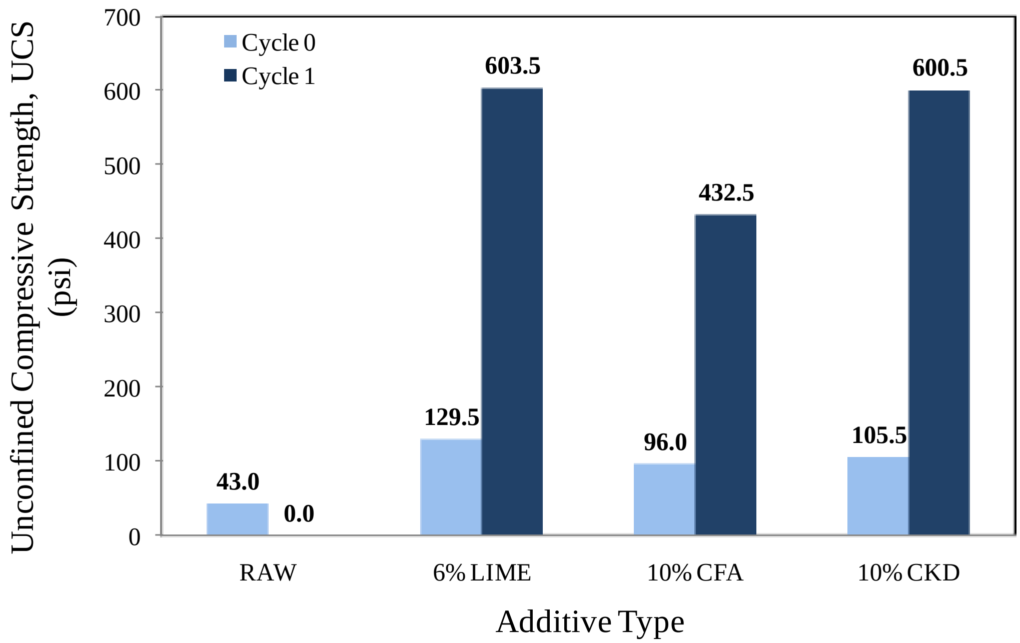


Figure 4.19: UCS Values of Stabilized Lomill Soil After Wet-Dry Cycles

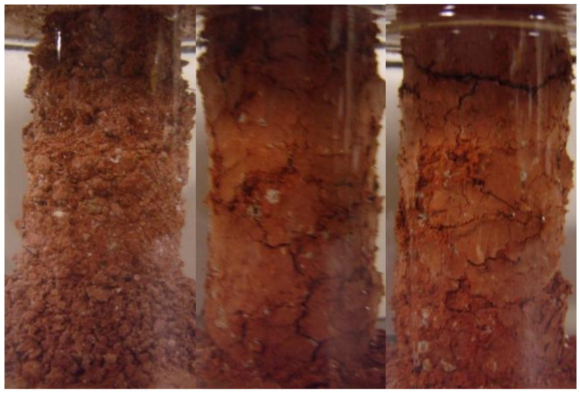


Figure 4.20: Harvard Miniature Kingfisher Specimens After 2 Wet-Dry Cycles at the End of 5-Hour Soaking Period (From Left to Right: Lime, CFA, CKD)

Figure 4.21: Harvard Miniature Carnasaw Specimens After 1 Wet-Dry cycle at the End of 5- Hour Soaking Period (From Left to Right: Lime, CFA, CKD)

Figure 4.22: Harvard Miniature Dennis Specimens After 2 Wet-Dry Cycles at the End of 5- Hour Soaking Period (From Left to Right: Lime, CFA, CKD)

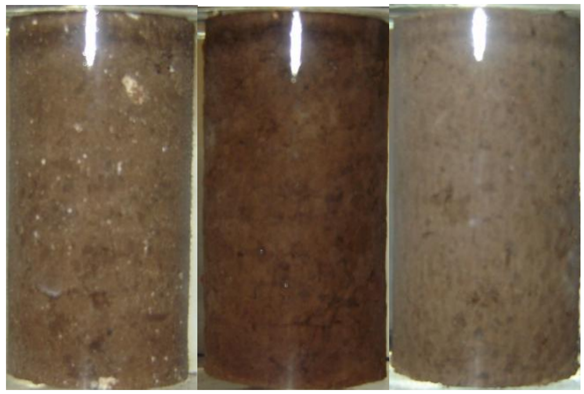


Figure 4.23: Harvard Miniature Lomill Specimens After 1 Wet-Dry Cycle at the End of 5- Hour Soaking Period (From Left to Right: Lime, CFA, CKD)

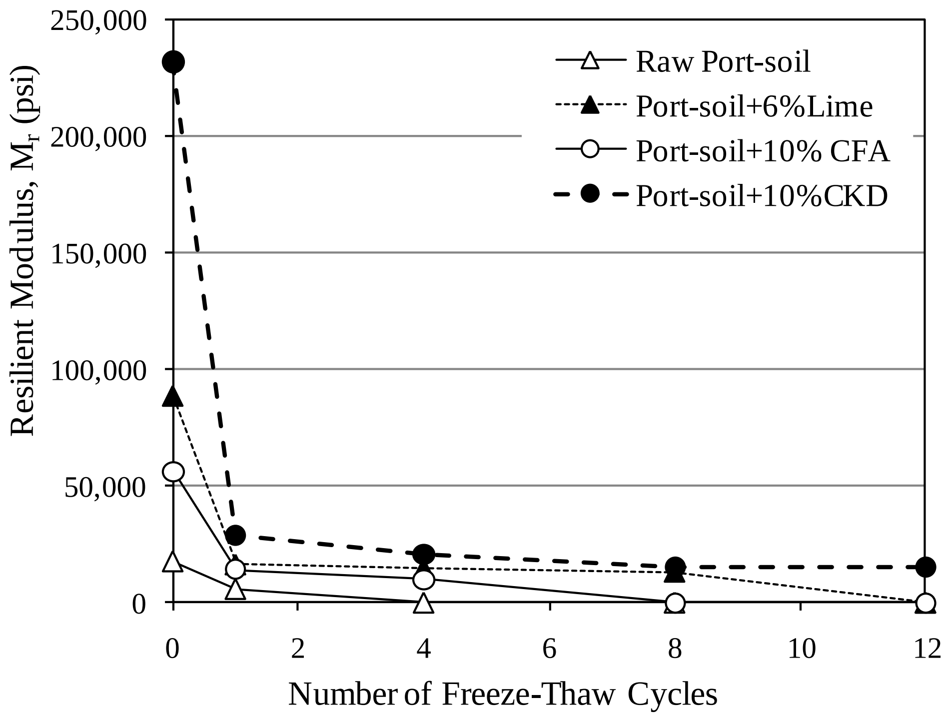


Figure 4.24: M_r Values of Stabilized Port Soil After Freeze-Thaw Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

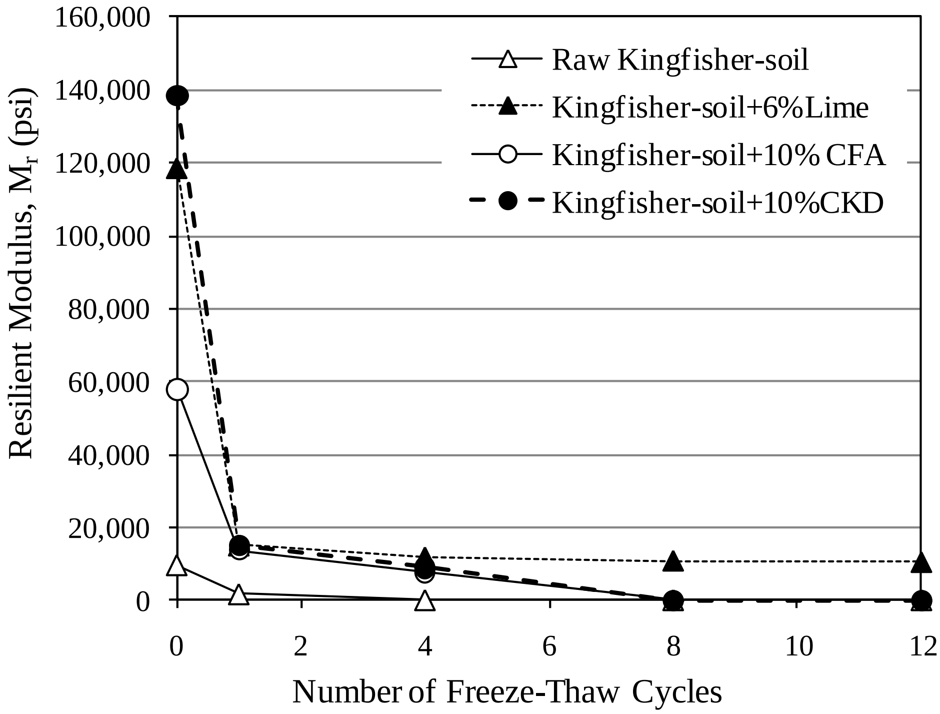


Figure 4. 25: M_r Values of Stabilized Kingfisher Soil After Freeze-Thaw Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

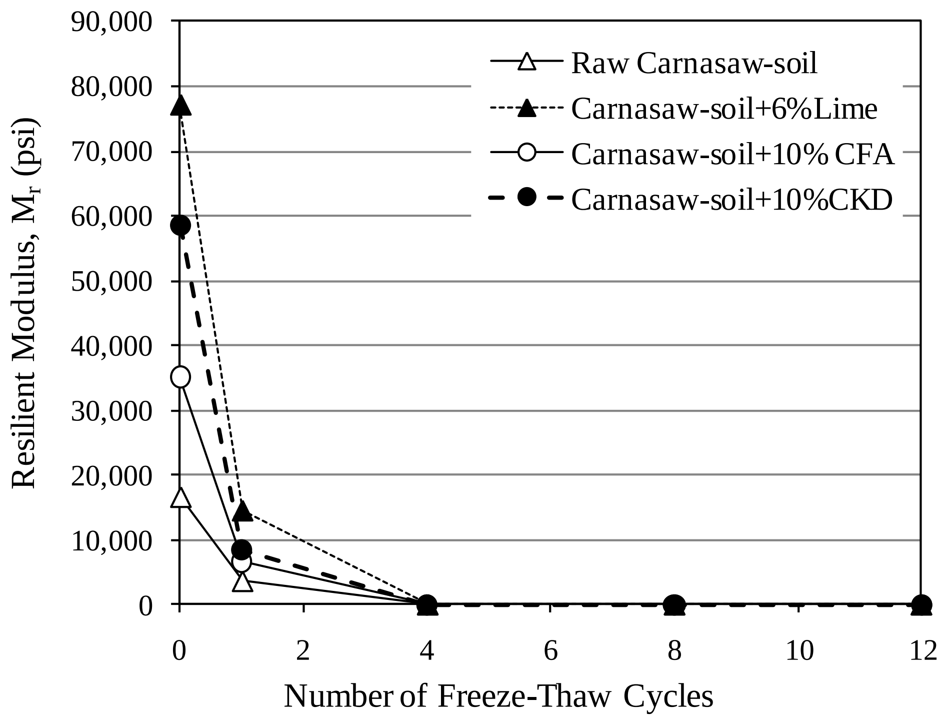


Figure 4.26: M_r Values of Stabilized Carnasaw Soil After Freeze-Thaw Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

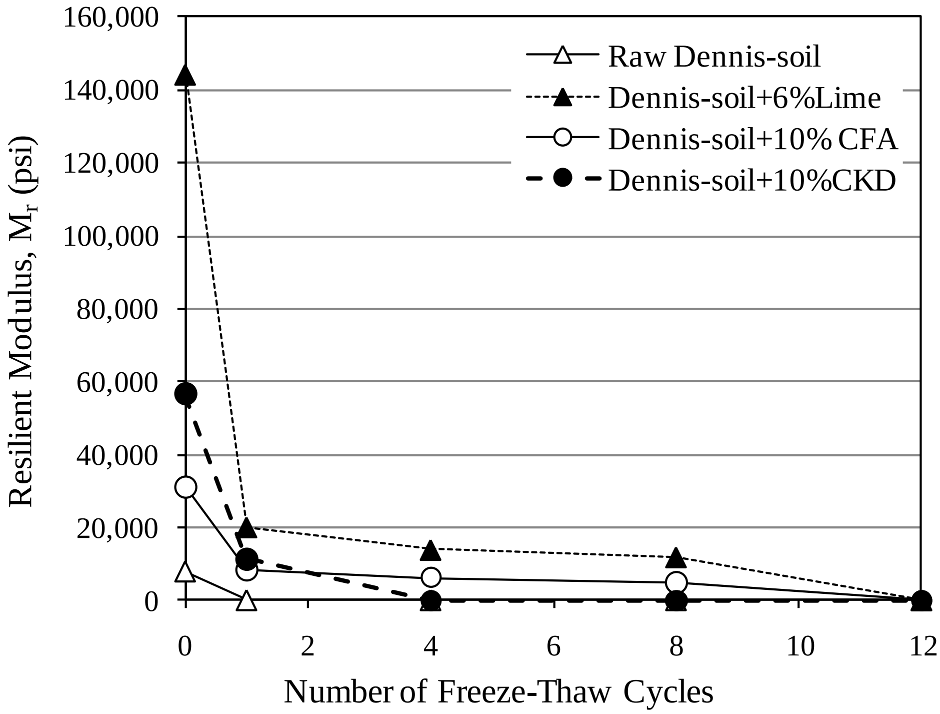


Figure 4.27: M_r Values of Stabilized Dennis Soil After Freeze-Thaw Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

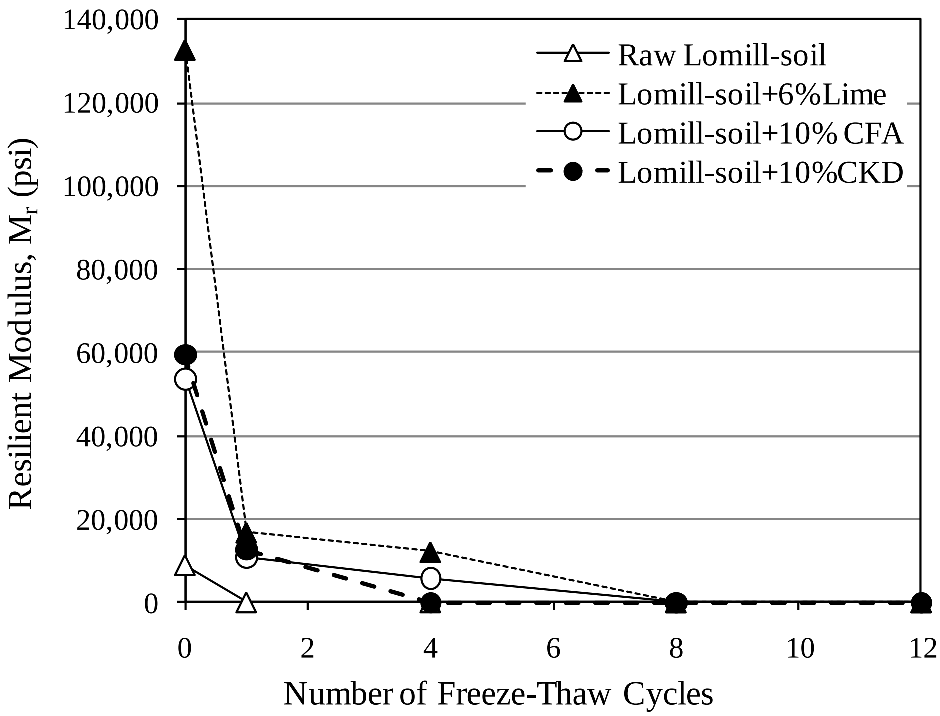


Figure 4.28: M_r Values of Stabilized Lomill Soil After Freeze-Thaw Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

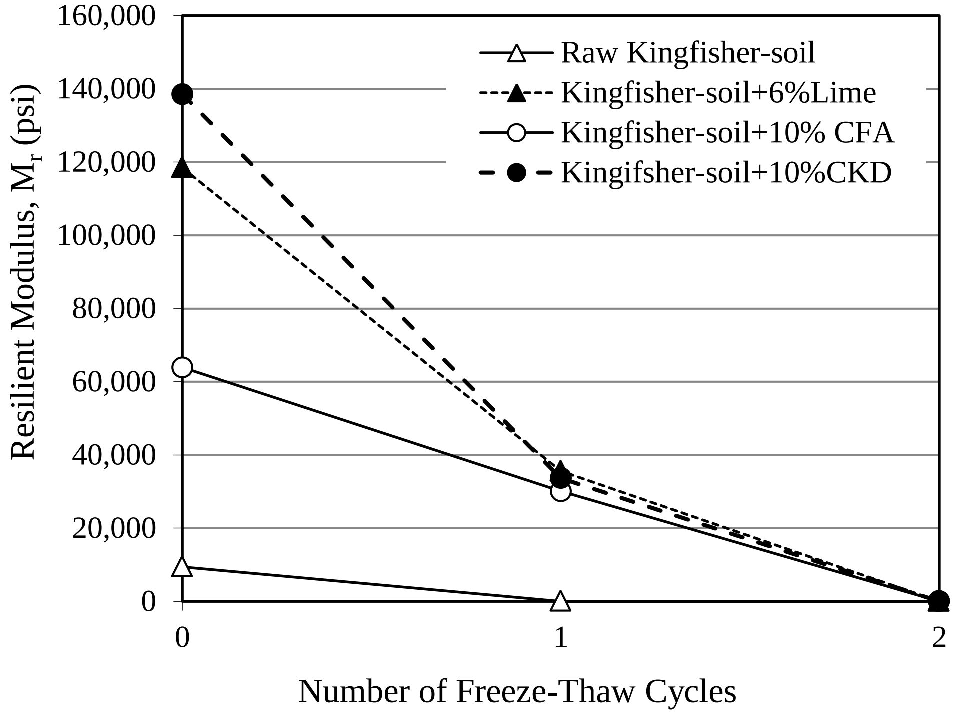


Figure 4.29: M_r Values of Stabilized Kingfisher Soil After Wet-Dry Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

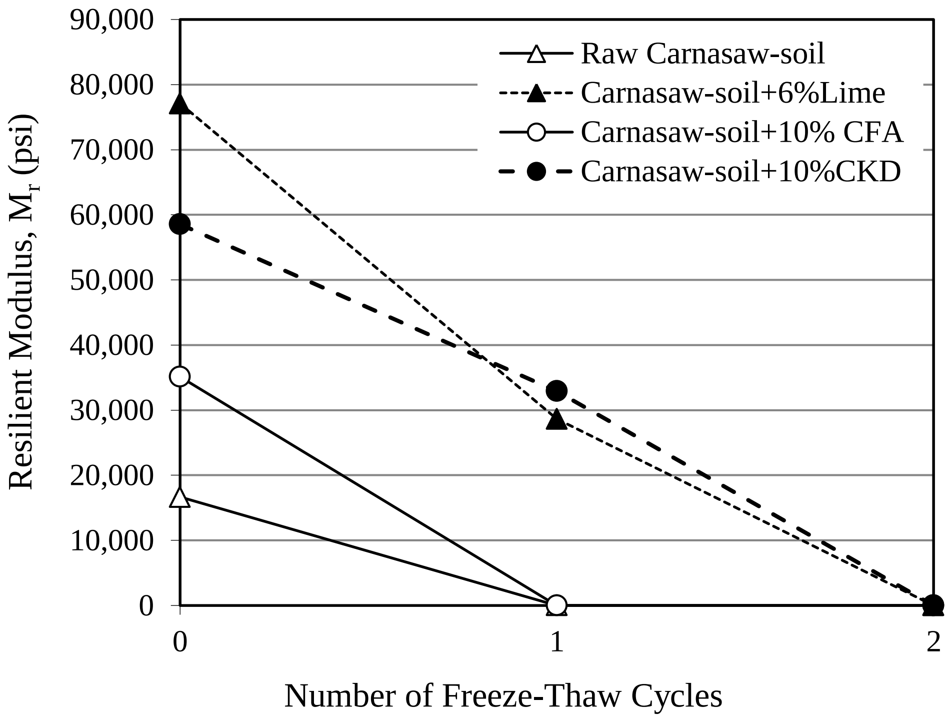


Figure 4.30: M_r Values of Stabilized Carnasaw Soil After Wet-Dry Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

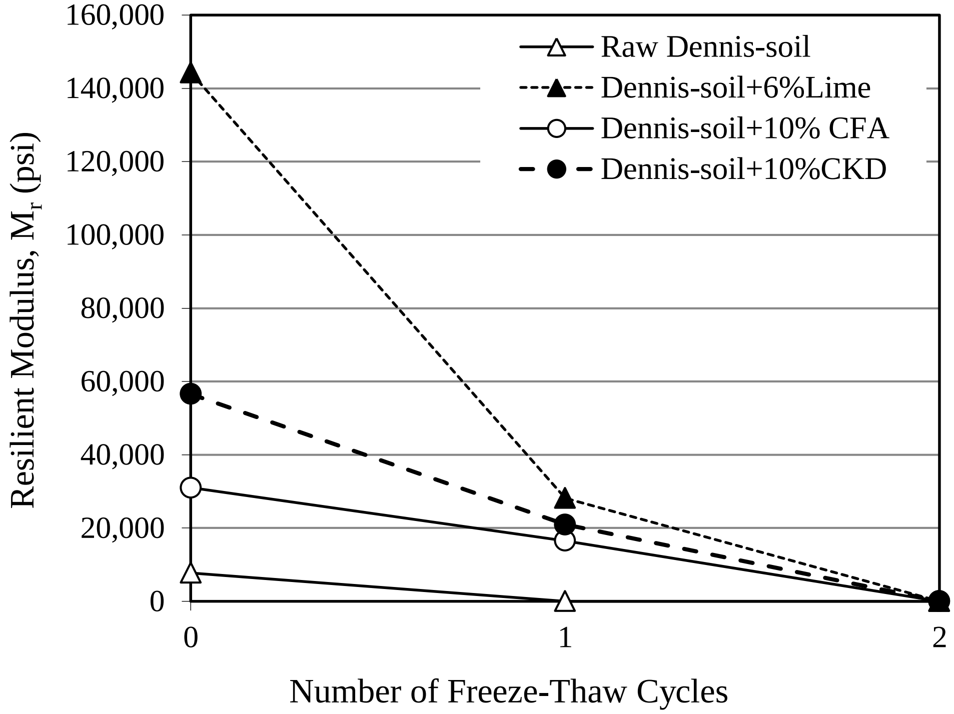


Figure 4.31: M_r Values of Stabilized Dennis Soil After Wet-Dry Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

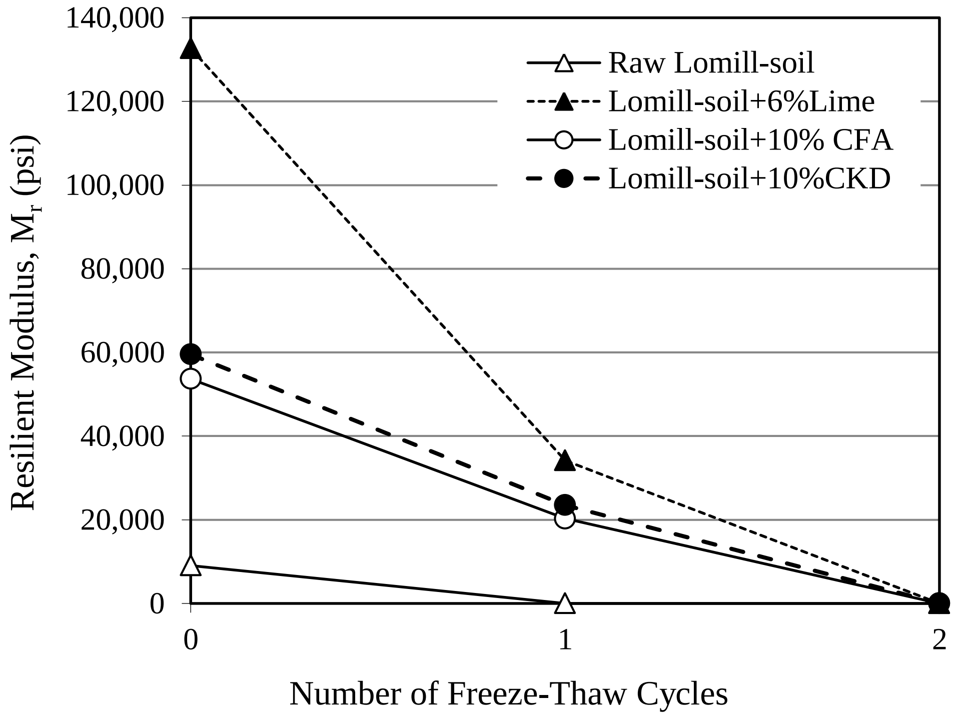


Figure 4.32: M_r Values of Stabilized Lomill Soil After Wet-Dry Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

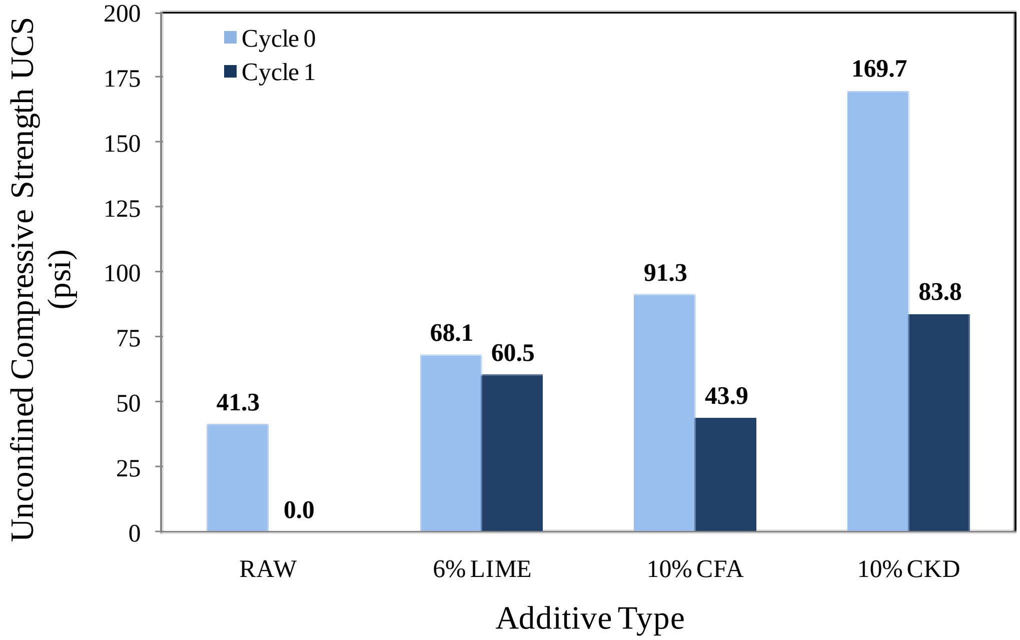


Figure 4.33: UCS Values of Port Soil Specimens Before and After 5-Hour Soaking Period

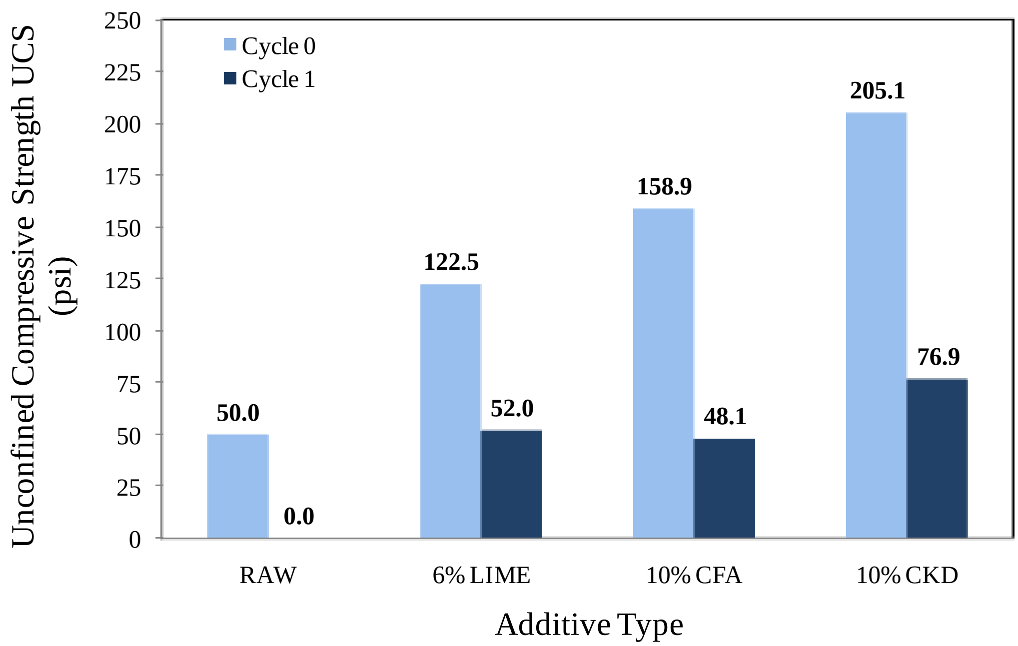


Figure 4.34: UCS Values of Kingfisher Soil Specimens Before and After 5-Hour Soaking Period

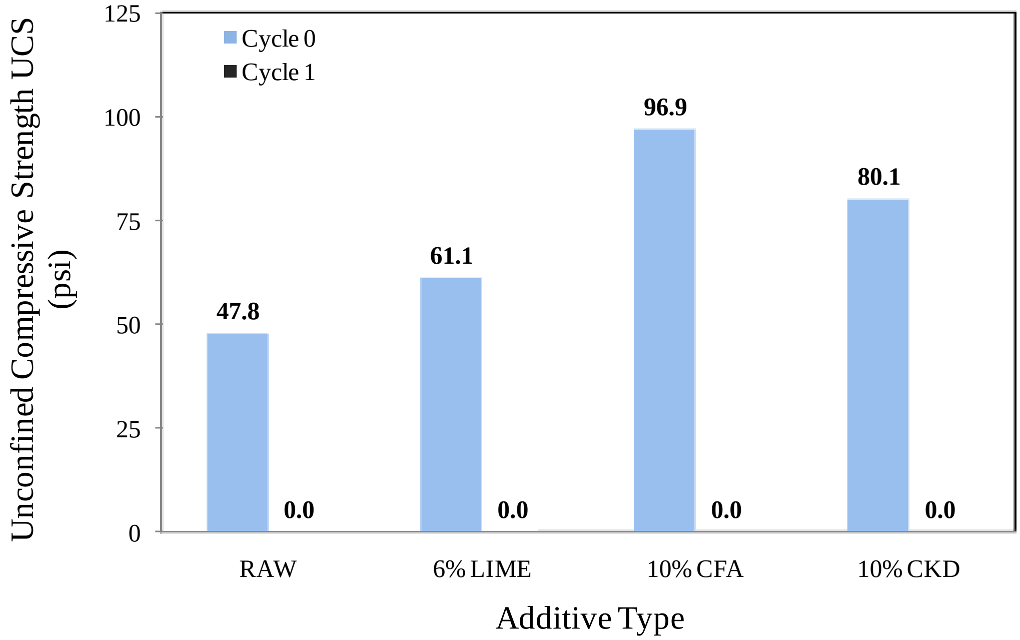


Figure 4.35: UCS Values of Carnasaw Soil Specimens Before and After 5-Hour Soaking Period

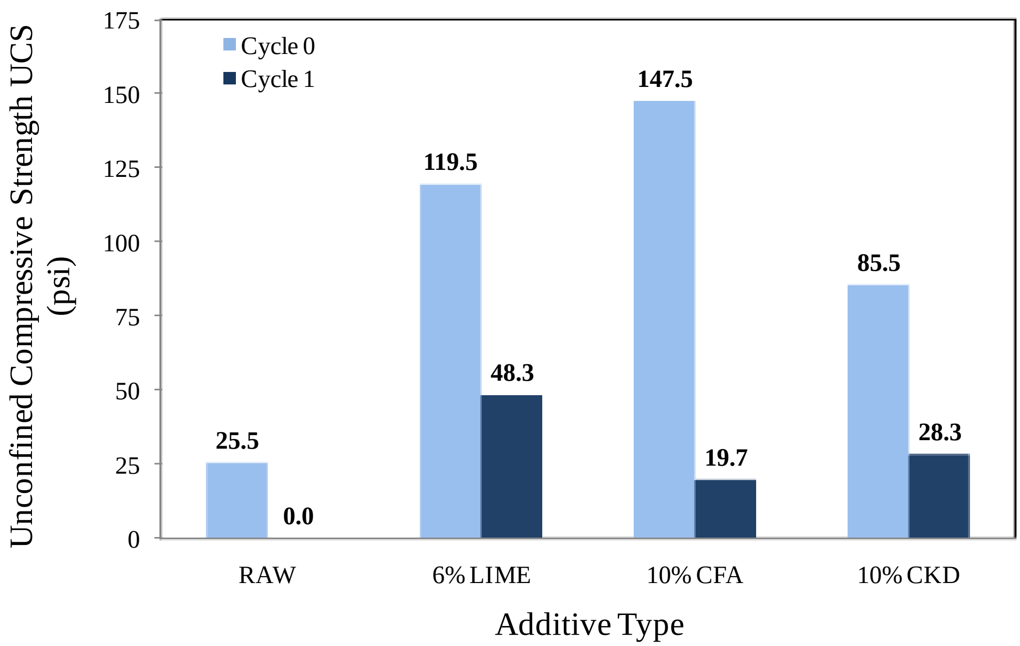


Figure 4.36: UCS Values of Dennis Soil Specimens Before and After 5-Hour Soaking Period

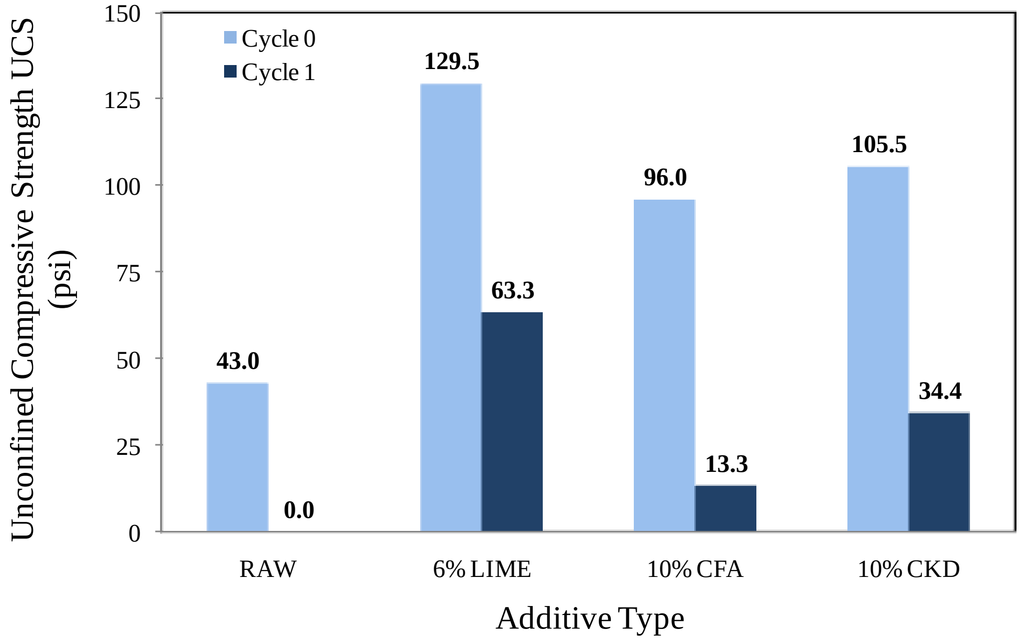


Figure 4.37: UCS Values of Lomill Soil Specimens Before and After 5-Hour Soaking Period

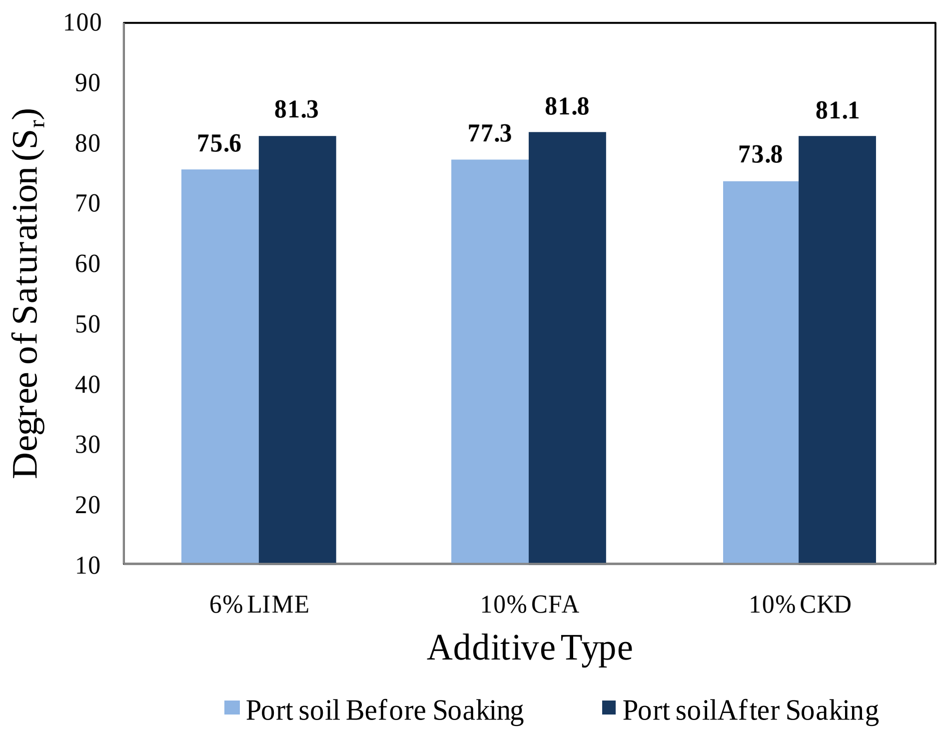


Figure 4.38: Degree of Saturation in Port Soil Specimens Before and After 5-Hour Soaking Period

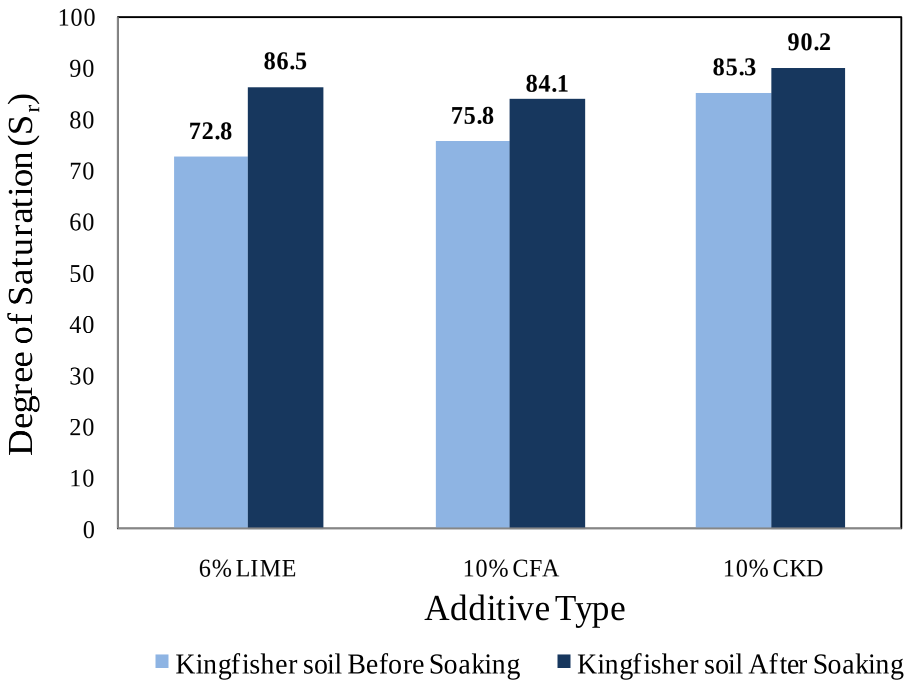


Figure 4.39: Degree of Saturation in Kingfisher Soil Specimens Before and After 5-Hour Soaking Period

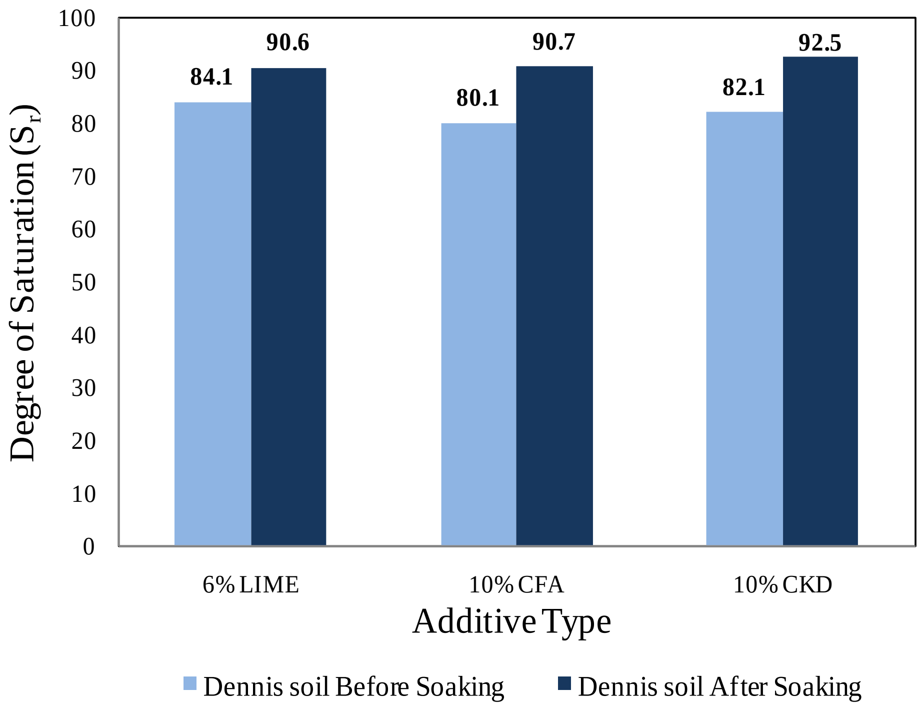


Figure 4.40: Degree of Saturation in Dennis Soil Specimens Before and After 5-Hour Soaking Period

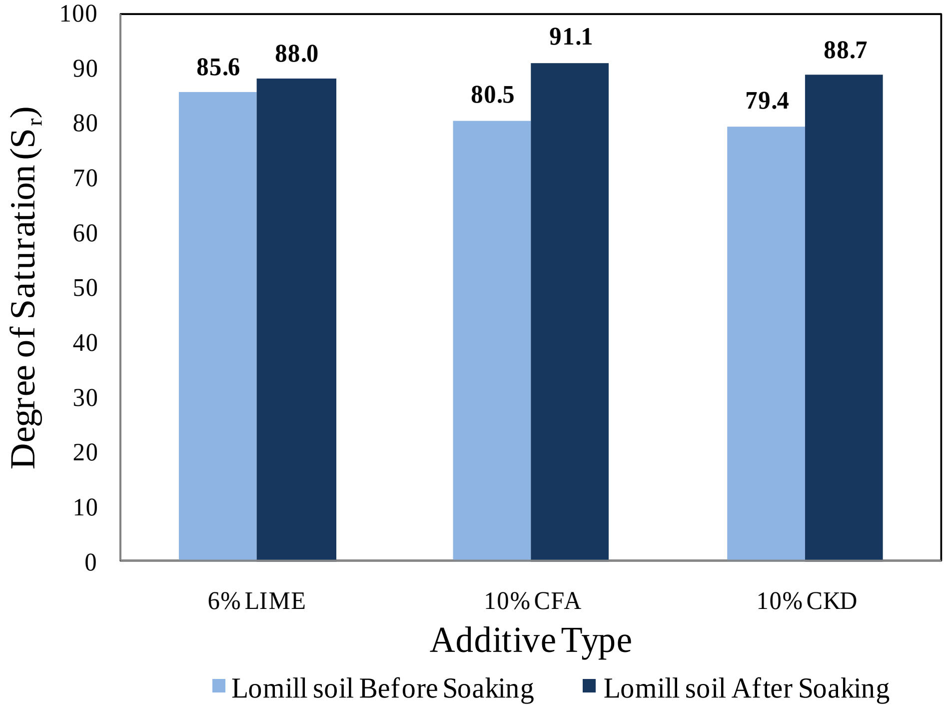


Figure 4.41: Degree of Saturation in Lomill Soil Specimens Before and After 5-Hour Soaking Period

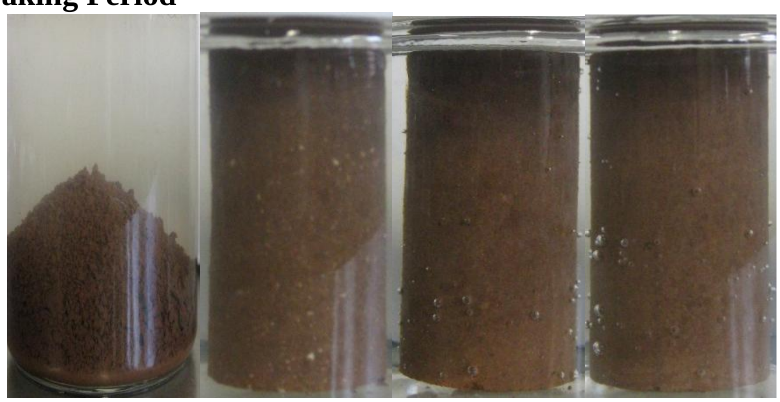


Figure 4.42: Port Specimens at the End of 5-Hour Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

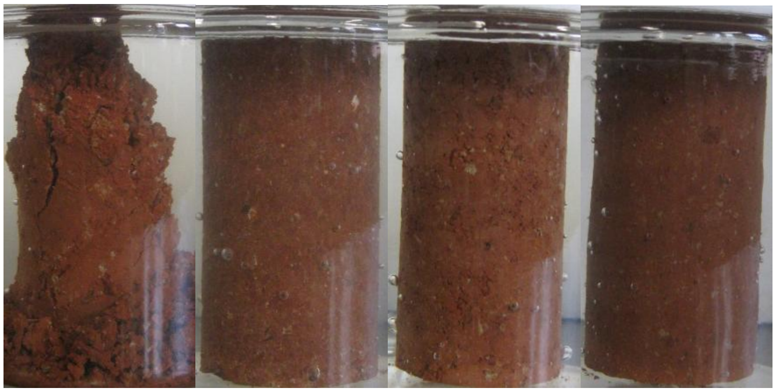


Figure 4.43: Kingfisher Specimens at the End of 5-Hour Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

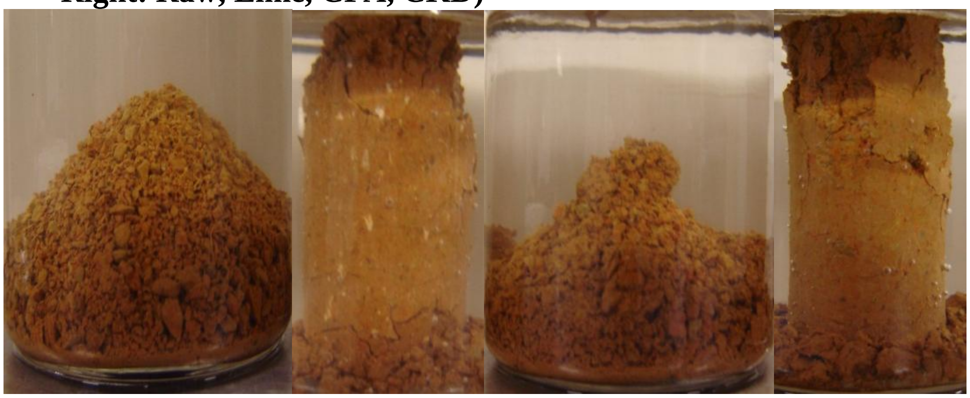


Figure 4.44: Carnasaw Specimens at the End of 5-Hour Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

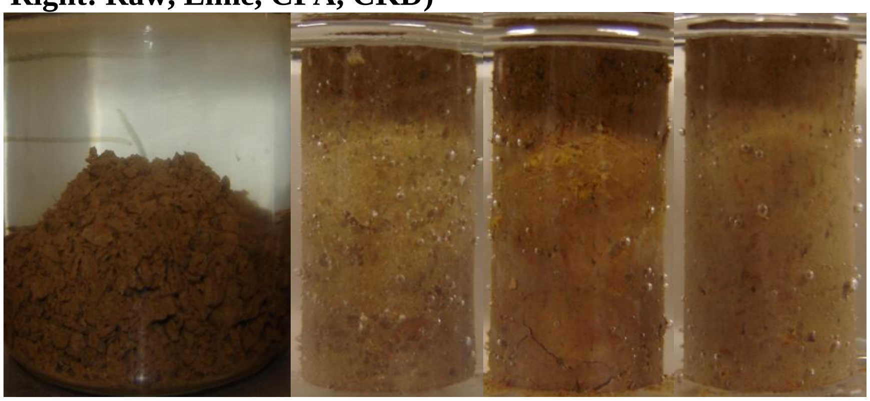


Figure 4.45: Dennis Specimens at the End of 5-Hour Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

Figure 4.46: Lomill Specimens at the End of 5-Hour Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

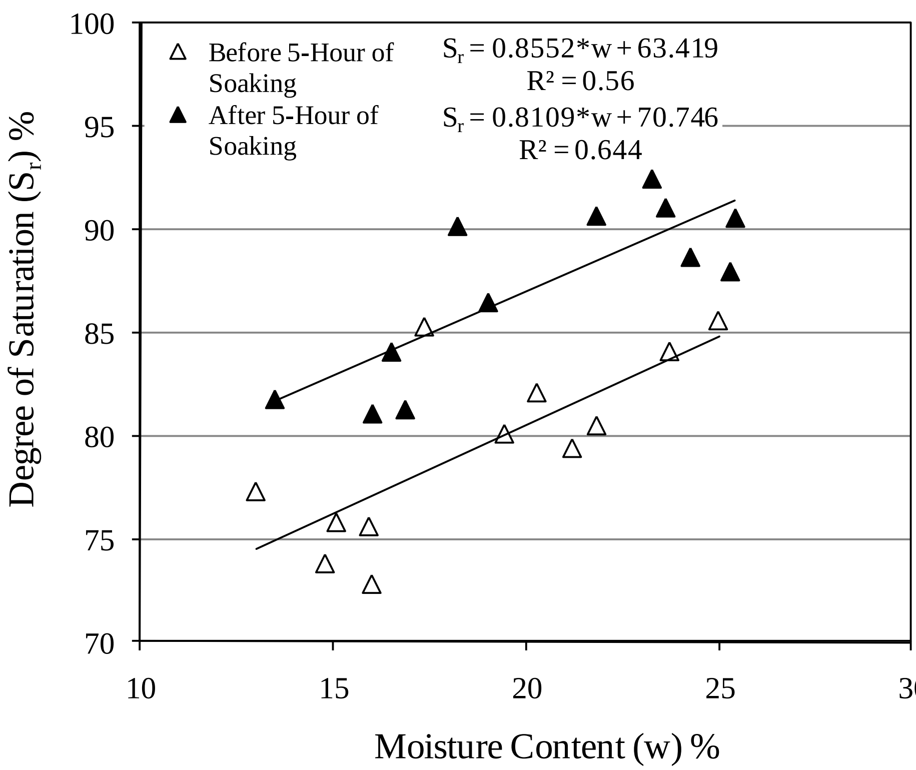


Figure 4.47: Relationship Between the Increase in Moisture Content and Degree of Saturation in all Specimens Before and After 5-Hour Soaking Period

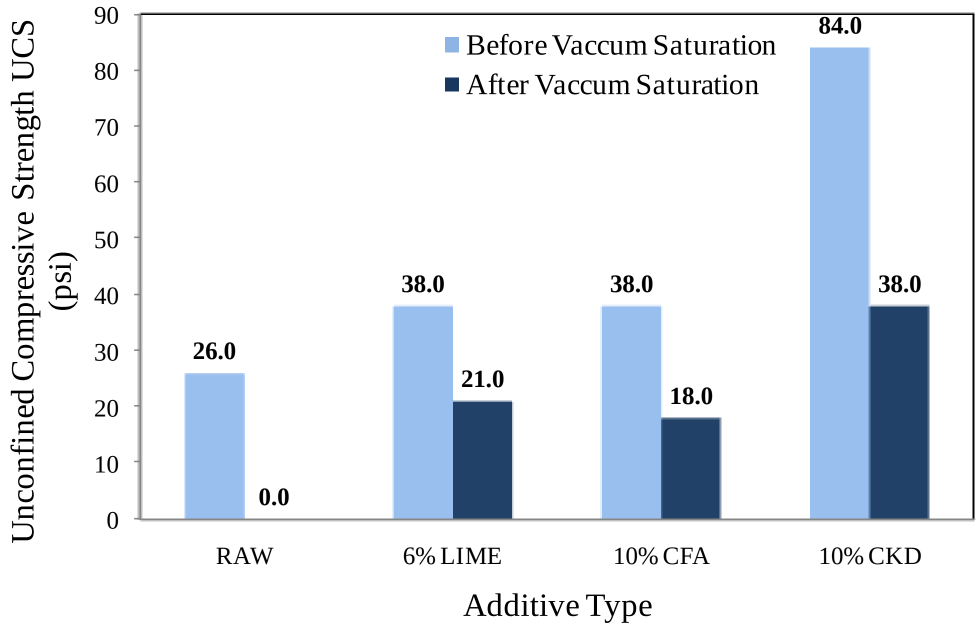


Figure 4.48: UCS Values of Raw and Stabilized Port Soil Specimens Before and After Vacuum Saturation

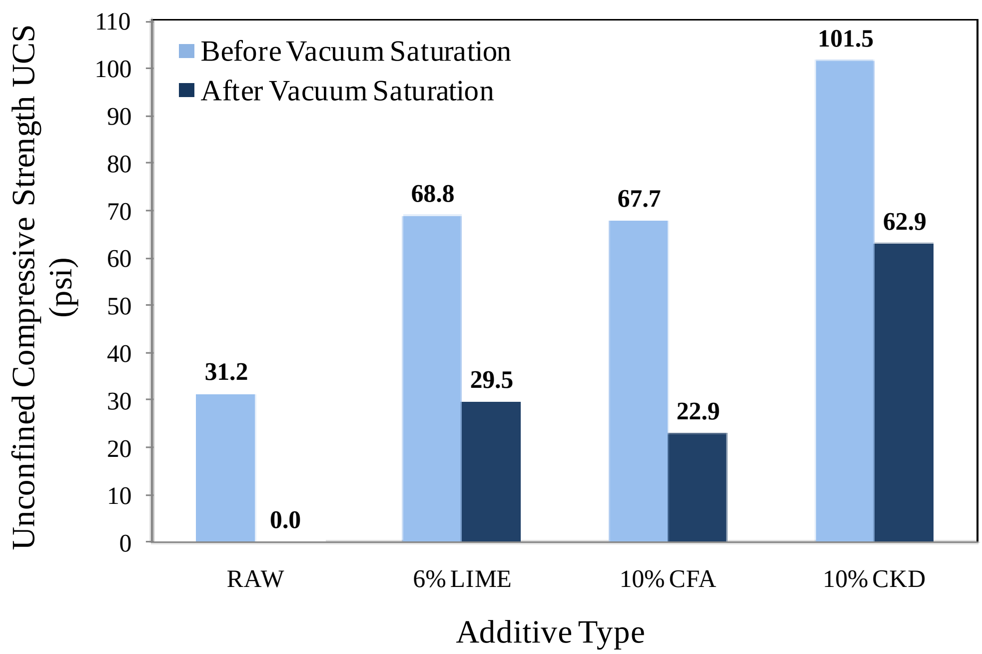


Figure 4.49: Comparison between UCS Values of Stabilized Kingfisher Soil Tested Before and After Vacuum Saturation

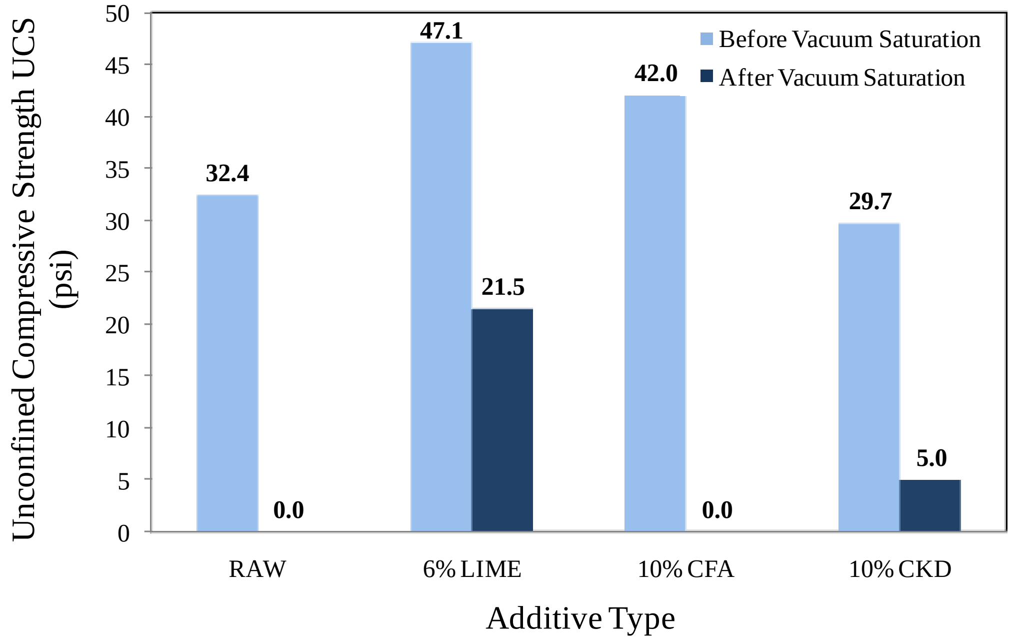


Figure 4.50: Comparison between UCS Values of Stabilized Carnasaw Soil Tested Before and After Vacuum Saturation

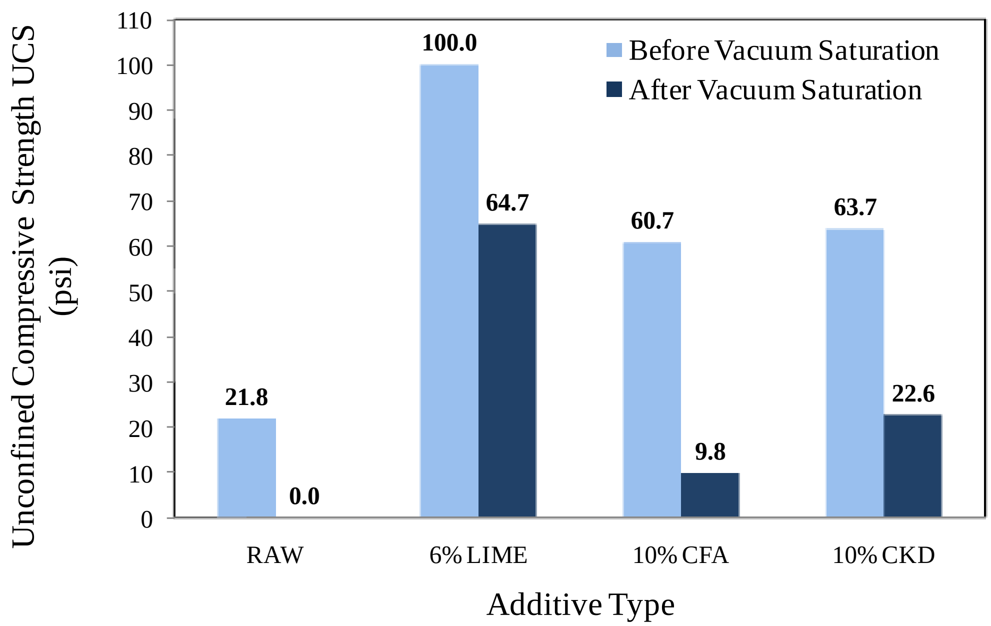


Figure 4.51: Comparison between UCS Values of Stabilized Dennis Soil Tested Before and After Vacuum Saturation

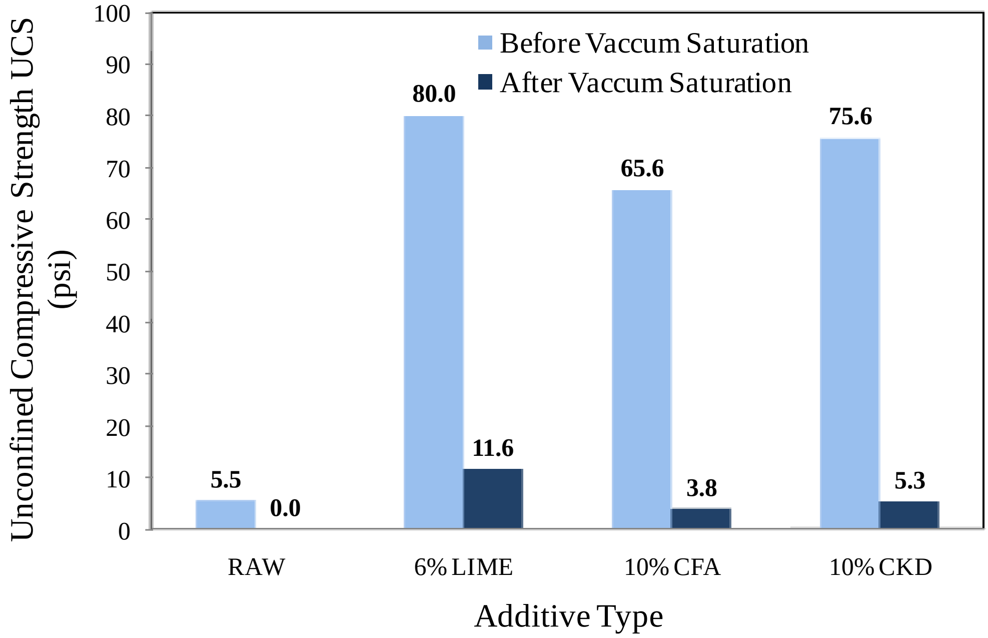


Figure 4.52: Comparison between UCS Values of Stabilized Lomill Soil Tested Before and After Vacuum Saturation

Figure 4.53: Kingfisher Specimens After Vacuum Saturation After UCS Test (From Left to Right: Lime, CFA, CKD)

Figure 4.54: Carnasaw Specimens After Vacuum Saturation After UCS Test (From Left to Right: Lime, CFA, CKD)

Figure 4.55: Dennis Specimens after Vacuum Saturation after UCS Test (From Left to Right: Lime, CFA)

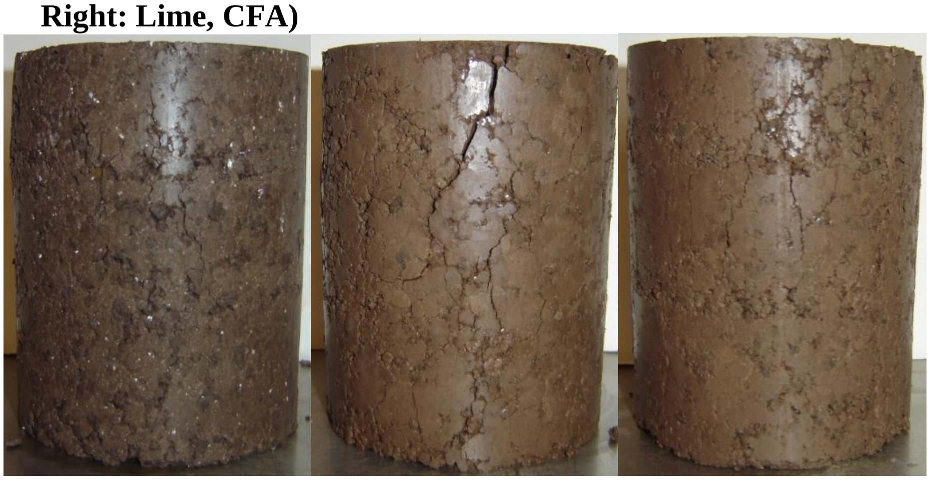


Figure 4.56: Lomill Specimens After Vacuum Saturation After UCS Test (From Left to Right: Lime, CFA, CKD)

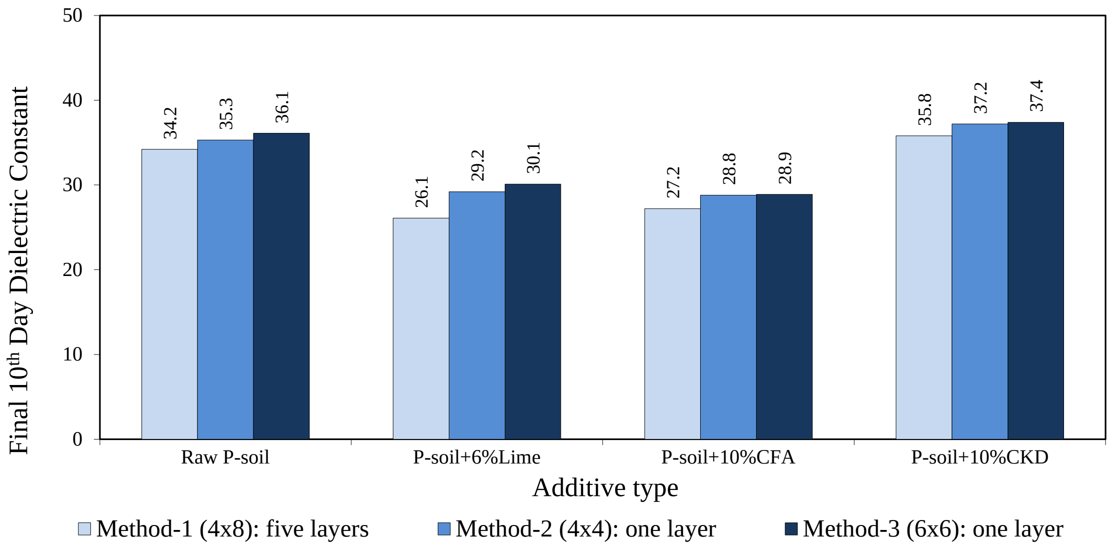


Figure 4.57: Final 10th Day Dielectric Constant Values of Raw and Stabilized Port Soil Specimens

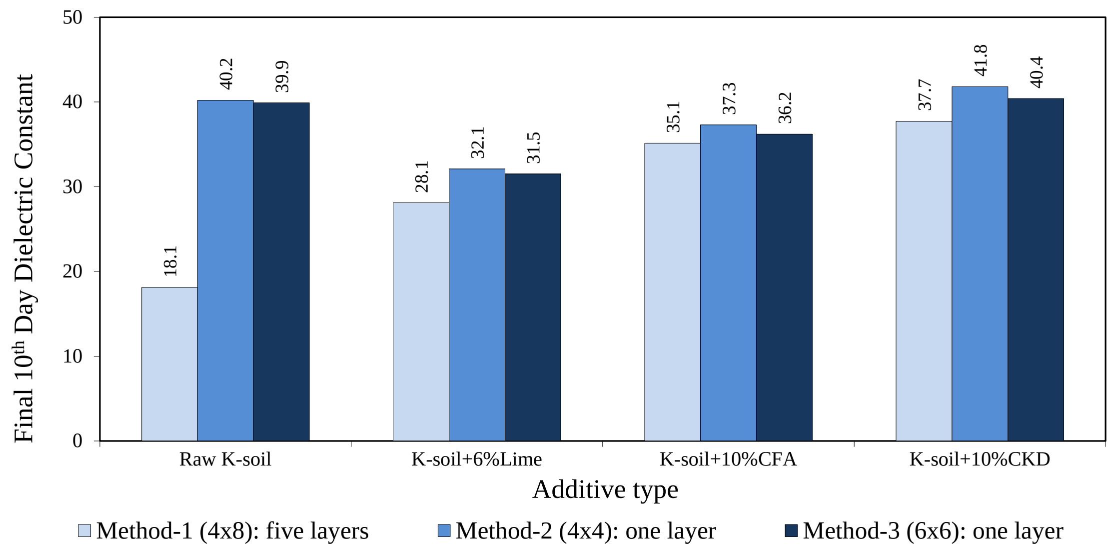


Figure 4.58: Final 10th Day Dielectric Constant Values of Raw and Stabilized Kingfisher Soil Specimens

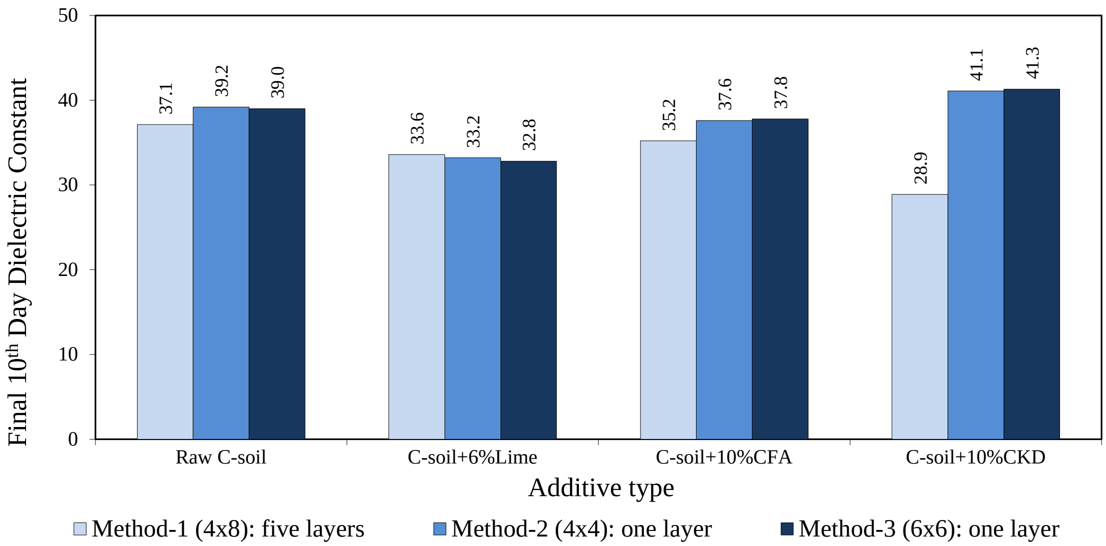


Figure 4.59: Final 10th Day Dielectric Constant Values of Raw and Stabilized Carnasaw Soil Specimens

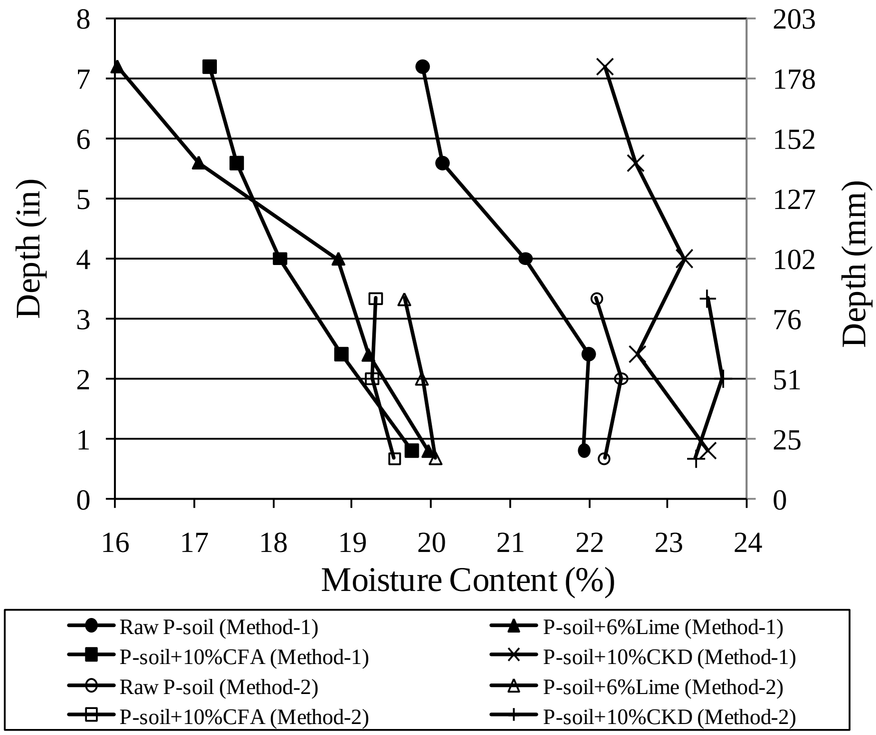


Figure 4.60: Variation of Moisture Content Along the Height of Raw and Stabilized Port Soil Specimens

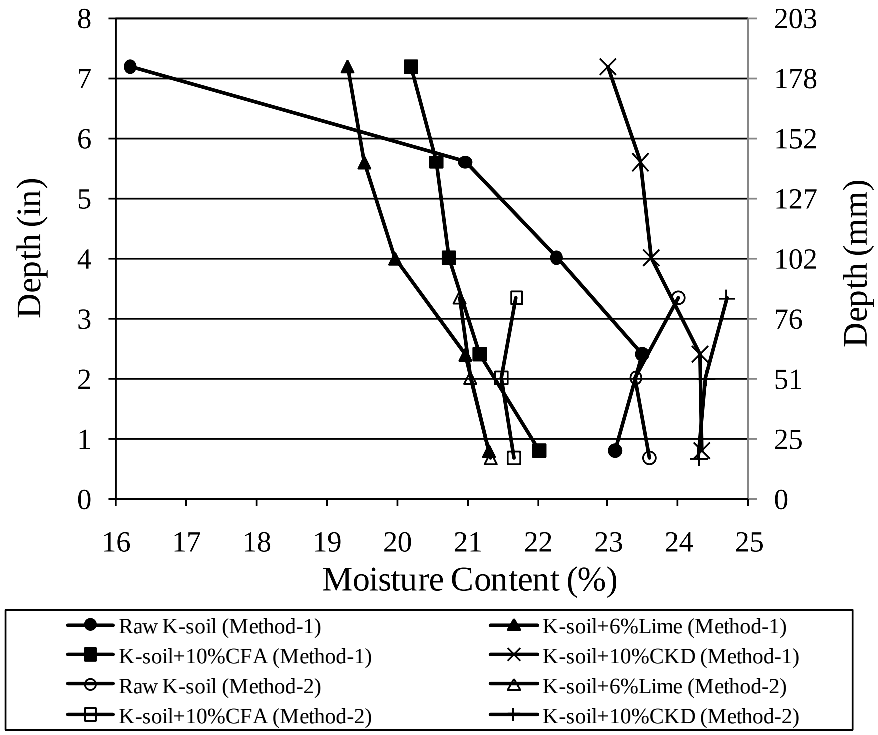


Figure 4.61: Variation of Moisture Content Along the Height of Raw and Stabilized Kingfisher Soil Specimens

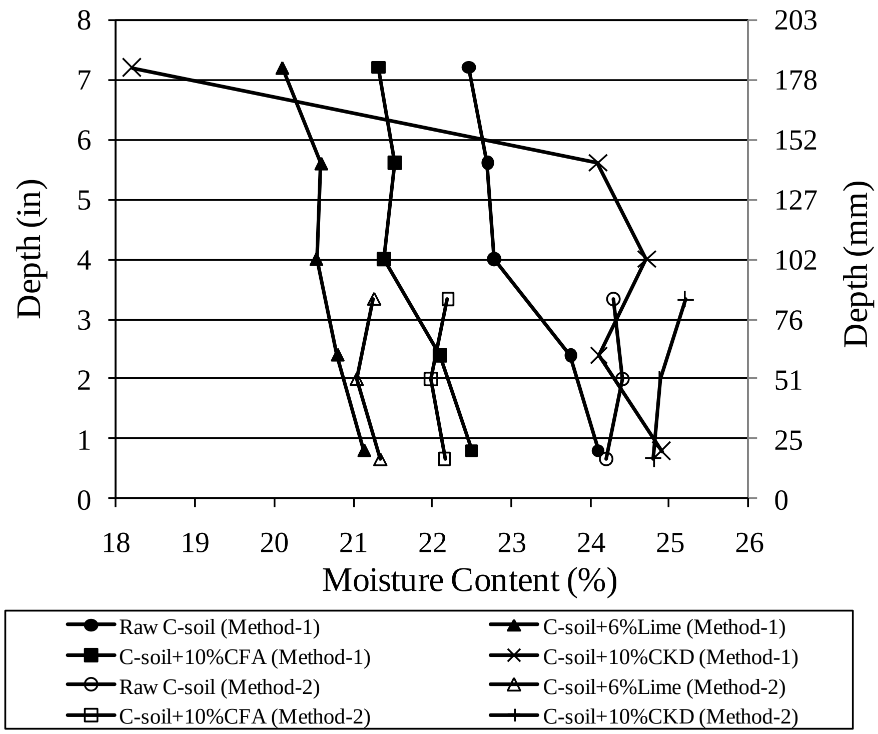
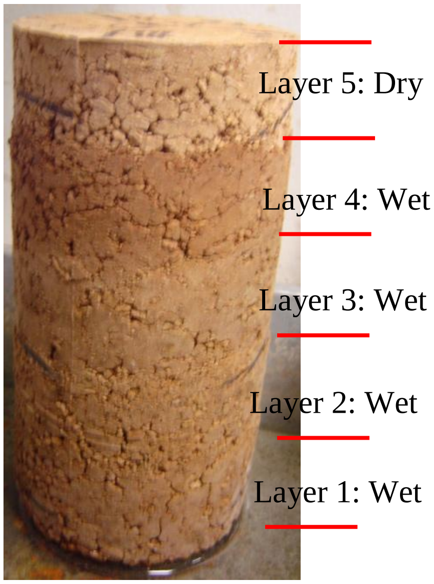
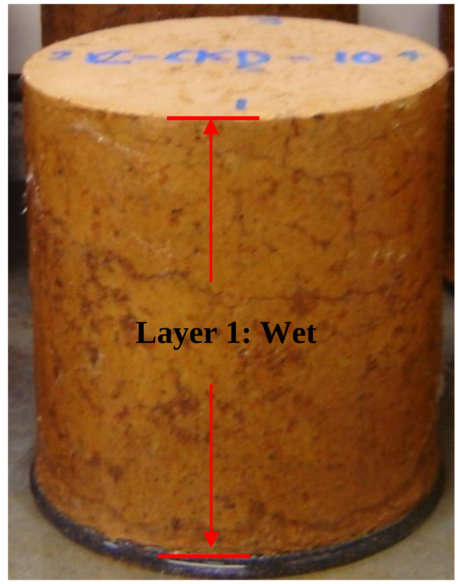


Figure 4.62: Variation of Moisture Content Along the Height of Raw and Stabilized Carnasaw Soil Specimens





(a) Method-1 **(b) Method-2**

Figure 4.63: Photographic View of C-soil Specimens Stabilized with 10% CKD Under Tube Suction Test (After 10 Days)

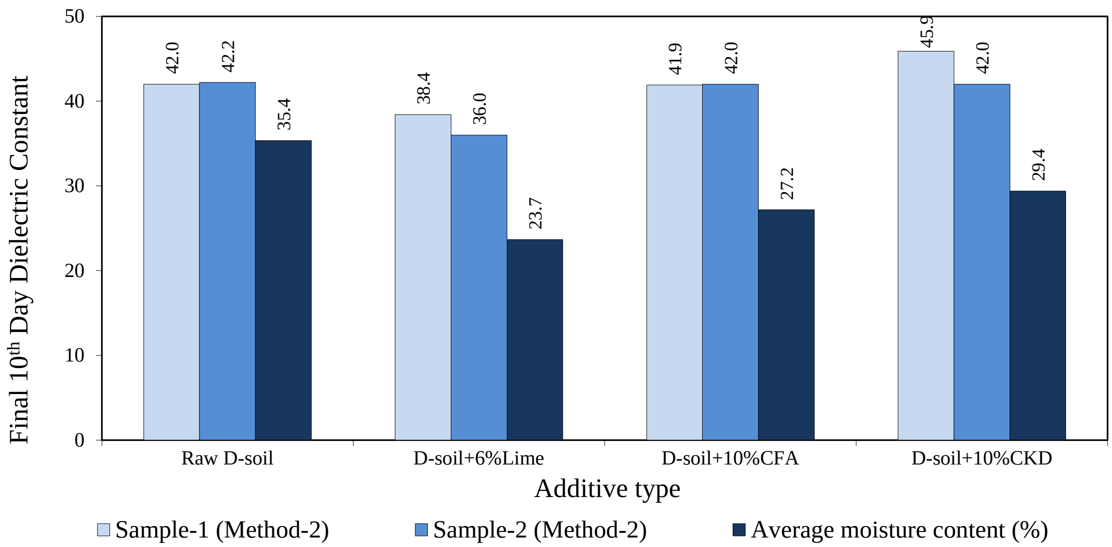


Figure 4.64: Final 10th Day Dielectric Constant Values of Raw and Stabilized Dennis Soil Specimens

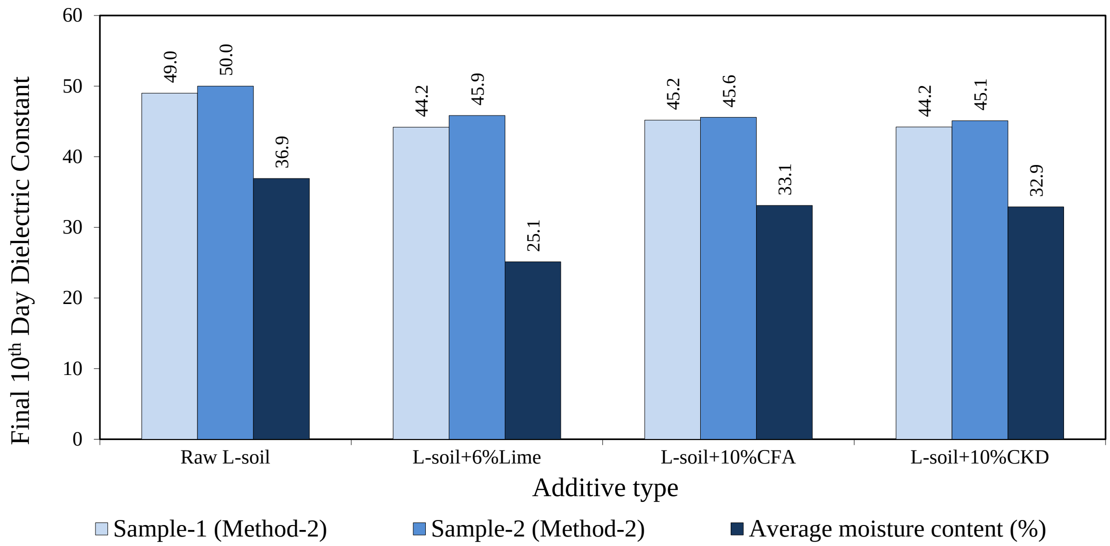


Figure 4.65: Final 10th Day Dielectric Constant Values of Raw and Stabilized Lomill Soil Specimens

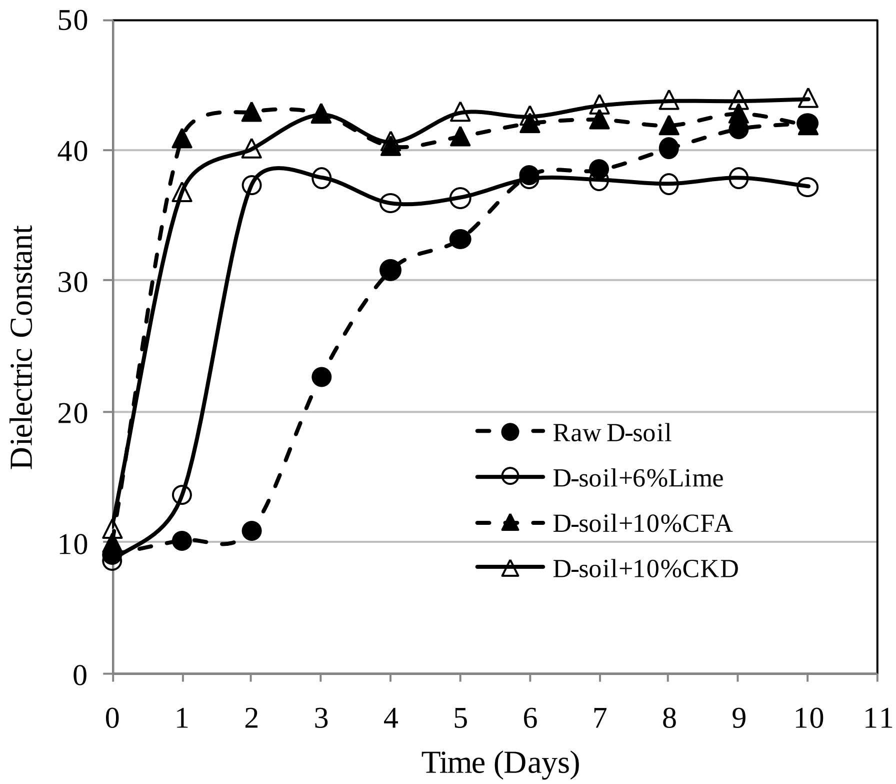


Figure 4.66: Variation of Dielectric Constant Values of Raw and Stabilized Dennis Soil Specimens with Time

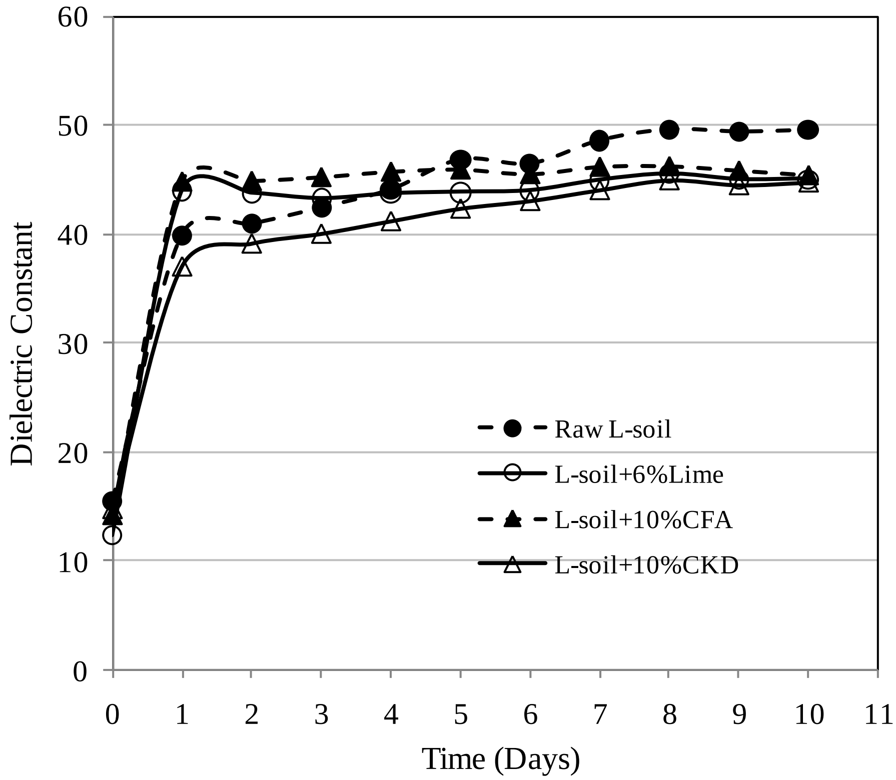


Figure 4.67: Variation of Dielectric Constant Values of Raw and Stabilized Lomill Soil Specimens with Time

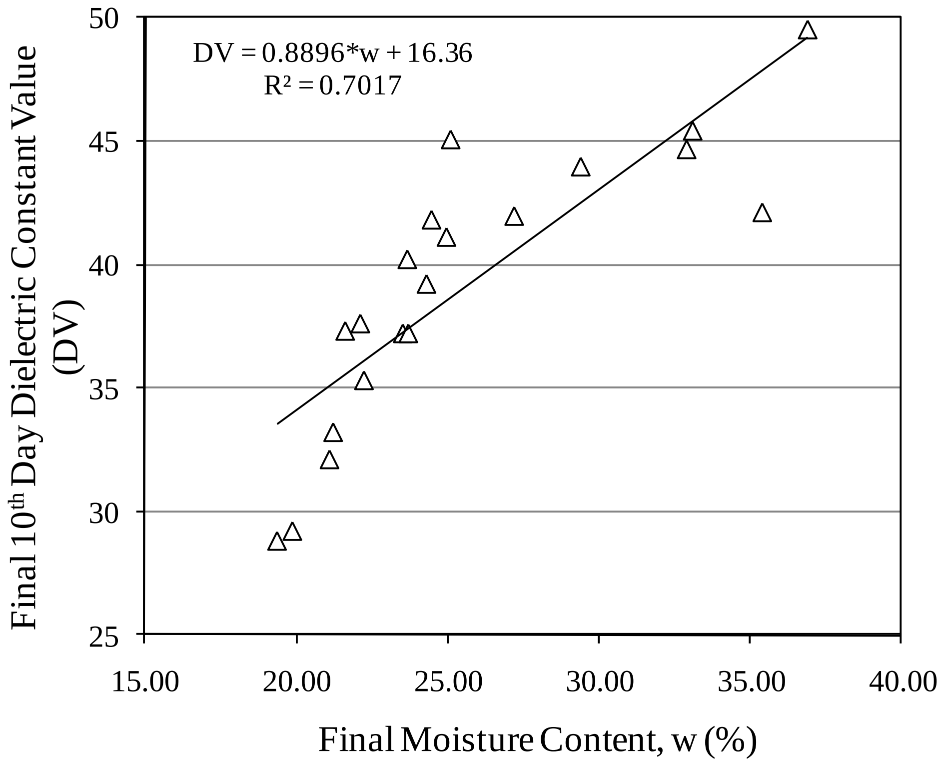


Figure 4.68: Correlations Between Final Dielectric Constant Value (Method-2) and Moisture Content

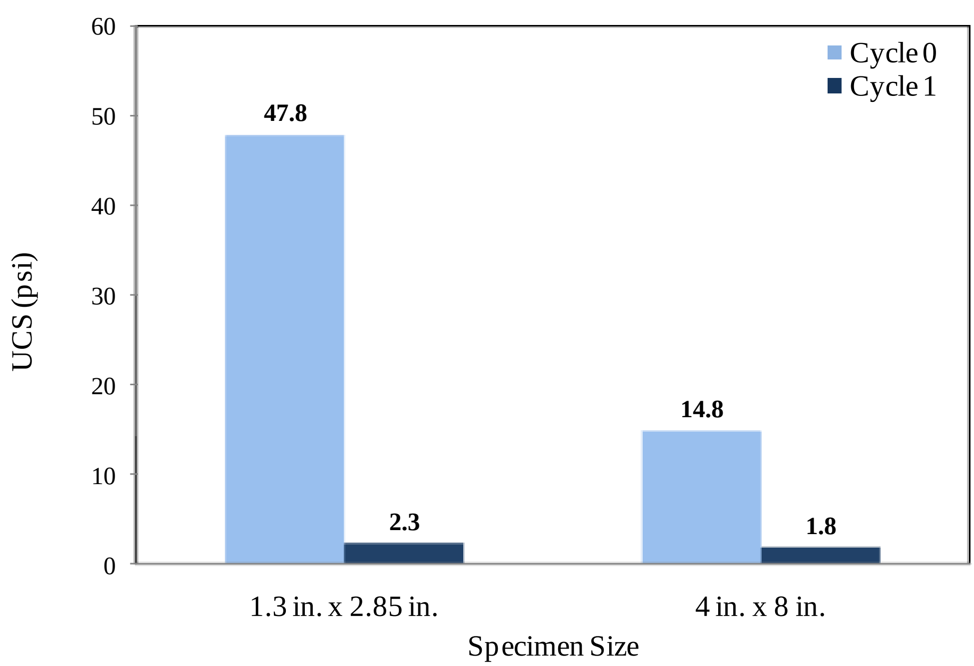


Figure 4.69: Effect of Different Sizes of Raw Carnasaw Soil Specimens on UCS Values at the End of Freeze-Thaw Cycles

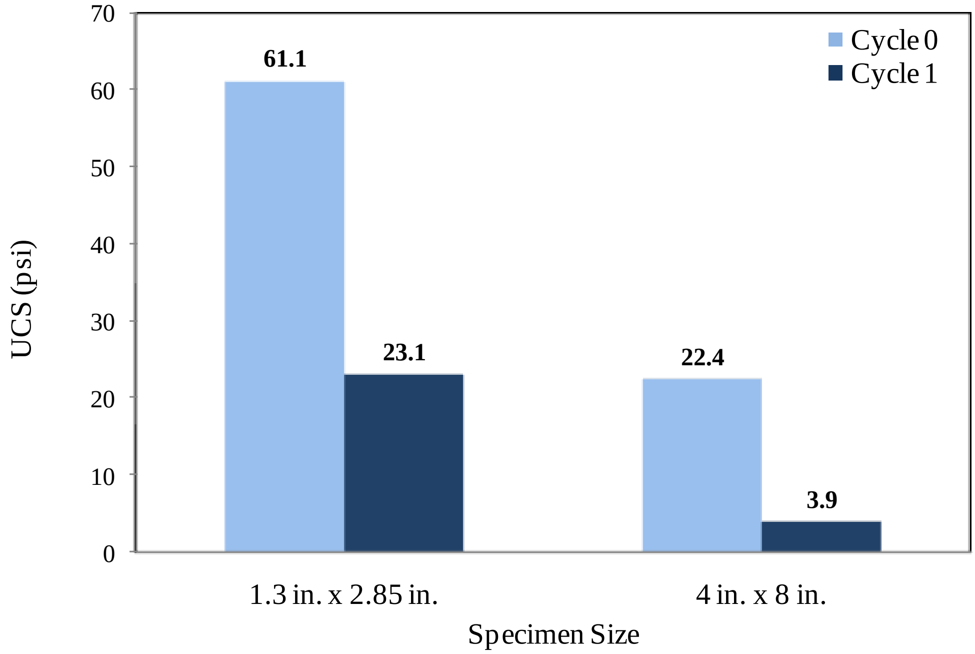


Figure 4.70: Effect of Different Sizes of Carnasaw Soil Specimens Stabilized with 6% Lime on UCS Values at the End of Freeze-Thaw Cycles

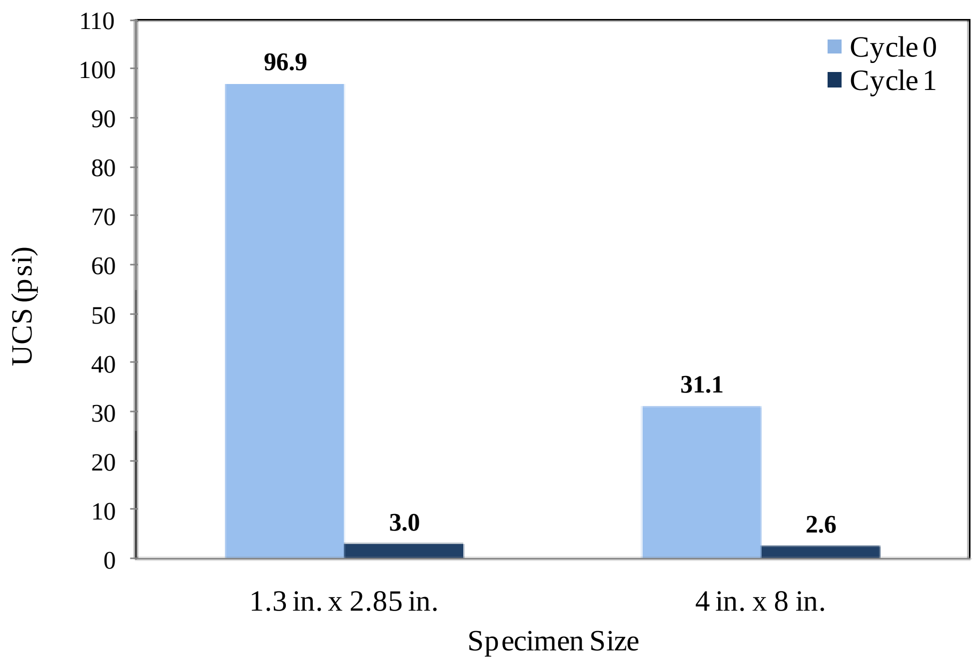


Figure 4.71: Effect of Different Sizes of Carnasaw Soil Specimens Stabilized with 10% CFA on UCS Values at the End of Freeze-Thaw Cycles

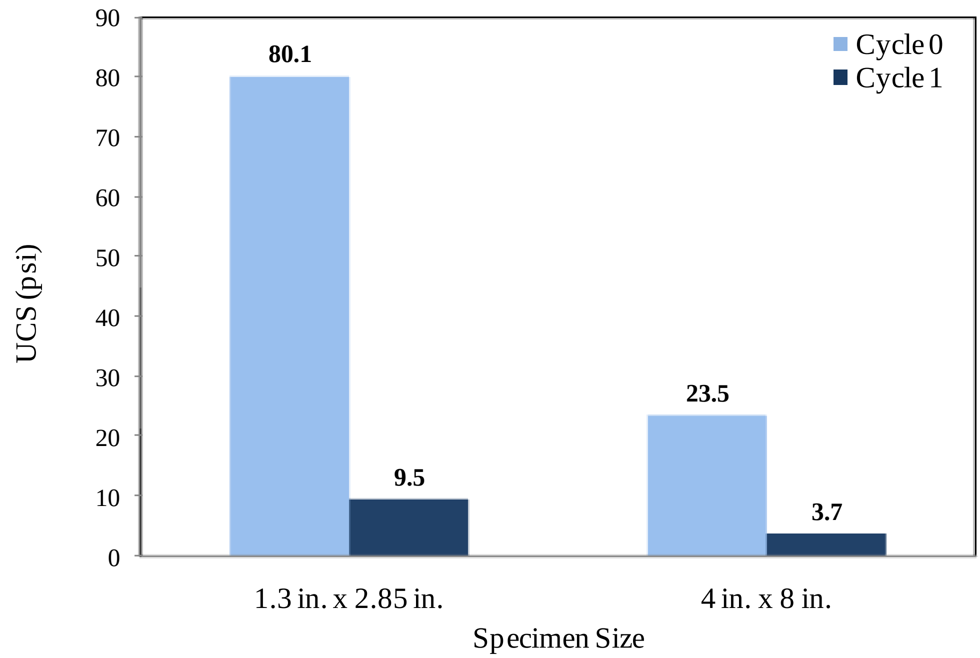


Figure 4.72: Effect of Different Sizes of Carnasaw Soil Specimens Stabilized with 10% CKD on UCS Values at the End of Freeze-Thaw Cycles

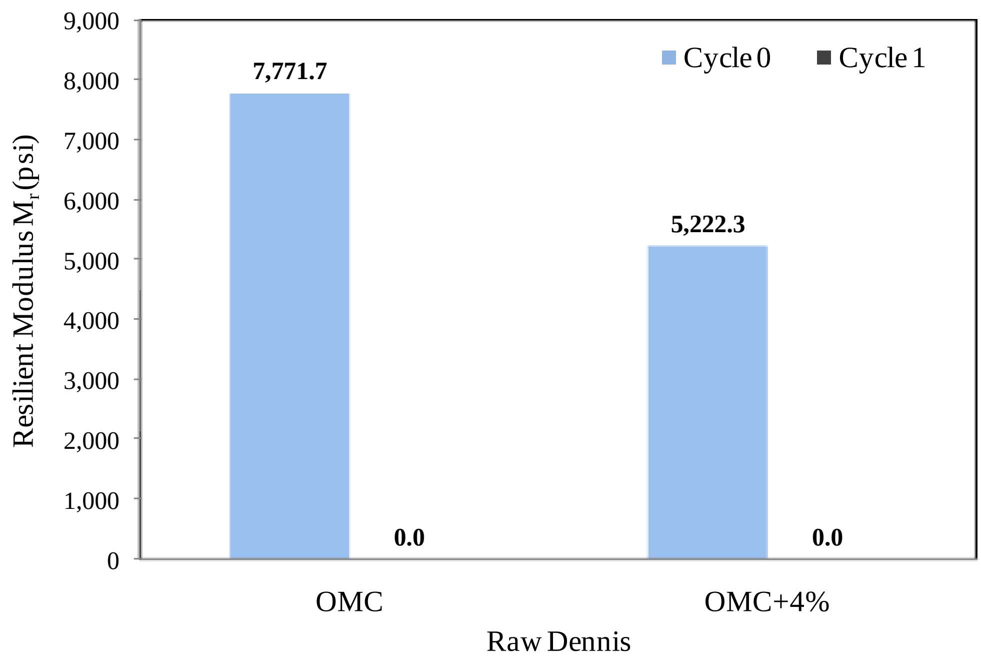


Figure 4.73: M_r Values of Raw Dennis (Compacted at OMC and OMC+4%) Soil Specimens at the End of 0 and 1 Freeze-Thaw Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

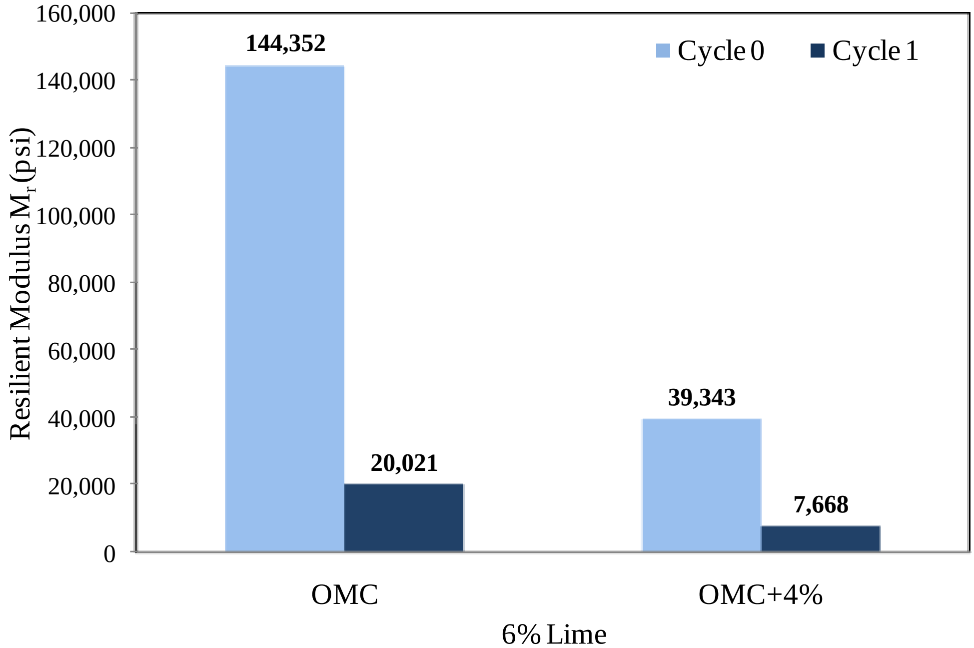


Figure 4.74: M_r Values of Dennis (Compacted at OMC and OMC+4%) Soil Specimens Stabilized with 6% Lime at the End of 0 and 1 Freeze-Thaw Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

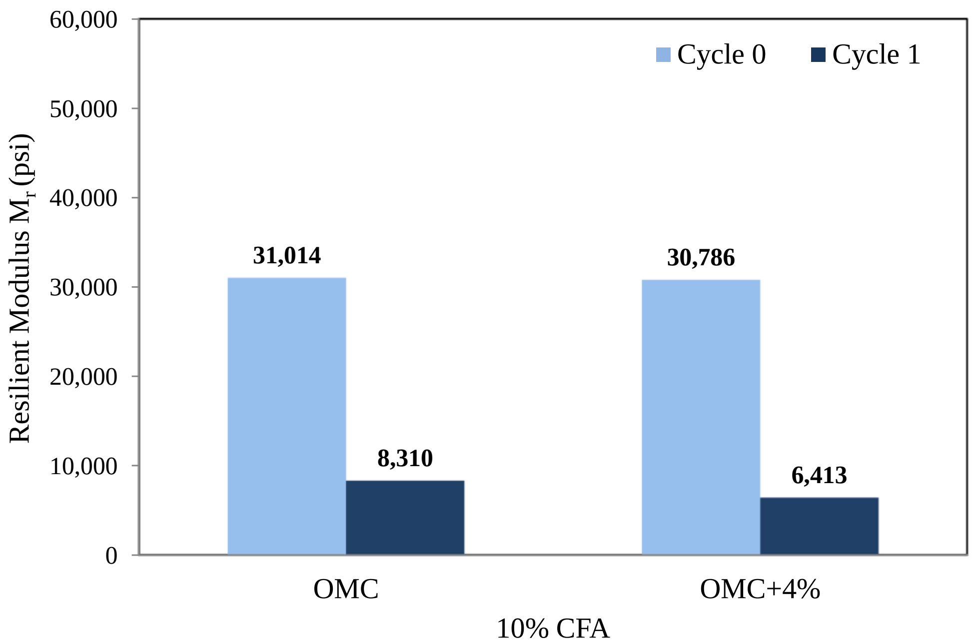


Figure 4.75: M_r Values of Dennis (Compacted at OMC and OMC+4%) Soil Specimens Stabilized with 10% CFA at the End of 0 and 1 Freeze-Thaw Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

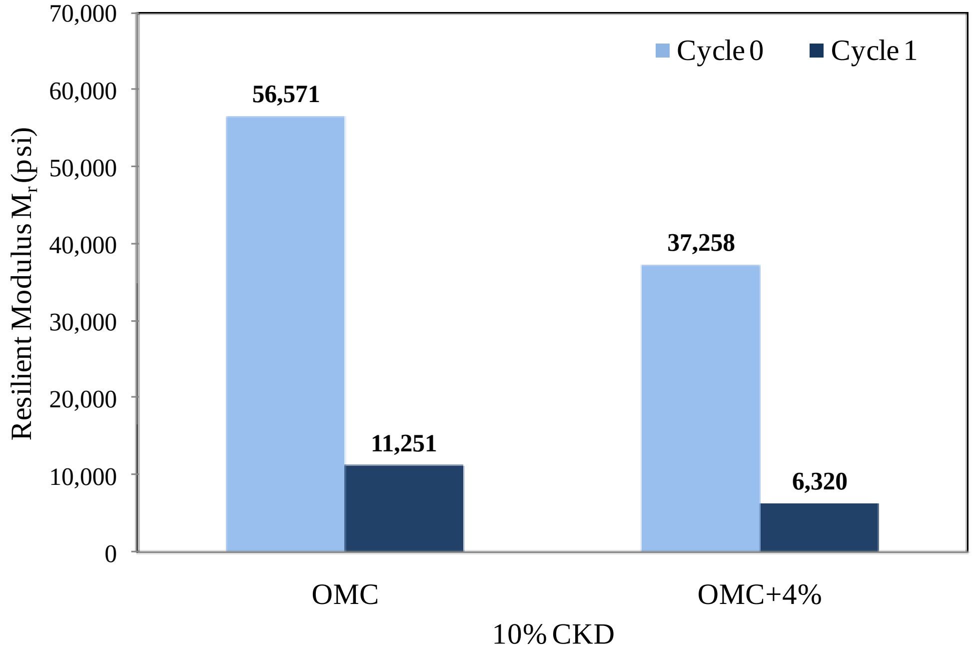


Figure 4.76: M_r Values of Dennis (Compacted at OMC and OMC+4%) Soil Specimens Stabilized with 10% CKD at the End of 0 and 1 Freeze-Thaw Cycles (σ_3 = 4 psi, σ_d = 5.4 psi)

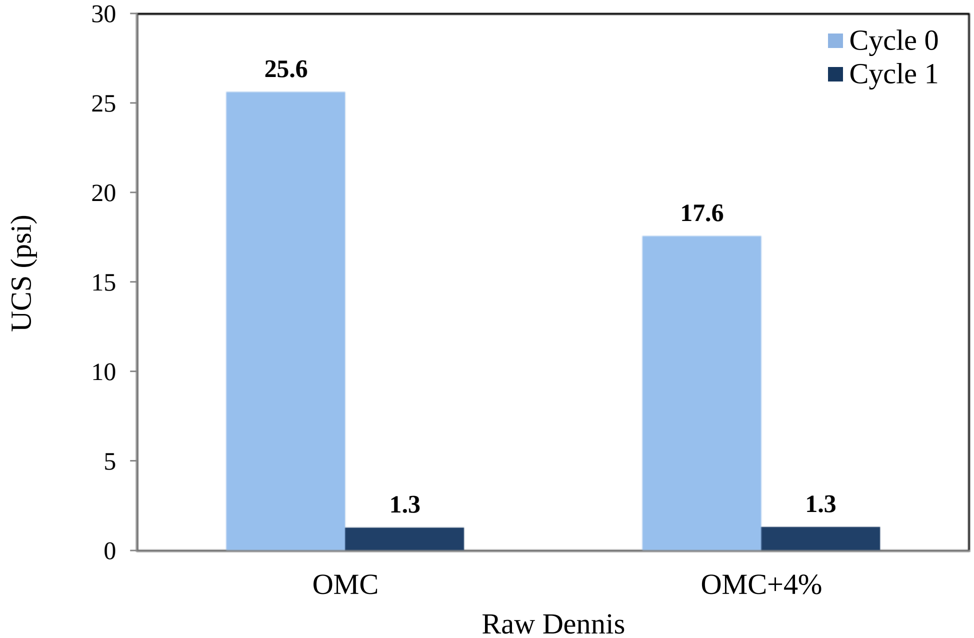


Figure 4.77: UCS Values of Raw Dennis Soil Specimens (Compacted at OMC and OMC+4%) at the End of 0 and 1 Freeze-Thaw Cycles

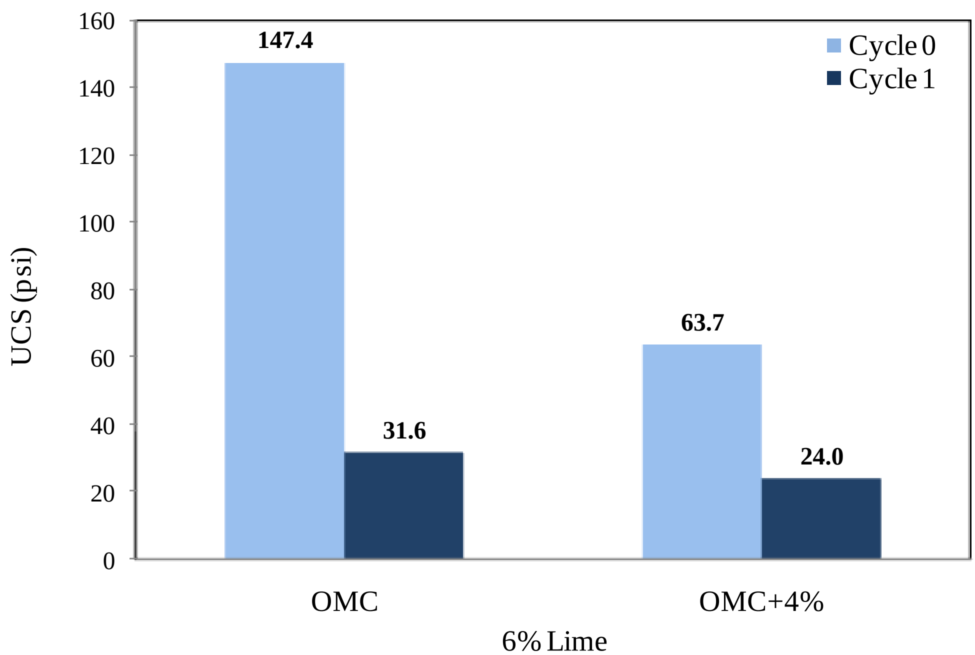


Figure 4.78: UCS Values of Dennis Soil Specimens Stabilized with 6% Lime (Compacted at OMC and OMC+4%) with Freeze-Thaw Cycles

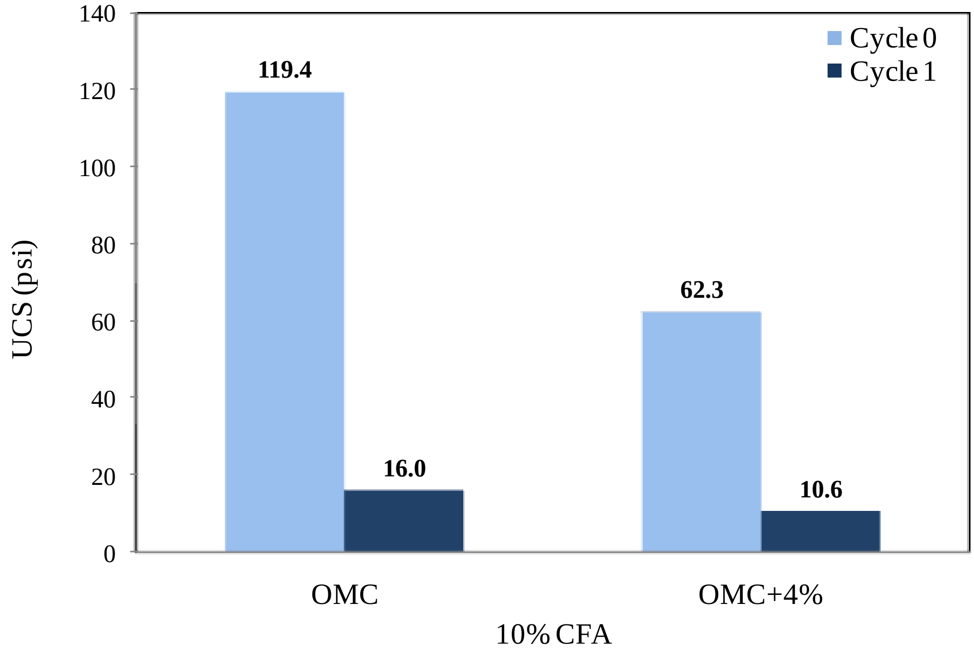


Figure 4.79: UCS Values of Dennis Soil Specimens Stabilized with 10% CFA (Compacted at OMC and OMC+4%) with Freeze-Thaw Cycles

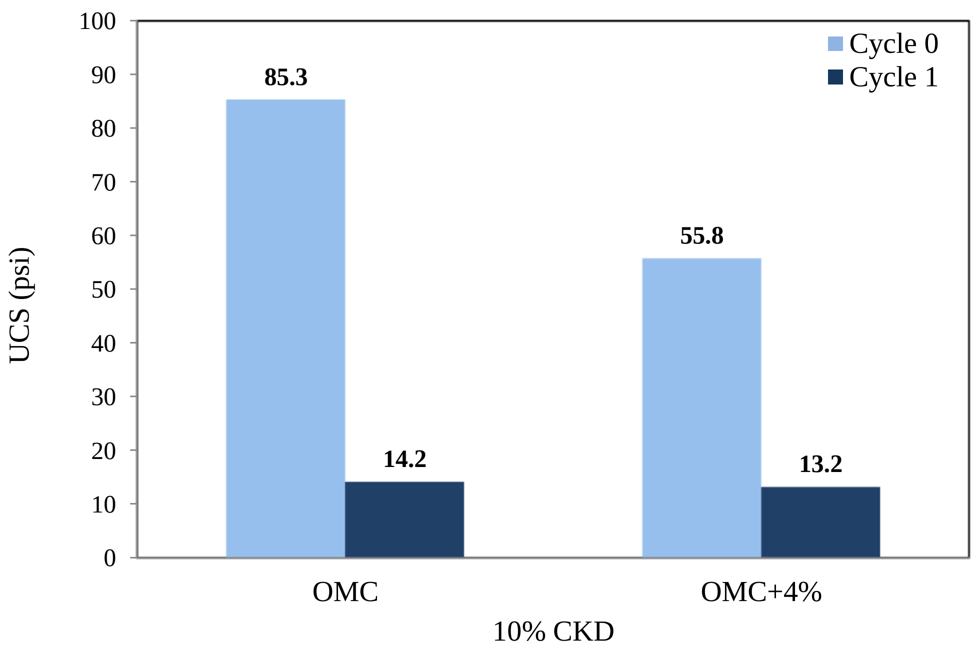


Figure 4.80: UCS Values of Dennis Soil Specimens Stabilized with 10% CKD (Compacted at OMC and OMC+4%) with Freeze-Thaw Cycles

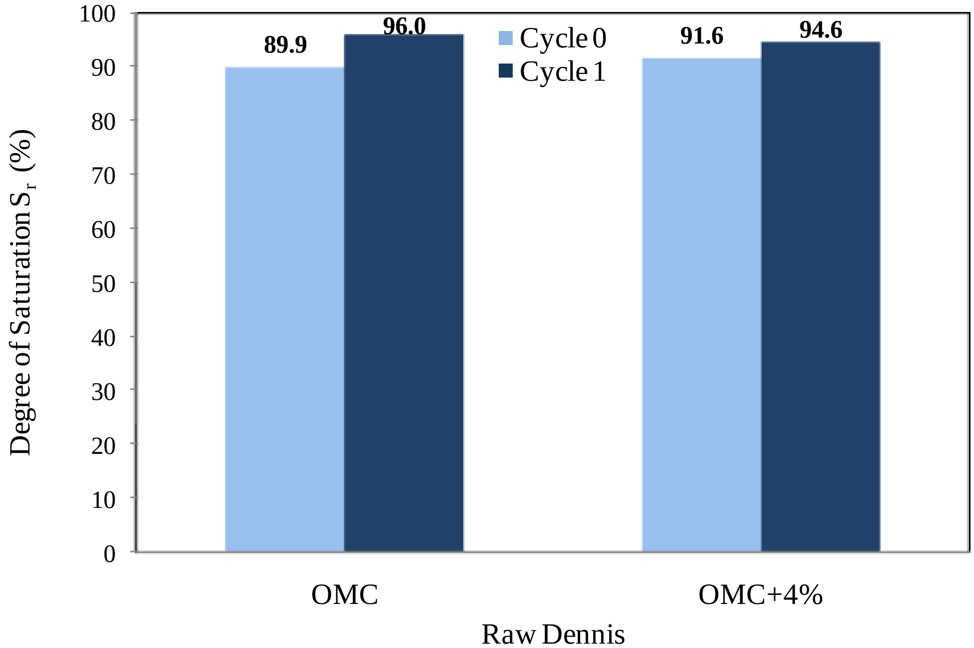


Figure 4.81: Degree of Saturation Values of Raw Dennis Soil Specimens (Compacted at OMC and OMC+4%) at the End of 0 and 1 Freeze-Thaw Cycles

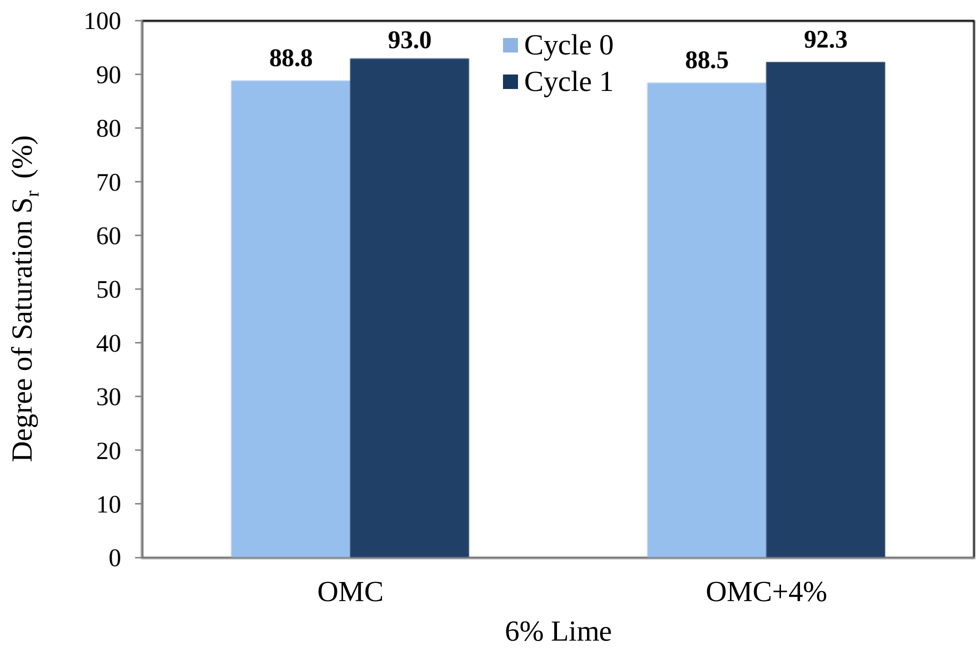


Figure 4.82: Degree of Saturation Values of Dennis Soil Specimens Stabilized with 6% Lime (Compacted at OMC and OMC+4%) with Freeze-Thaw Cycles

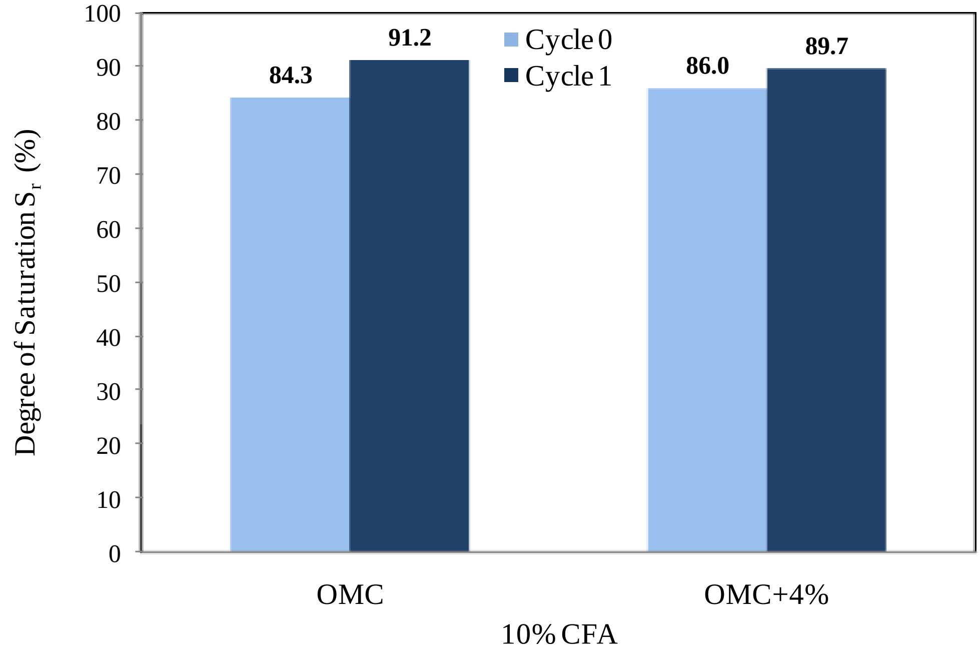


Figure 4.83: Degree of Saturation Values of Dennis Soil Specimens Stabilized with 10% CFA (Compacted at OMC and OMC+4%) with Freeze-Thaw Cycles

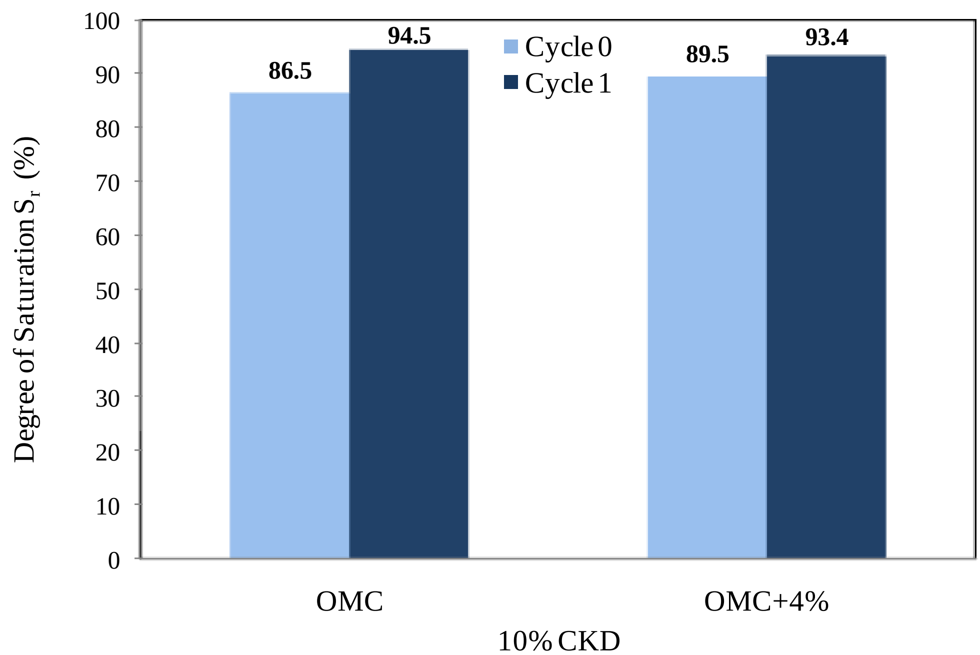


Figure 4.84: Degree of Saturation Values of Dennis Soil Specimens Stabilized with 10% CKD (Compacted at OMC and OMC+4%) with Freeze-Thaw Cycles

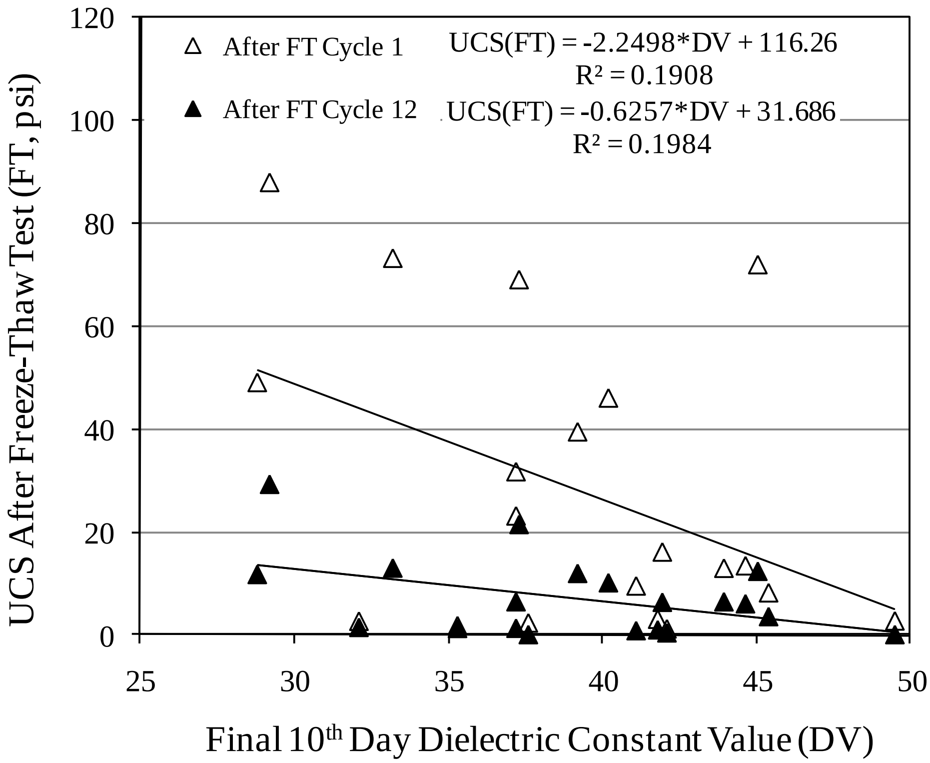


Figure 4.85: Correlations Between UCS At the End of Freeze-Thaw Test and Final Dielectric Constant Value (Method-2)

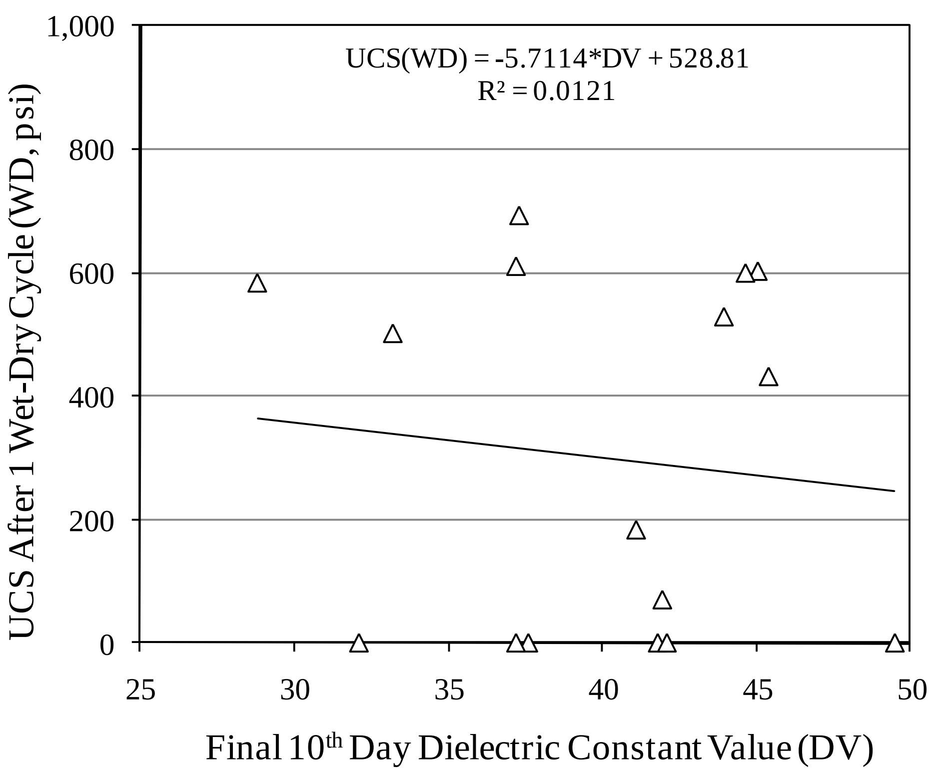


Figure 4.86: Correlations Between UCS At the End of Wet-Dry Test and Final Dielectric Constant Value (Method-2)

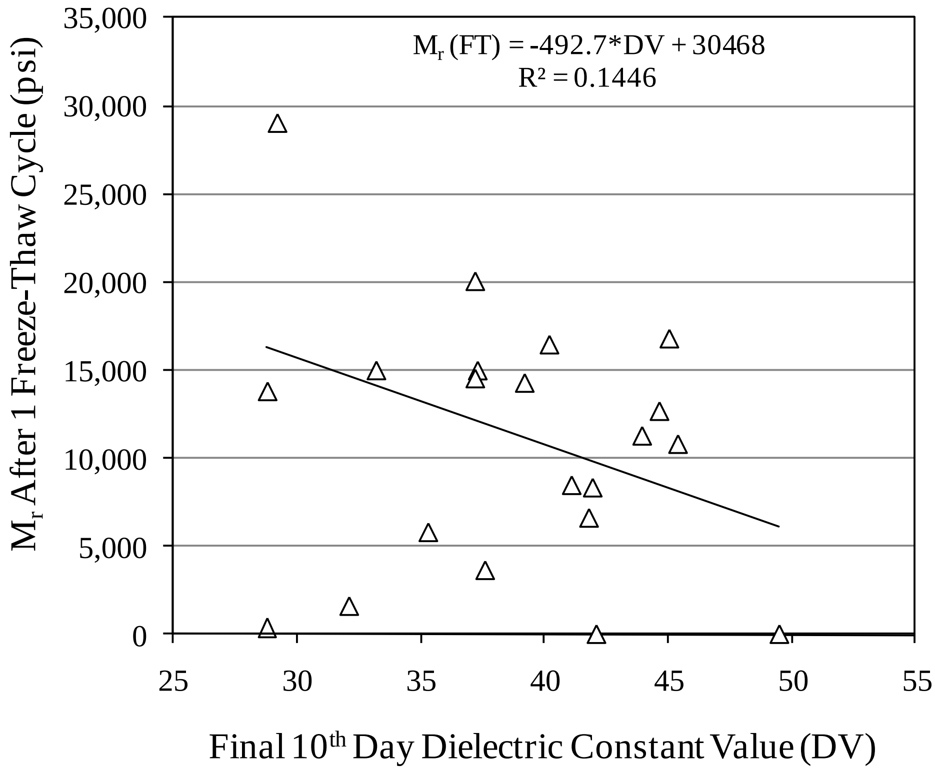


Figure 4.87: Correlations Between M_r At the End of Freeze-Thaw Test and Final Dielectric Constant Value (Method-2)

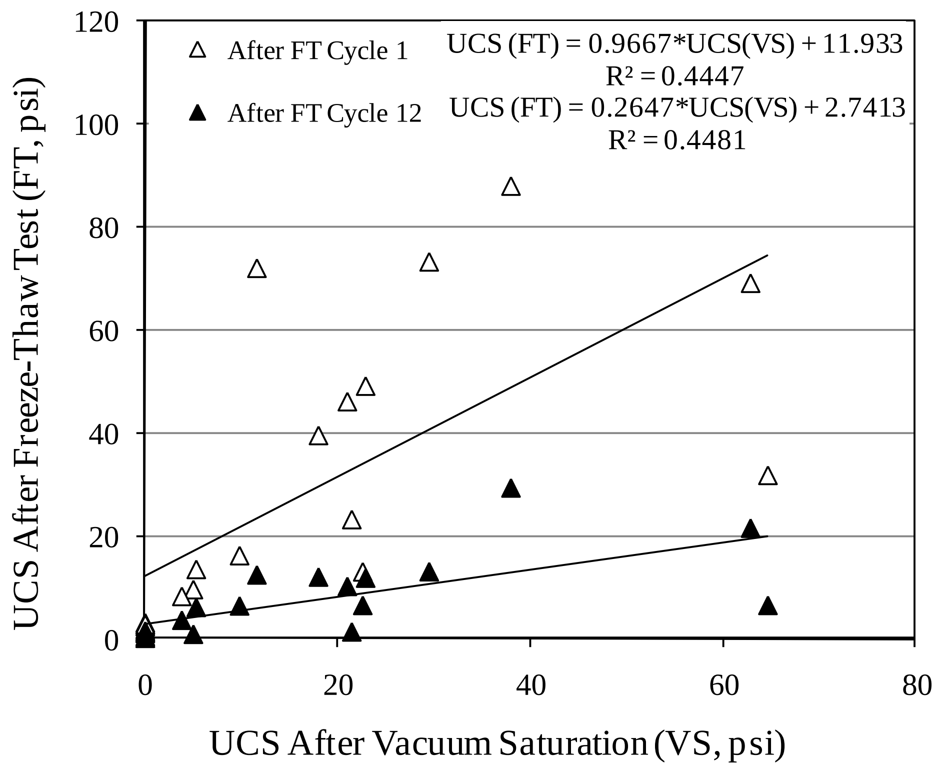


Figure 4.88: Correlations Between UCS At the End of Freeze-Thaw Test and UCS At the End of Vacuum Saturation Test

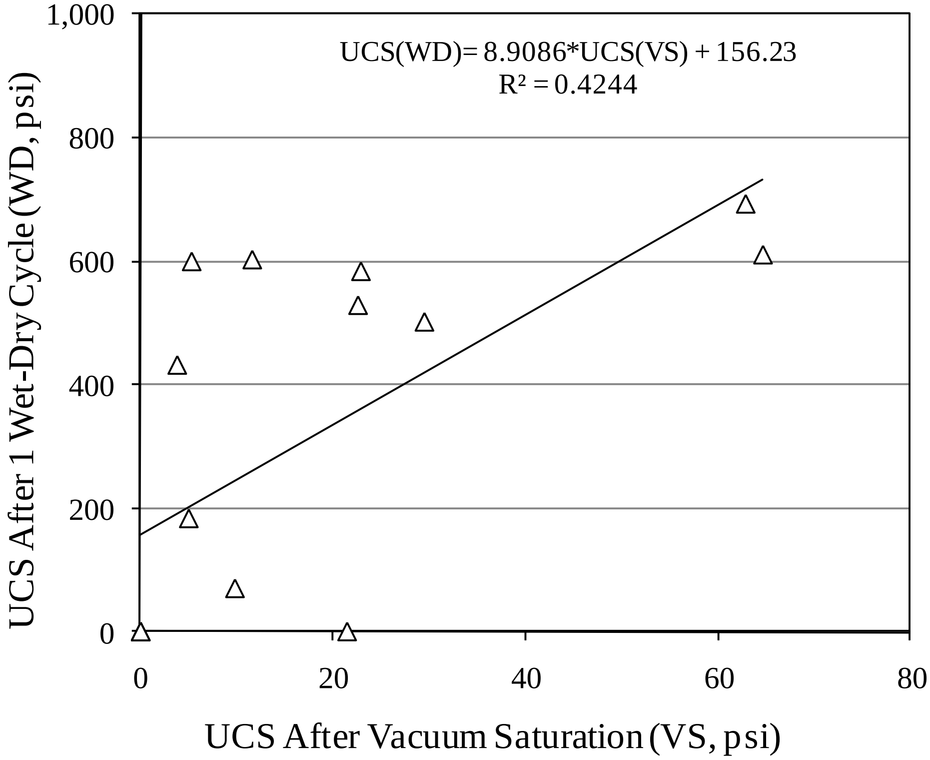


Figure 4.89: Correlations Between UCS At the End of Wet-Dry Test and UCS At the End of Vacuum Saturation Test

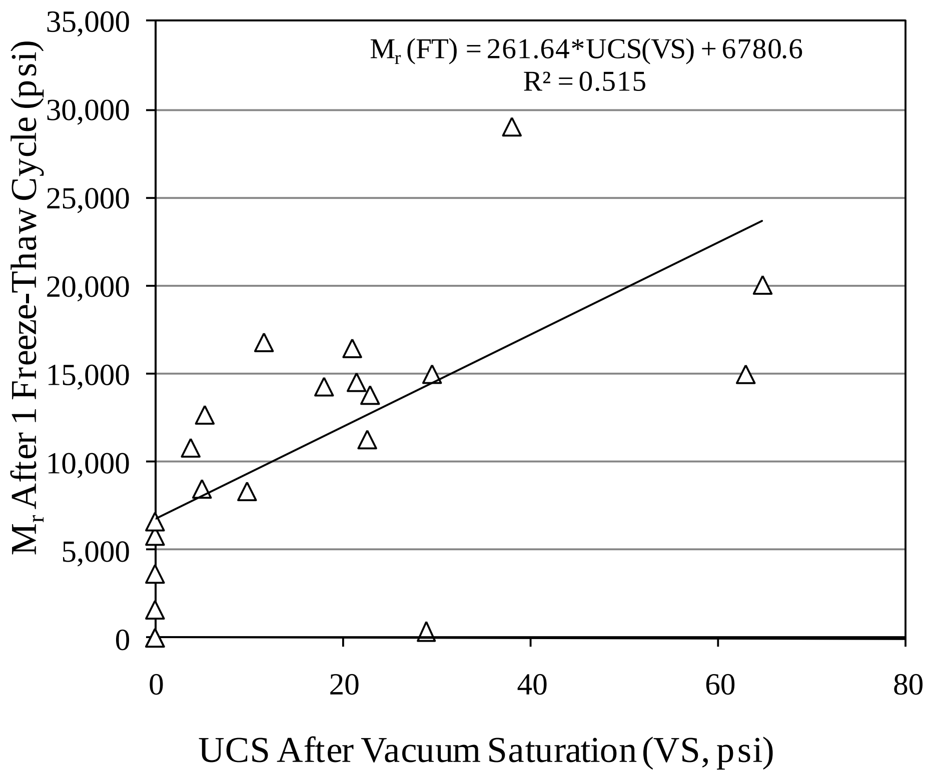


Figure 4.90: Correlations Between M_r At the End of Freeze-Thaw Test and UCS At the End of Vacuum Saturation Test

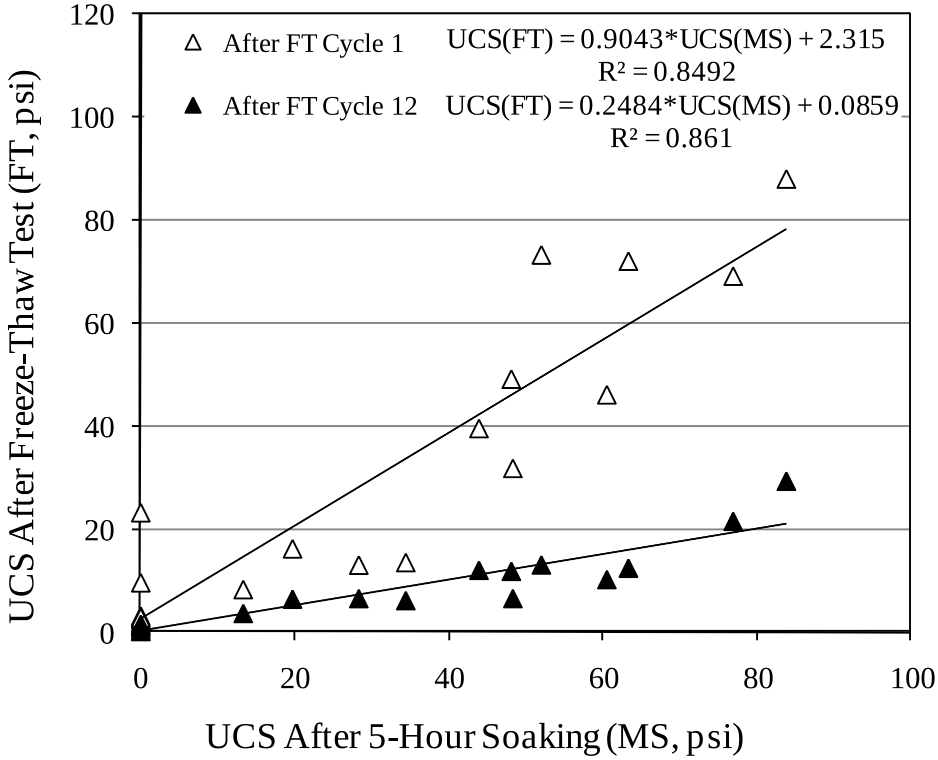


Figure 4.91: Correlations Between UCS At the End of Freeze-Thaw Test and UCS At the End of 5-Hour Soaking Period

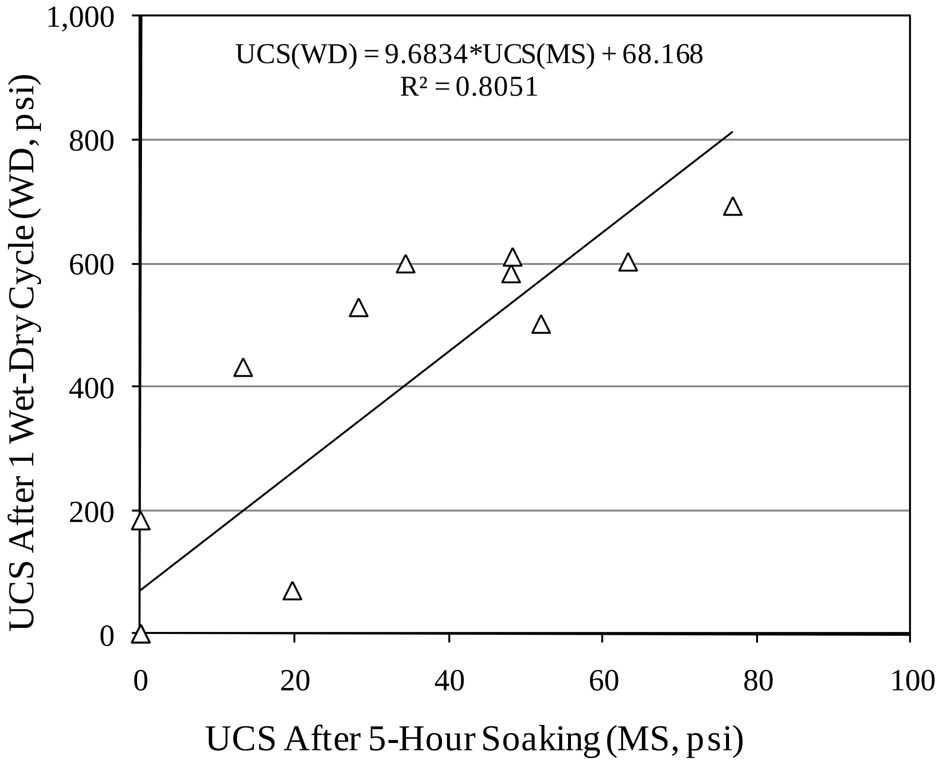


Figure 4.92: Correlations Between UCS At the End of Wet-Dry Test and UCS At the End of 5-Hour Soaking Period

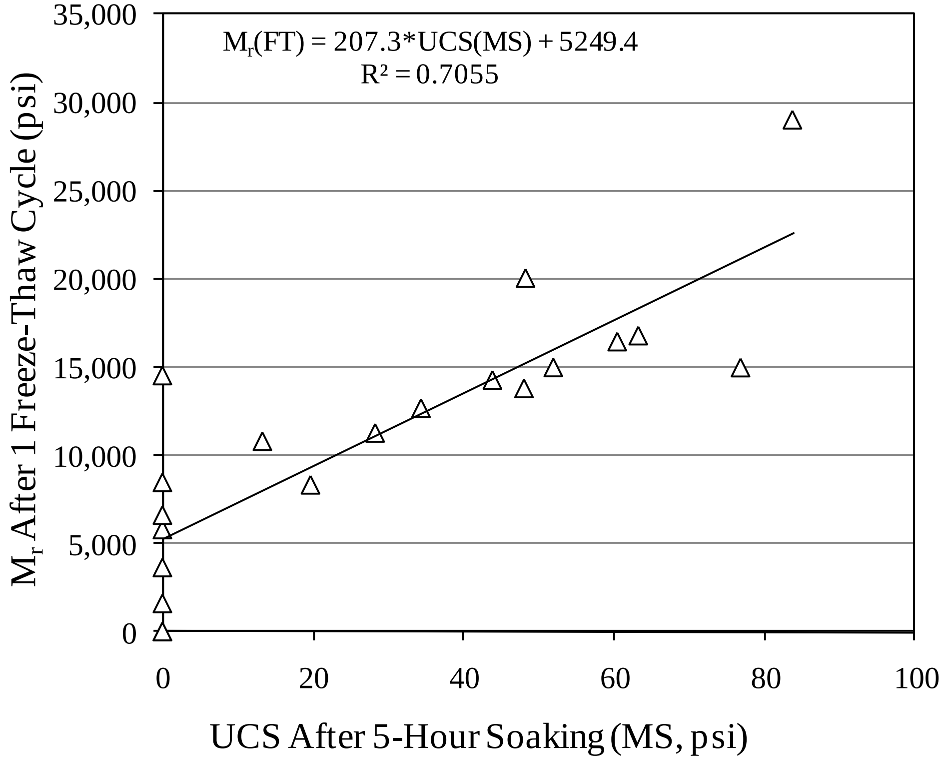


Figure 4.93: Correlations Between M_r At the End of Freeze-Thaw Test and UCS At the End of 5-Hour Soaking Period

CHAPTER 5 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter presents a summary of this study and conclusions drawn from the laboratory testing results and the analyses performed in the preceding chapters. Finally, recommendations for further research are suggested.

5.2 Summary

Strength and stability of subgrade soil, which supports the pavement structure, is a key factor in the pavement performance. Although cementitious stabilization is widely used in Oklahoma to improve subgrade soil properties, effect of freeze-thaw (F-T) and wet-dry (W-D) conditions, referred to as *"durability"* in this project is not frequently addressed. This is partly because the current methods for assessment of durability of cementitiously stabilized subgrade soils are time-consuming and costly. A total of three more time-efficient, inexpensive and non-abrasive test methods, namely, moisture susceptibility, vacuum saturation and tube suction tests are being used in the present study to evaluate durability of selected stabilized soils that are frequently encountered in Oklahoma. Further, the results from the aforementioned tests were compared with the conventional durability test methods, namely, wet-dry (ASTM D 559) and freeze-thaw (ASTM D 560) tests.

In this two year study, a total of five soils commonly encountered as subgrades in Oklahoma, namely, Port series (silty clay with sand), Kingfisher series (lean clay), Carnasaw series (fat clay), Dennis series (fat clay), and Lomill series (fat clay), were utilized. A fairly comprehensive laboratory study was undertaken to determine the durability of these soils when cementitiously stabilized with the selected additives. The laboratory tests conducted included soil classification, moisture-density, unconfined compressive strength (UCS) at the end of F-T or W-D cycles, resilient modulus (M_r) at the end of F-T or W-D cycles, UCS at the end of 5-hour soaking (moisture susceptibility, vacuum saturation, and tube suction tests of both raw and stabilized soil specimens. The soils were stabilized with three locally produced and economically viable cementitious additives used in Oklahoma, namely, hydrated lime (or lime), class C fly ash (CFA), and cement kiln dust (CKD) used at a percentage of 6%, 10% and 10%, respectively.

Cylindrical specimens of two different sizes namely, Harvard miniature and 4 in. x 8 in. were compacted with a target dry density between 95-100% of maximum dry density (MDD), and cured for 7 days in a moist room having a constant temperature (23.0 ± 1.7^{o}C) and a relative humidity of approximately 96%. These specimens were then placed in a F-T chamber and tested in accordance with ASTM D 560 test method. The procedure requires freezing specimens for 24 hours at a temperature not warmer than -23.3^{o}C (-10^{o}F) and thawing for 23 hours at 21.1^{o}C (70^{o}F) and 100 percent relative humidity. Following the specified thawing periods, namely 1, 4, 8, and 12 F-T cycles, the specimens were tested for UCS. Similarly, Harvard miniature specimens were also prepared for conducting UCS tests on specimens subjected to W-D cycles in accordance with ASTM D 559 test method. Each W-D cycle consisted of placing a 7-day cured specimen in a water bath at room temperature for five hours and then placing it in an oven at a temperature of 71^{o}C (160^{o}F) for 42 hours. Following the specified drying period, the specimens were tested for UCS. Cylindrical specimens of bigger size (4 in. x 8 in.) were subjected to F-T or W-D cycles followed by M_r testing after 1, 4, 8, and 12 cycles. All the specimens tested in this study showed a decrease in the UCS values with increase in the number of F-T cycles. It was found that the level of reduction in the UCS values is influenced by the type of soil and type and amount of stabilizing agent. A major loss in strength was observed between 0 and 1 F-T cycle. All the specimens tested in this study, in general, showed an increase in the UCS values at the end of 1 W-D cycle. All raw specimens collapsed during the 1 W-D cycle whereas no stabilized specimens survived beyond 1 W-D cycle. The M_r values of both raw and stabilized soil specimens were found to decrease with an increase in the number of F-T or W-D cycles.

Additional Harvard miniature specimens were tested for UCS after soaking for 5 hours in water. None of the raw specimen survived a 5-hour soaking period of moisture susceptibility test. All stabilized soil specimens tested in this study showed a reduction in UCS values and increase in degree of saturation due to soaking in water for 5 hours, as expected. Raw and stabilized Proctor size specimens (diameter = 4.0 in., height = 4.6 in.) were tested for vacuum saturation by subjecting 7-day cured specimens to a vacuum pressure of 11.8 psi (24 in Hg) for 30 minutes followed by soaking with water for 1 hour. After the saturation period, the water was drained, and the specimens were immediately tested for UCS. All the raw soil specimens collapsed whereas stabilized soil specimens showed a reduction in the UCS values after being subjected to vacuum saturation.

A total of three different methods were used for conducting tube suction tests by taking into account different specimen sizes (4.0 in. x 4.0 in., 6.0 in. x 6.0 in., 4.0 in. x 8.0 in.) and compaction methods (standard Proctor and Superpave gyratory compactor). The final dielectric constant values (DV) measured by conducting tube suction test were found to influence by the method of specimen preparation. The final DVs of all the raw and stabilized specimens tested in this study were above the value of 16. Further, a strong correlation was found between the final DV and moisture content of specimens suggesting that DV is affected by the amount of moisture present in the specimens.

Specimens of different sizes (Harvard miniature, 4.0 in. x 8.0 in) were also tested for UCS at the end of F-T cycles to account for the effect of size on durability. The UCS values of specimens having bigger size (4.0 in x 8.0 in) was found to be lower than the UCS values of corresponding specimens having smaller size (Harvard miniature). Specimens prepared at both OMC and OMC+4% were also tested for UCS and M_r at the end of F-T cycle to study the effect of molding moisture content on durability. It was also found that the UCS (or M_r) values of specimens compacted at OMC is higher than the UCS (or M_r) values of corresponding specimens compacted at OMC+4%.

Further, attempts were made to observe the correlations among the different durability tests conducted in this study. Moisture susceptibility test results showed better correlations with other durability indicators such as retained UCS after 1 F-T cycle, retained UCS after 1 W-D cycle, and retained M_r after 1 F-T cycle. This is an indication that moisture susceptibility could be used for evaluating durability of stabilized soil specimens because of the shorter test duration, low cost, and lack of a need for daily specimens monitoring. Specific conclusions and recommendations from this study are given below.

5.3 Conclusions

From the laboratory tests and analyses of data presented in the preceding chapters, the following conclusions can be drawn:

1. All the specimens tested in this study showed a decrease in the UCS values with increase in the number of F-T cycles. Such a decrease could be explained by the increase in moisture absorbed by specimens during the thawing portion of the cycle and pore

structure of the stabilized specimens. The level of reduction in the UCS values was influenced by the type of soil and type and amount of stabilizing agent.

2. A major loss in strength was observed between 0 and 1 F-T cycle. The percentage reduction in UCS values due to application of 1 F-T cycle was found between 33 – 57%, 40 – 69%, 62 – 97%, 74 – 89%, and 45 – 92% for stabilized specimens of Port, Kingfisher, Carnasaw, Dennis, and Lomill soils, respectively.
3. All the specimens tested in this study, in general, showed an increase in the UCS values at the end of 1 W-D cycle. The increase in UCS values can be explained by the drying phase where the moisture content in the specimen is decreased to levels below 1%, eliminating the effect of pore water in the specimens. All raw specimens collapsed during the 1 W-D cycle whereas no stabilized specimens survived beyond 1 W-D cycle.
4. The M_r values of both raw and stabilized soil specimens were found to decrease with an increase in the number of F-T cycles. It was also found that the percentage reduction in M_r values between 0 – 1 F-T cycle is higher than the reduction in M_r values between other F-T cycles.
5. The M_r values were observed to decrease due to the application of W-D cycle for all the stabilized specimens tested in this study. No raw specimen survived 1 W-D cycle. Also, all stabilized specimens failed during the application of 2 W-D cycles.
6. None of the raw specimen survived a 5-hour soaking period of moisture susceptibility test. All stabilized soil specimens tested in this study showed a reduction in UCS values due to soaking in water for 5 hours. The percentage decrease in UCS values due to 5-hour soaking was found between 11 – 52%, 58 – 70%, 100%, 60 – 87%, and 51 – 86% for

stabilized specimens of Port, Kingfisher, Carnasaw, Dennis, and Lomill soils, respectively.

7. Degree of saturation increased in all the stabilized specimens due to 5-hour soaking. The percentage increase in degree of saturation was found between 4.5 – 5.7%, 4.9 – 13.7%, 6.5 – 10.6%, and 2.4 – 10.6% for stabilized specimens of Port, Kingfisher, Dennis, and Lomill soils, respectively.
8. All the raw soil specimens collapsed during the 1-hour soaking period in vacuum saturation tests. All stabilized soil specimens showed a reduction in the UCS values after being subjected to vacuum saturation. The percentage decrease in UCS values due to vacuum saturation was found to be between 45 – 55%, 38 – 66%, 54 – 100%, 35 – 84%, and 86 – 94% for stabilized specimens of Port, Kingfisher, Carnasaw, Dennis, and Lomill soils, respectively.
9. The final dielectric constant values measured by conducting tube suction test are influenced by the method of specimen preparation. However, final DV is not affected by the specimen size, as evident from similar results obtained by using Method-2 and Method-3.
10. The final DVs of all the raw and stabilized specimens tested in this study were above the value of 16. Thus, the maximum DV criterion (Guthrie and Scullion, 2003) for selecting durable aggregate base material seems more conservative for raw and stabilized soil specimens.
11. A strong correlation ($R^2 = 0.70$) was found between the final DV and moisture content of specimens suggesting that DV is affected by the amount of moisture present in the specimens.

12. The UCS values of specimens having bigger size (4.0 in x 8.0 in) was found to be lower than the UCS values of corresponding specimens having smaller size (Harvard miniature specimens, 1.3 in x 2.8 in). The UCS values of 4.0 in x 8.0 in specimens was found approximately 22%, 83%, 13%, and 61% lower than the UCS values of corresponding smaller specimens of Carnasaw soil stabilized with 0%, 6% lime-, 10% CFA-, and 10% CKD, respectively.
13. It was found that the UCS (or M_r) values of specimens compacted at OMC is higher than the UCS (or M_r) values of corresponding specimens compacted at OMC+4%. However, the difference in values is higher for specimens tested without any F-T cycle than corresponding specimens tested at the end of 1 F-T cycle.
14. Overall, the Port series soil specimens (silty clay with sand) stabilized with 10% CKD offered maximum resistance towards F-T and W-D cycles. A similar trend of behavior is evident from the results obtained by moisture susceptibility and vacuum saturation tests where the Port series soil specimens stabilized with 10% CKD produced the highest retained UCS values.
15. The Kingfisher series soil specimens (lean clay) did not show any clear trend with one particular additive. However, specimens stabilized with 6% lime and 10% CKD showed better performance, as compared to specimens stabilized with 10% CFA.
16. All three fat clays used in this study (Carnasaw, Dennis, and Lomill) showed maximum resistance towards F-T and W-D cycles after stabilizing with 6% lime as compared to 10% CFA and 10% CKD. This fact was also evident from both moisture susceptibility and vacuum saturation tests.

17. On the contrary to other durability tests (namely, retained UCS/M_r after F-T cycle, retained UCS after W-D cycle, vacuum saturation, moisture susceptibility), final DVs indicated that stabilization with 10% CFA is more effective in reducing the DV of Port soil specimens. Also, tube suction test showed contrary behavior by indicating lime- and CFA-stabilization providing more or less same degree of effectiveness in reducing the DVs for Lomill soil specimens.
18. Kingfisher, Carnasaw, Dennis, and Lomill soil specimens showed more effectiveness with 6% lime by decreasing the DVs of corresponding specimens by 20%, 15%, 12%, and 9%, respectively.
19. Raw and stabilized Carnasaw soil (fat clay) specimens showed worst performance among all the soils tested in this study. This could be attributed to the acidic nature of Carnasaw soil (pH = 4.17), which will decrease the rate of cementitious reactions.
20. A weak correlation ($R^2 < 0.2$) between DV and other durability indicators such as retained UCS after 1 F-T cycle, retained UCS after 1 W-D cycle, and retained M_r after 1 F-T cycle is evident from this study.
21. The test results indicated that the 12 F-T cycles are more severe than the vacuum saturation test for the particular soils used in this study. Also, a moderate level ($R^2 = 0.44$) of correlation exists between UCS values retained after vacuum saturation and F-T cycles.
22. A moderate level of correlation ($R^2 \approx 0.40 – 0.50$) between retained UCS after vacuum saturation test and other durability indicators such as retained UCS after 1 F-T cycle, retained UCS after 1 W-D cycle, and retained M_r after 1 F-T cycle is evident from this study.

23. For all the soils used in this study, the application of 12 F-T cycles are more severe than the moisture susceptibility test. Also, a strong ($R^2 > 0.8$) correlation exists between UCS values retained after moisture susceptibility test and F-T cycles.
24. A strong correlation ($R^2 \approx 0.70 – 0.86$) between retained UCS after moisture susceptibility test and other durability indicators such as retained UCS after 1 F-T cycle, retained UCS after 1 W-D cycle, and retained M_r after 1 F-T cycle is evident from this study. This is an indication that moisture susceptibility could be used for evaluating long-term performance of stabilized soil specimens.

5.4 Recommendations

Based on the laboratory test results and discussion presented in the preceding chapters, the following recommendations are suggested by the research team:

1. The moisture susceptibility test is recommended over F-T cycle, vacuum saturation and tube suction tests for evaluating durability because of the shorter test duration, low cost, and lack of a need for daily specimen monitoring.
2. It is important to note that the quality of additives (CFA and CKD) can vary significantly from plant to plant (Ferguson and Levorson 1999, Miller and Zaman 2000, ACAA 2003, Peethamparan and Olek, 2008), resulting in different long-term performance. This can pose a major problem for adopting a pavement construction specification for general use of CFA and CKD. Therefore, it is suggested that a proper mix design with locally available cementitious additives be conducted. Such mix designs, including the type and amount of additive, will ensure compatibility and satisfactory performance.
3. Further research is recommended for developing appropriate thresholds for laboratory test values in conjunction with actual field performance of corresponding soil-additive mix.

The field performance of stabilized subgrade layer under freeze-thaw and wet-dry cycles could be partly simulated in an accelerated pavement testing facility (e.g., Accelerated Load Facility at Louisiana Transportation Research Center, Wu et al., 2009).

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APPENDIX A: Photographic View of Specimens Tested for UCS at the End of Freeze-Thaw Cycles

Figure A 1: Harvard Miniature Port Specimens at the End of 0 Freeze-Thaw Cycles before UCS (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 2: Harvard Miniature Port Specimens at the End of 0 Freeze-Thaw Cycles After UCS (From Left to Right: Raw, Lime, CFA, CKD)

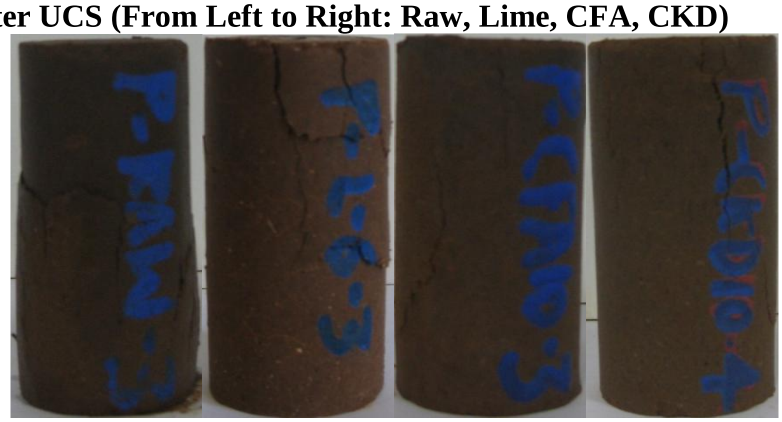

Figure A 3: Harvard Miniature Port Specimens at the End of 1 Freeze-Thaw Cycle After UCS (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 4: Harvard Miniature Port Specimens at the End of 4 Freeze-Thaw Cycles After UCS (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 5: Harvard Miniature Port Specimens at the End of 8 Freeze-Thaw Cycles After UCS (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 6: Harvard Miniature Port Specimens at the End of 12 Freeze-Thaw Cycles After UCS (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 7: Harvard Miniature Kingfisher Specimens at the End of 0 Freeze-Thaw Cycles Before UCS. (From Left to Right: Raw, Lime, CFA, CKD)

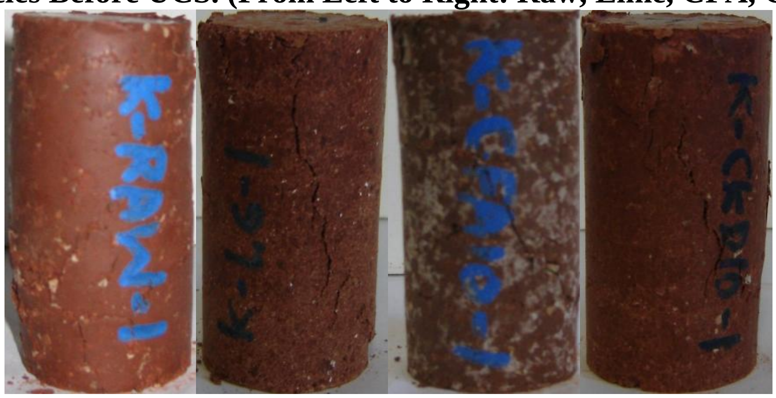

Figure A 8: Harvard Miniature Kingfisher Specimens at the End of 0 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 9: Harvard Miniature Kingfisher Specimens at the End of 1 Freeze-Thaw Cycle After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 10: Harvard Miniature Kingfisher Specimens at the End of 4 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 11: Harvard Miniature Kingfisher Specimens at the End of 8 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

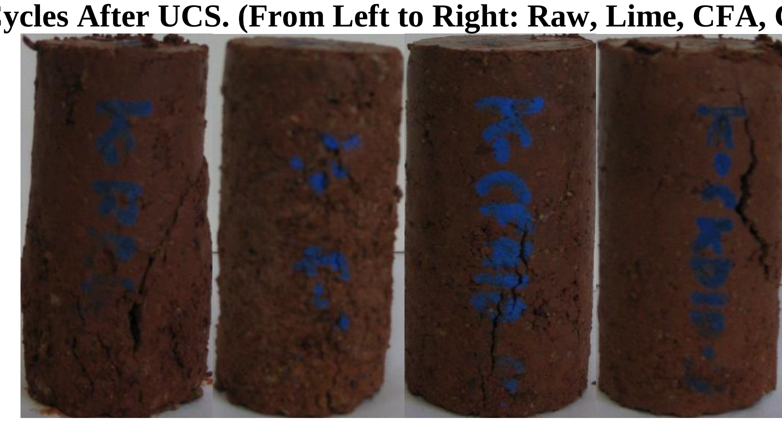

Figure A 12: Harvard Miniature Kingfisher Specimens at the End of 12 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 13: Harvard Miniature Carnasaw Specimens at the End of 0 Freeze-Thaw Cycles Before UCS. (From Left to Right: Raw, Lime, CFA, CKD)

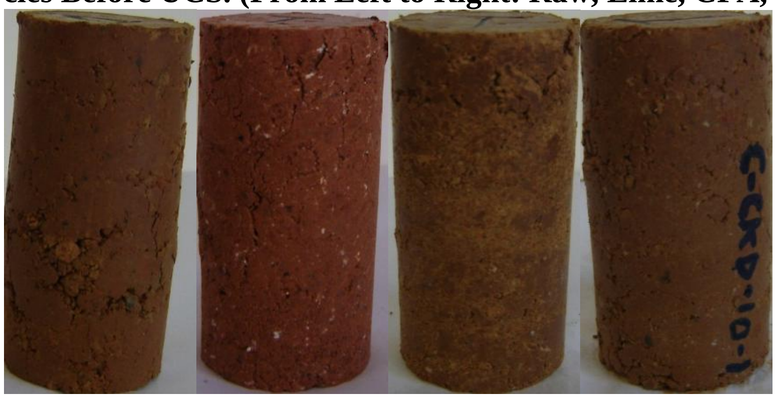

Figure A 14: Harvard Miniature Carnasaw Specimens at the End of 0 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 15: Harvard Miniature Carnasaw Specimens at the End of 1 Freeze-Thaw Cycle After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 16: Harvard Miniature Carnasaw Specimens at the End of 4 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

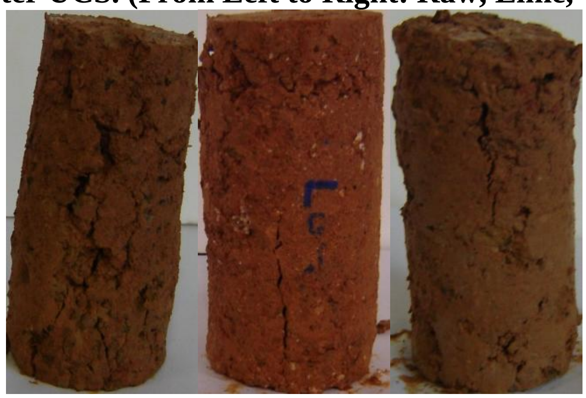

Figure A 17: Harvard Miniature Carnasaw Specimens at the End of 8 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CKD)

Figure A 18: Harvard Miniature Carnasaw Specimens at the End of 12 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 19: Harvard Miniature Dennis Specimens at the End of 0 Freeze-Thaw Cycles Before UCS. (From Left to Right: Raw, Lime, CFA, CKD)

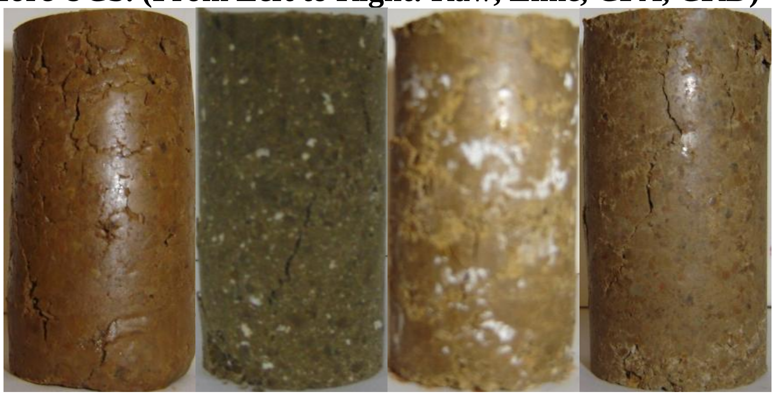

Figure A 20: Harvard Miniature Dennis Specimens at the End of 0 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 21: Harvard Miniature Dennis Specimens at the End of 1 Freeze-Thaw Cycle After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 22: Harvard Miniature Dennis Specimens at the End of 4 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 23: Harvard Miniature Dennis Specimens at the End of 8 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 24: Harvard Miniature Dennis Specimens at the End of 12 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 25: Harvard Miniature Lomill Specimens at the End of 0 Freeze-Thaw Cycles Before UCS. (From Left to Right: Raw, Lime, CFA, CKD)

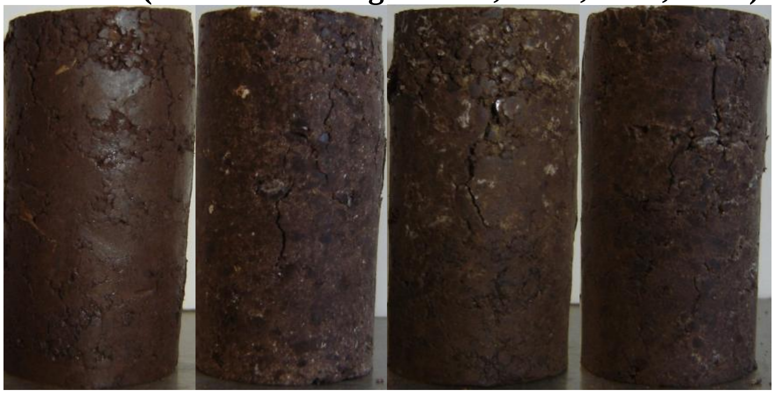

Figure A 26: Harvard Miniature Lomill Specimens at the End of 0 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 27: Harvard Miniature Lomill Specimens at the End of 1 Freeze-Thaw Cycle After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 28: Harvard Miniature Lomill Specimens at the End of 4 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 29: Harvard Miniature Lomill Specimens at the End of 8 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

Figure A 30: Harvard Miniature Lomill Specimens at the End of 12 Freeze-Thaw Cycles After UCS. (From Left to Right: Raw, Lime, CFA, CKD)

APPENDIX B: Photographic View of Specimens Tested for UCS at the End of Wet-Dry Cycles

Figure B 1: Harvard Miniature Kingfisher Specimens Before 1 Wet-Dry Cycle. (From Left to Right: Raw, Lime, CFA, CKD)

Figure B 2: Harvard Miniature Kingfisher Specimens After 1 Wet-Dry cycle at the End of 5 Hours of Soaking Period. (From Left to Right: Raw, Lime, CFA, CKD)

Figure B 3: Harvard Miniature Kingfisher Specimens After 1 Wet-Dry Cycle at the End of 42 Hours of Drying Period. (From Left to Right: Lime, CFA, CKD)

Figure B 4: Harvard Miniature Kingfisher Specimens After 1 Wet-Dry Cycle After UCS. (From Left to Right: Lime, CFA, CKD)

Figure B 5: Harvard Miniature Kingfisher Specimens Before 2 Wet-Dry Cycles. (From Left to Right: Lime, CFA, CKD)

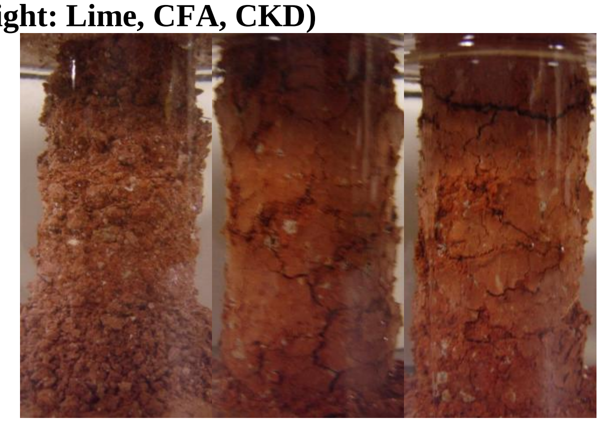

Figure B 6: Harvard Miniature Kingfisher Specimens After 2 Wet-Dry Cycles at the End of 5 Hours of Soaking Period. (From Left to Right: Lime, CFA, CKD)

Figure B 7: Harvard Miniature Carnasaw Specimens Before 1Wet-Dry Cycle. (From Left to Right: Lime, CFA, CKD)

Figure B 8: Harvard Miniature Carnasaw Specimens After 1 Wet-Dry Cycle at the End of 5 Hours of Soaking Period. (From Left to Right: Lime, CFA, CKD)

Figure B 9: Harvard Miniature Dennis Specimens Before 1Wet-Dry Cycle. (From Left to Right: Raw, Lime, CFA, CKD)

Figure B 10: Harvard Miniature Dennis Specimens After 1 Wet-Dry Cycle at the End of 5 Hours of Soaking Period. (From Left to Right: Lime, CFA, CKD)

Figure B 11: Harvard Miniature Dennis Specimens After 1 Wet-Dry Cycle at the End of 42 Hours of Drying Period. (From Left to Right: Lime, CFA, CKD)

Figure B 12: Harvard Miniature Dennis Specimens After 1 Wet-Dry Cycle After UCS. (From Left to Right: Lime, CFA, CKD)

Figure B 13: Harvard Miniature Dennis Specimens Before 2 Wet-Dry Cycles. (From Left to Right: Lime, CFA, CKD)

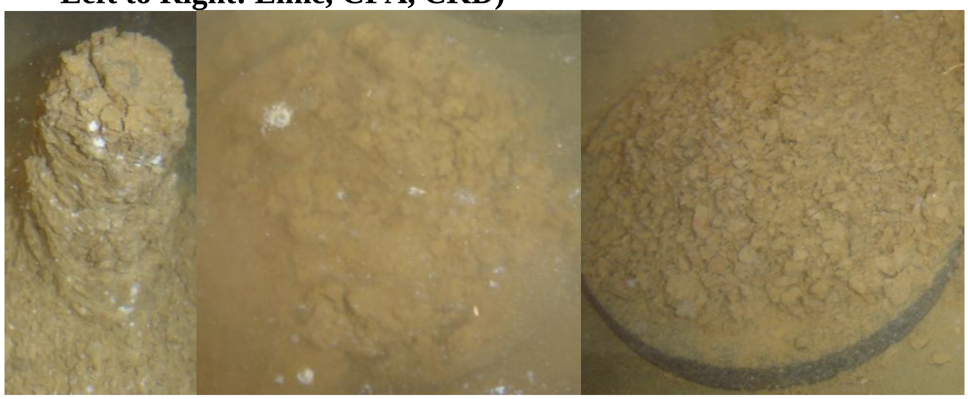

Figure B 14: Harvard Miniature Dennis Specimens After 2 Wet-Dry Cycles at the End of 5 Hours of Soaking Period. (From Left to Right: Lime, CFA, CKD)

Figure B 15: Harvard Miniature Lomill Specimens Before 1Wet-Dry Cycle. (From Left to Right: Raw, Lime, CFA, CKD)

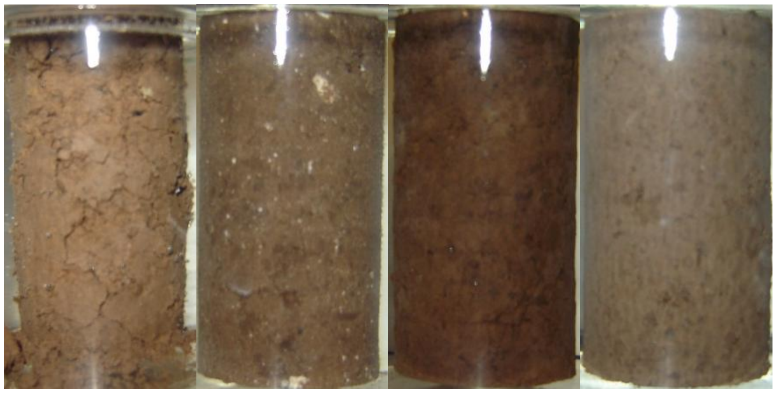

Figure B 16: Harvard Miniature Lomill Specimens After 1 Wet-Dry Cycle at the End of 5 Hours of Soaking Period. (From Left to Right: Raw, Lime, CFA, CKD)

Figure B 17: Harvard Miniature Lomill Specimens After 1 Wet-Dry Cycle at the End of 42 Hours of Drying Period. (From Left to Right: Lime, CFA, CKD)

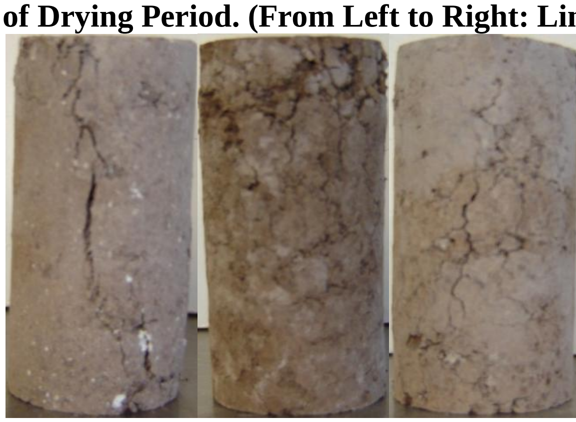

Figure B 18: Harvard Miniature Lomill Specimens After 1 Wet-Dry Cycle After UCS. (From Left to Right: Lime, CFA, CKD)

APPENDIX C: Photographic View of Specimens Tested for M_r at the End of F-T Cycles

Figure C 1: Port Specimens Tested for M_r at the End of 0 Freeze-Thaw Cycles (From Left to Right: Raw, Lime, CFA, CKD)

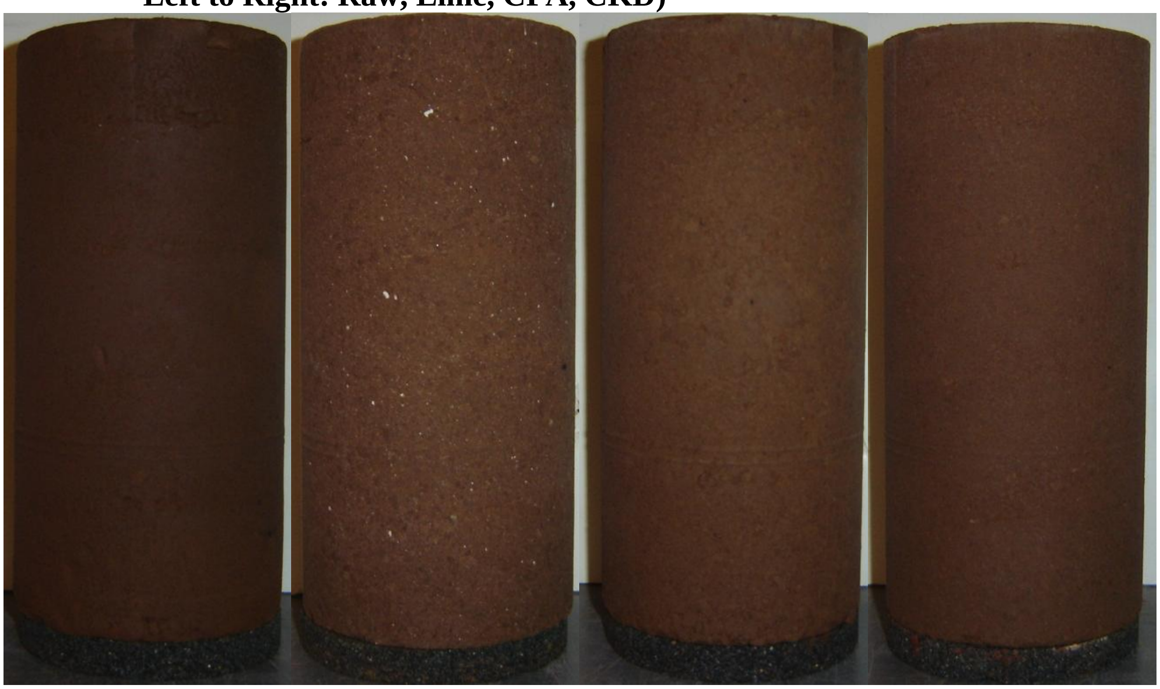

Figure C 2: Port Specimens Tested for M_r at the End of 1 Freeze-Thaw Cycle (From Left to Right: Raw, Lime, CFA, CKD)

Figure C 3: Port Specimens Tested for M_r at the End of 4 Freeze-Thaw Cycles (From Left to Right: Lime, CFA, CKD)

Figure C 4: Port Specimens Tested for M_r at the end of 8 Freeze-Thaw Cycles (From Left to Right: Lime, CKD; CFA Failed Before Test in Cycle 8)

Figure C 5: Kingfisher Specimens Tested for M_r at the end of 0 Freeze-Thaw Cycles (From Left to Right: Raw, Lime, CFA, CKD)

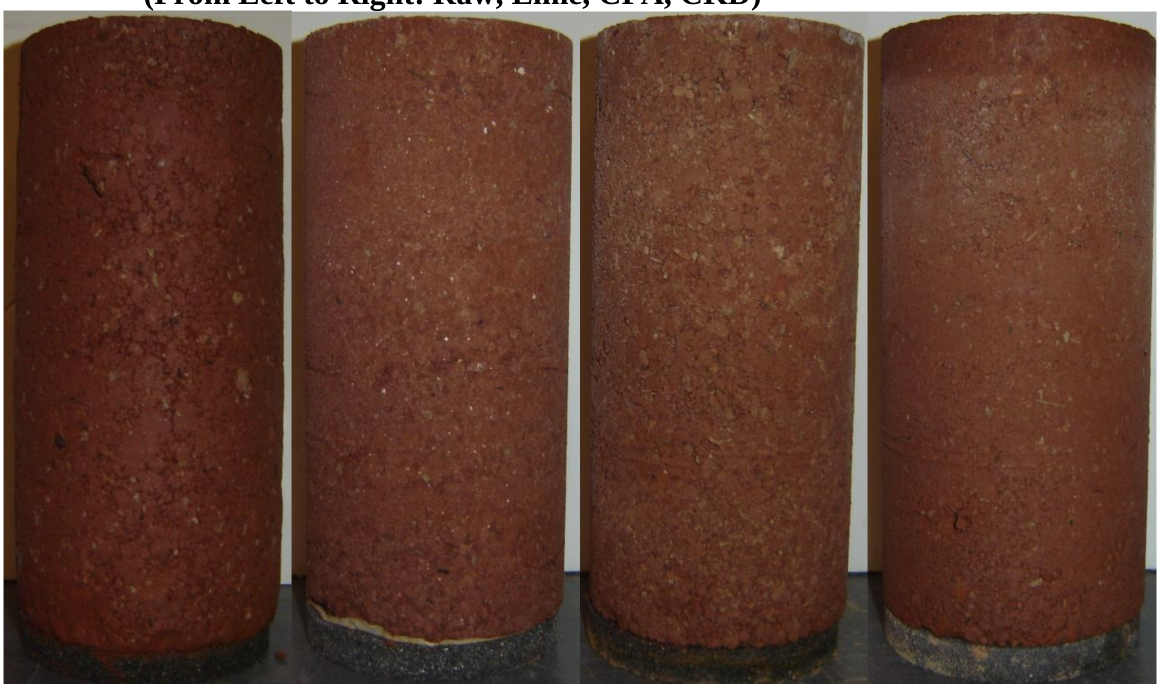

Figure C 6: Kingfisher Specimens Tested for M_r at the end of 1 Freeze-Thaw Cycle (From Left to Right: Raw, Lime, CFA, CKD)

Figure C 7: Kingfisher Specimens Tested for M_r at the end of 4 Freeze-Thaw Cycles (From Left to Right: Lime, CFA, CKD)

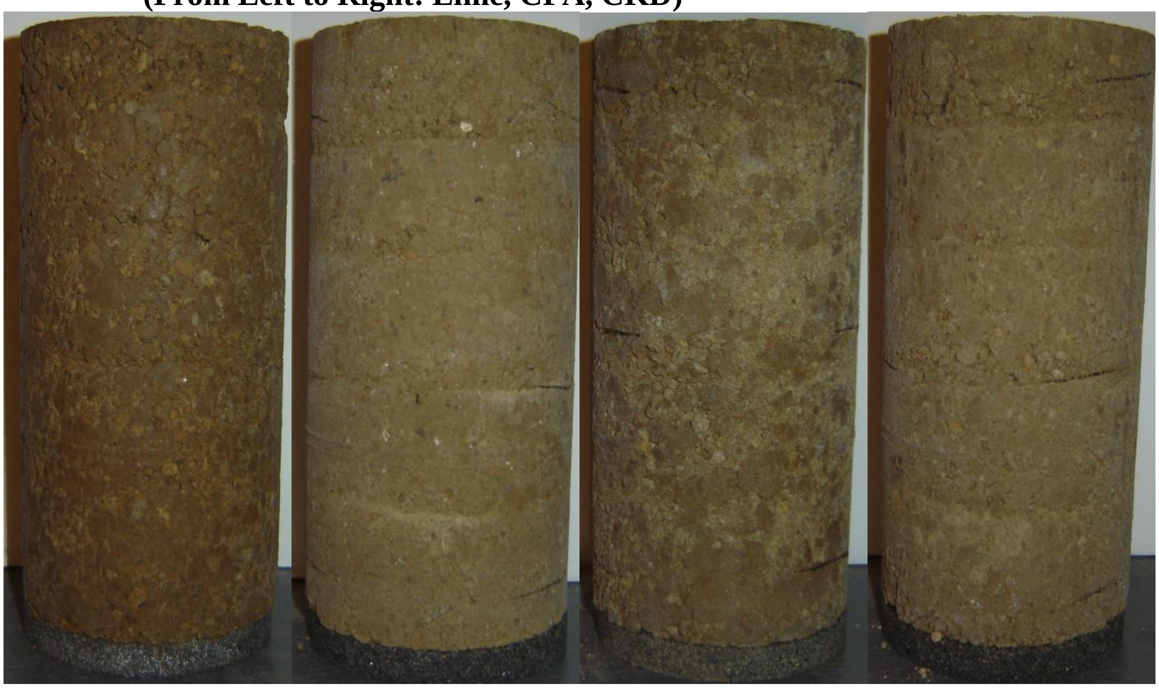

Figure C 8: Dennis Specimens Tested for M_r at the end of 0 Freeze-Thaw Cycles (From Left to Right: Raw, Lime, CFA, CKD)

Figure C 9: Dennis Specimens Tested for M_r at the End of 1 Freeze-Thaw Cycle (From Left to Right: Raw, Lime, CFA, CKD)

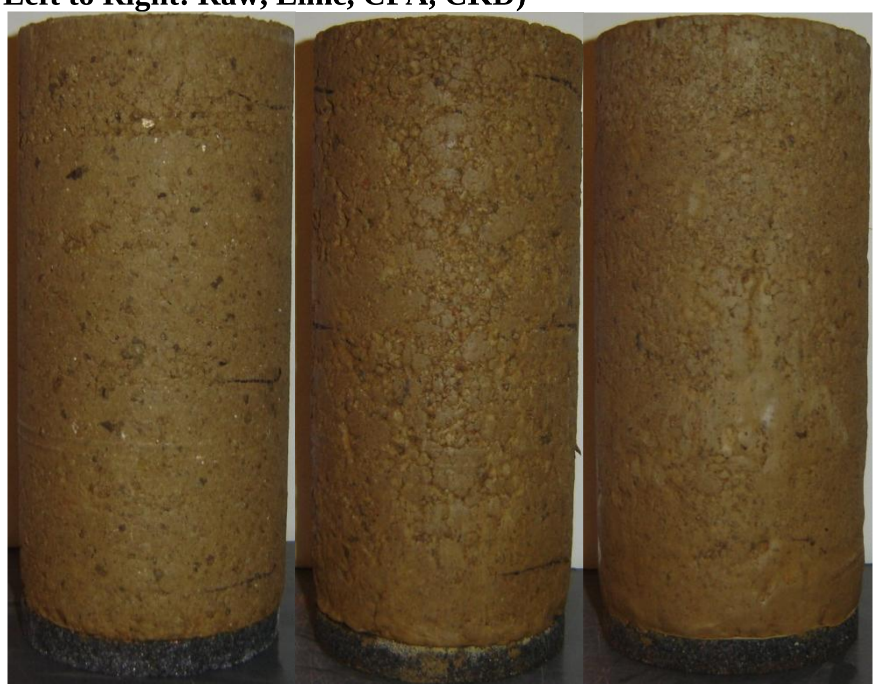

Figure C 10: Dennis Specimens Tested for M_r at the End of 4 Freeze-Thaw Cycles (From Left to Right: Lime, CFA, CKD)

Figure C 11: Lomill Specimens Tested for M_r at the End of 0 Freeze-Thaw Cycles (From Left to Right: Raw, Lime, CFA, CKD)

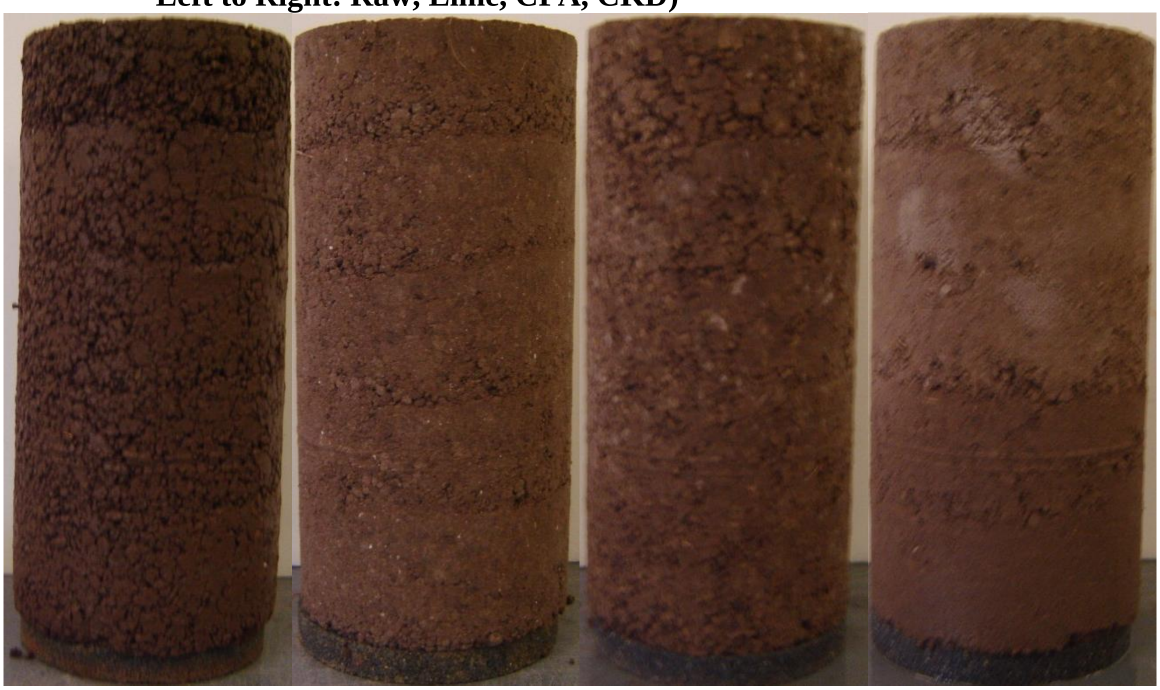

Figure C 12: Dennis Specimens Tested for M_r at the End of 1 Freeze-Thaw Cycle (From Left to Right: Raw, Lime, CFA, CKD)

Figure C 13: Dennis Specimens Tested for M_r at the End of 4 Freeze-Thaw Cycles (From Left to Right: Lime, CFA, CKD)

Figure C 14: Dennis Specimens Tested for M_r at the End of 8 Freeze-Thaw Cycles (From Left to Right: Lime, CFA)

APPENDIX D: Photographic View of Specimens Tested for M_r at the End of Wet-Dry Cycles

Figure D 1: Kingfisher Specimens Tested for M_r after 0 Wet-Dry Cycles (From Left to Right: Raw, Lime, CFA, CKD)

Figure D 2: Kingfisher Specimens Tested for M_r After 1 Wet-Dry Cycle (From Left to Right: Lime, CFA, CKD)

Figure D 3: Kingfisher Specimens Failed Before M_r After 2 Wet-Dry Cycles (From Left to Right: Lime, CFA, CKD)

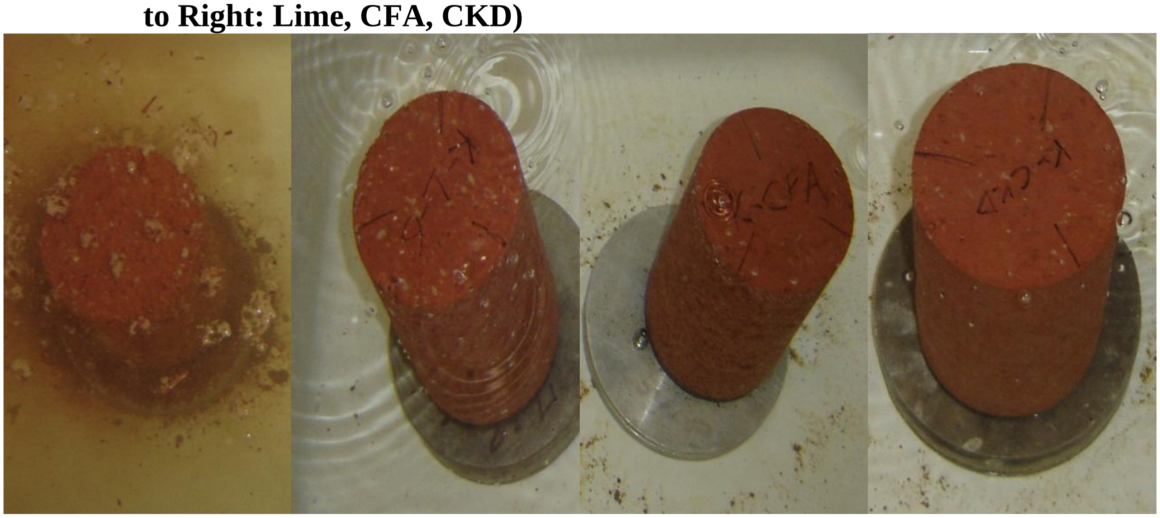

Figure D 4: Kingfisher Specimens in Water During 1 Wet-Dry Cycle (From Left to Right: Raw, Lime, CFA, CKD)

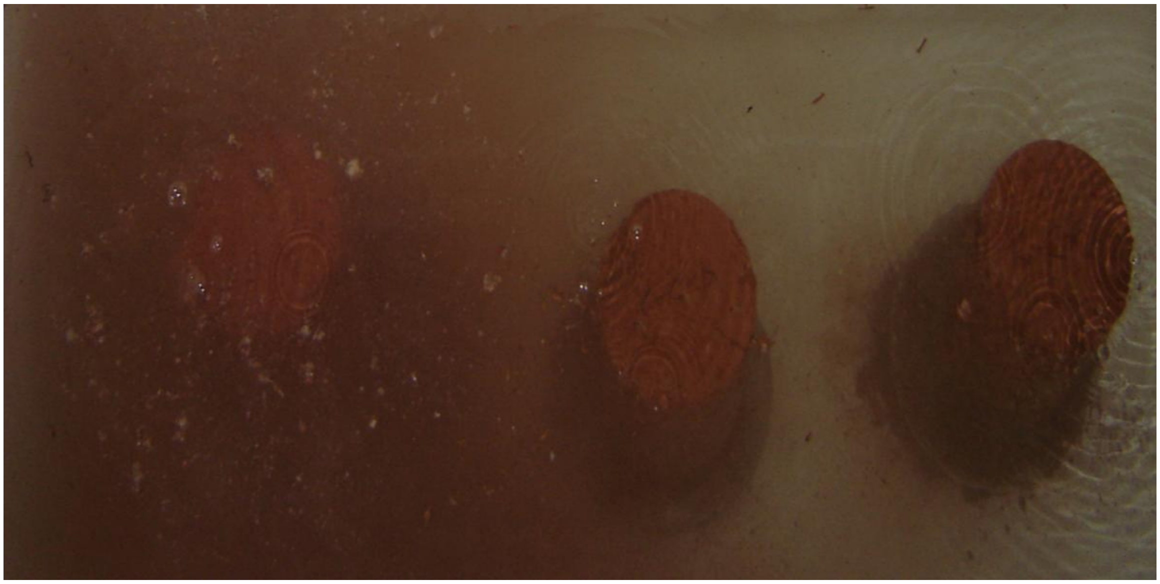

Figure D 5: Kingfisher Specimens in Water during 2 Wet-Dry Cycles (From Left to Right: Lime, CFA, CKD)

Figure D 6: Kingfisher Specimens in Oven during 2 Wet-Dry Cycles (From Left to Right: Lime, CFA, CKD)

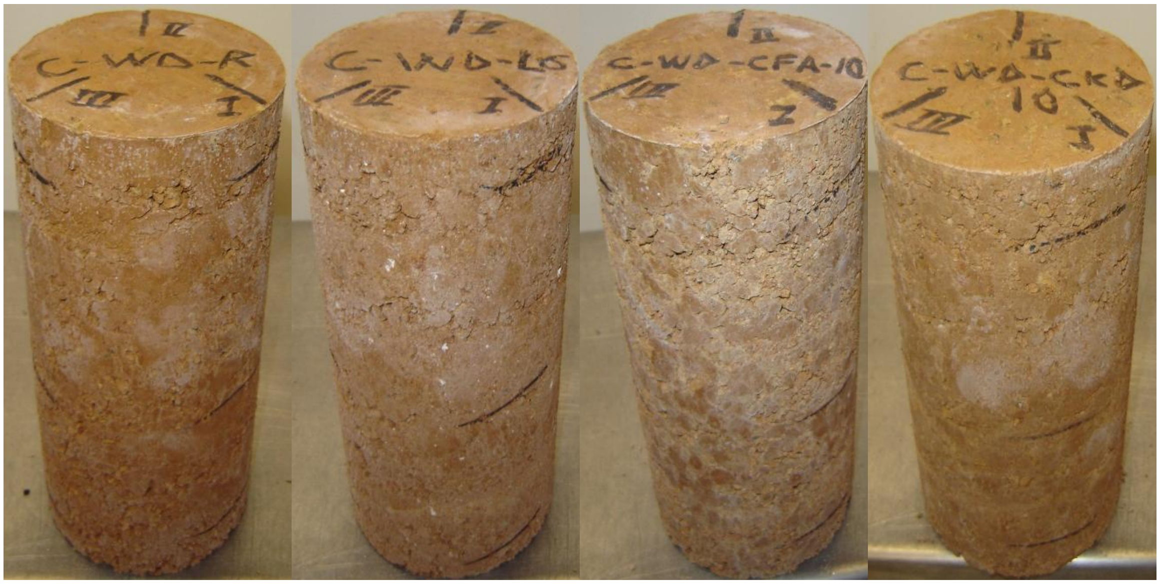

Figure D 7: Carnasaw Specimens Tested for M_r at the End of 0 Wet-Dry Cycles (From Left to Right: Raw, Lime, CFA, CKD)

Figure D 8: Carnasaw Specimens Tested for M_r After 1 Wet-Dry Cycle (From Left to Right: Lime, CKD)

Figure D 9: Carnasaw Specimens in Water During 1 Wet-Dry Cycle (From Left to Right: Raw, Lime, CFA, CKD)

Figure D 10: Dennis Specimens Tested for M_r after 0 Wet-Dry Cycles (From Left to Right: Raw, Lime, CFA, CKD)

Figure D 11: Dennis Specimens in Water during 1 Wet-Dry Cycle (From Left to Right: Raw, Lime, CFA, CKD)

Figure D 12: Dennis Specimens Tested for M_r after 1 Wet-Dry Cycle (From Left to Right: Lime, CFA, CKD)

Figure D 13: Dennis Specimens in Oven during 1 Wet-Dry Cycle (From Left to Right: Lime, CFA, CKD)

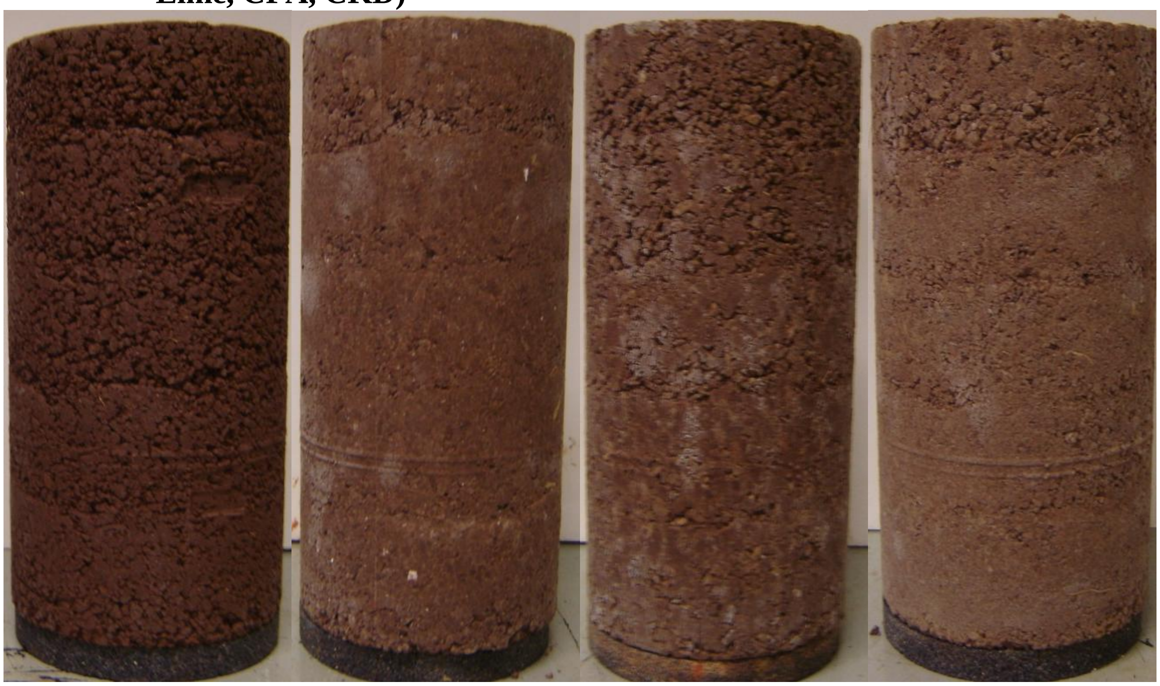

Figure D 14: Lomill Specimens Tested for M_r After 0 Wet-Dry Cycles (From Left to Right: Raw, Lime, CFA, CKD)

Figure D 15: Lomill Specimens in Water during 1 Wet-Dry Cycle (From Left to Right: Raw, Lime, CFA, CKD)

Figure D 16: Lomill Specimens After 5 Hour Soaking During 1 Wet-Dry Cycle (From Left to Right: Raw, Lime, CFA, CKD)

Figure D 17: Lomill Specimens During 1 Wet-Dry Cycle During Oven Drying (From Left to Right: Lime, CFA, CKD)

Figure D 18: Lomill Specimens after 42 Hour Oven Drying During 1 Wet-Dry Cycle (From Left to Right: Lime, CFA, CKD)

APPENDIX E: Photographic View of Specimens Tested for Moisture Susceptibility

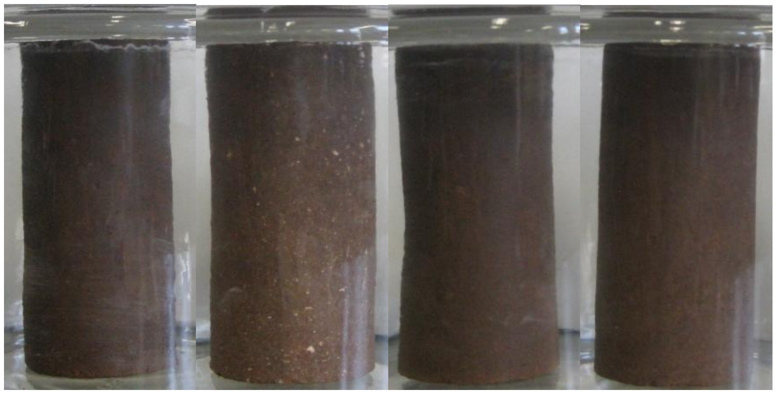

Figure E 1: Port Specimens at the Beginning of 5 Hours of Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

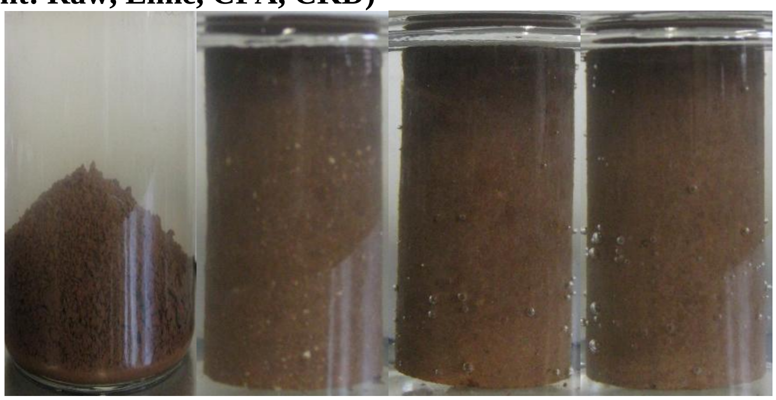

Figure E 2: Port Specimens at the End of 5 Hours of Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

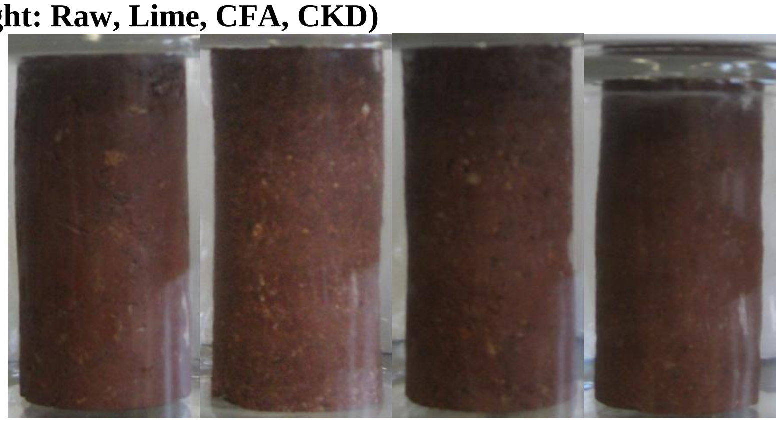

Figure E 3: Kingfisher Specimens at the Beginning of 5 Hours of Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

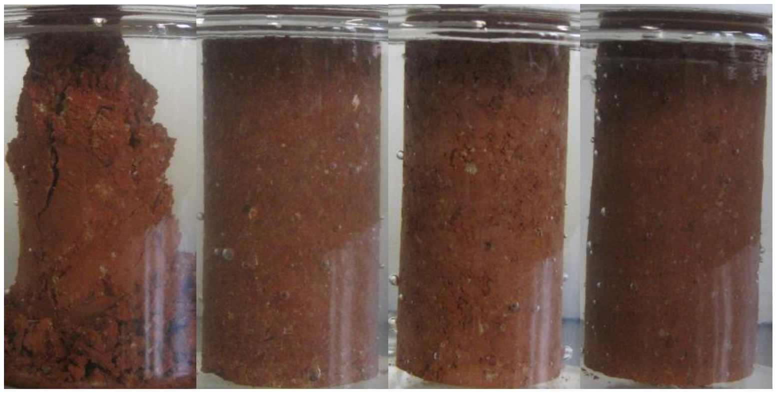

Figure E 4: Kingfisher Specimens at the End of 5 Hours of Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

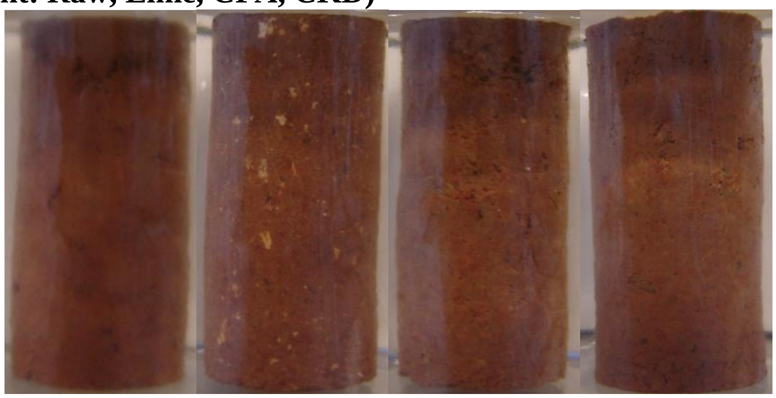

Figure E 5: Carnasaw Specimens at the Beginning of 5 Hours of Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

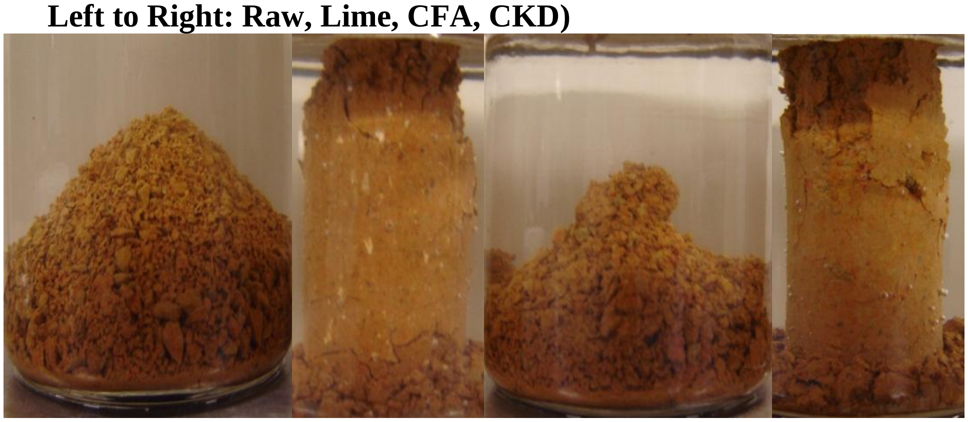

Figure E 6: Carnasaw Specimens at the End of 5 Hours of Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

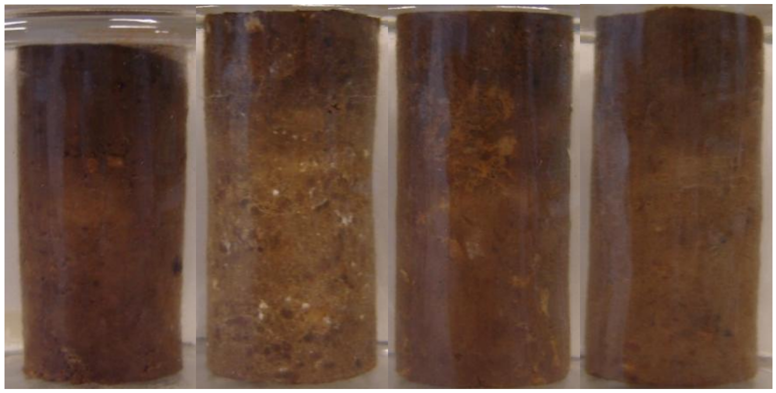

Figure E 7: Dennis Specimens at the Beginning of 5 Hours of Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

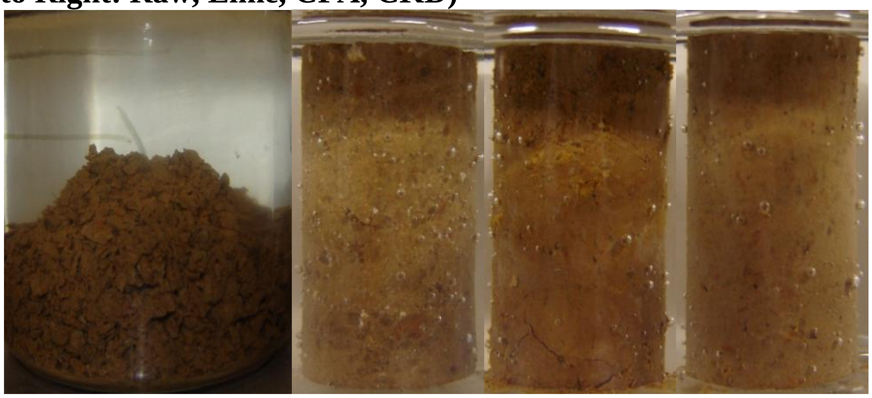

Figure E 8: Dennis Specimens at the End of 5 Hours of Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

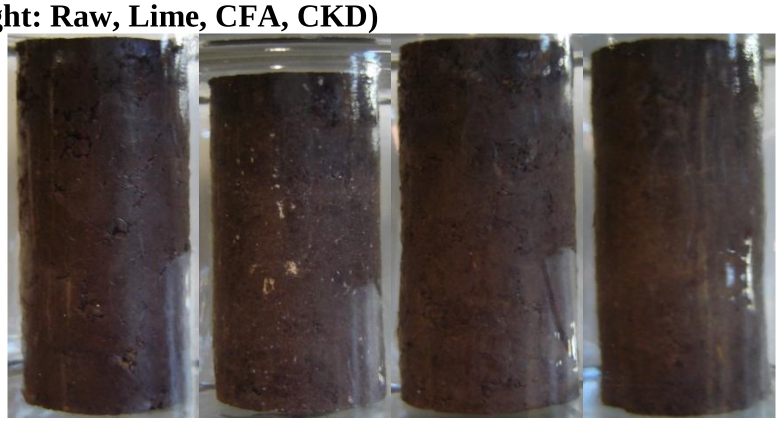

Figure E 9: Lomill Specimens at the Beginning of 5 Hours of Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

Figure E 10: Lomill Specimens at the End of 5 Hours of Soaking Period (From Left to Right: Raw, Lime, CFA, CKD)

APPENDIX F: Photographic View of Specimens Tested for Vacuum Saturation

Figure F 1: Kingfisher Specimens Before Vacuum Saturation at the End of UCS Test (From Left to Right: Raw, Lime, CFA, CKD)

Figure F 2: Kingfisher Specimens After Vacuum Saturation at the End of UCS Test (From Left to Right: Lime, CFA, CKD)

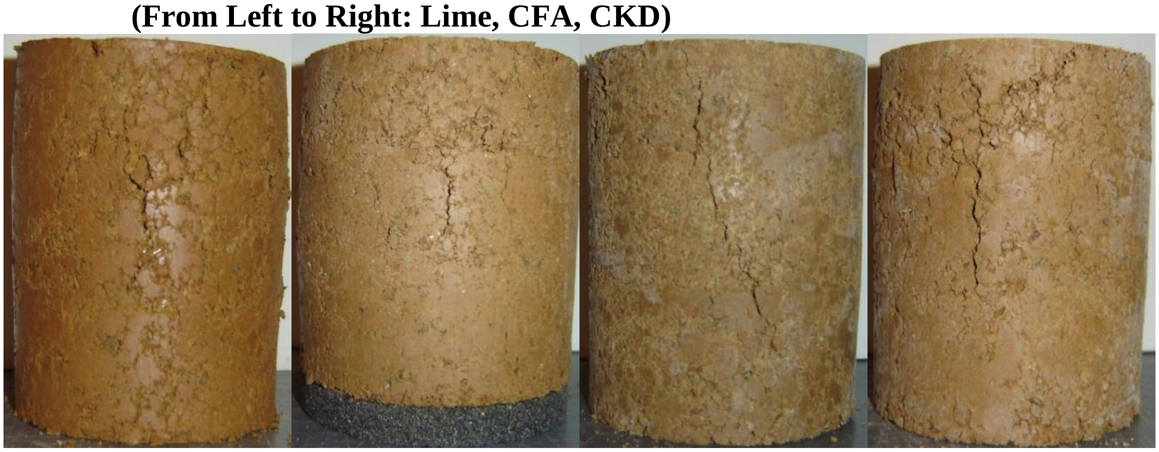

Figure F 3: Carnasaw Specimens Before Vacuum Saturation at the End of UCS test (From Left to Right: Raw, Lime, CFA, CKD)

Figure F 4: Carnasaw Specimens After Vacuum Saturation at the End of UCS Test (From Left to Right: Lime, CFA, CKD)

Figure F 5: Dennis Specimens Before Vacuum Saturation at the End of UCS test (From Left to Right: Raw, Lime, CFA, CKD)

Figure F 6: Dennis Specimens After Vacuum Saturation After UCS Test (Raw (Left) and CKD failed before UCS)

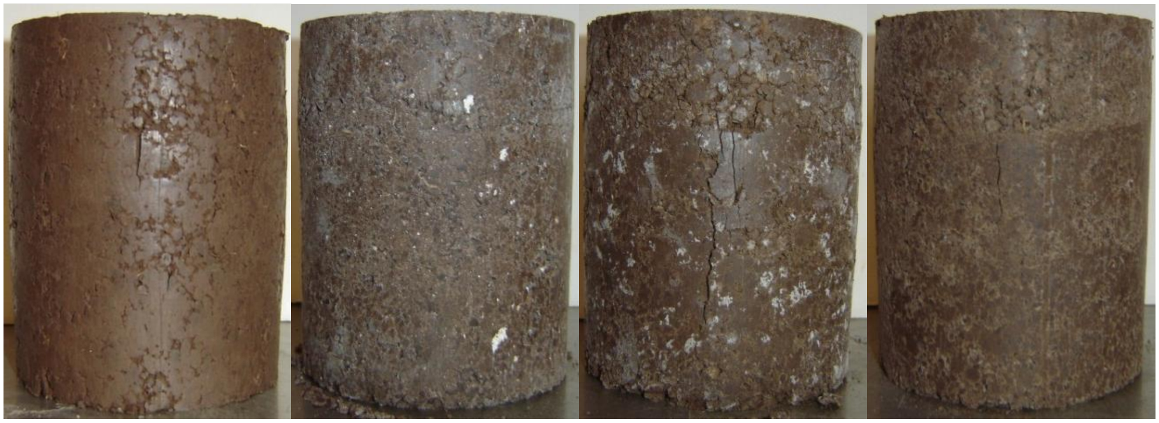

Figure F 7: Lomill Specimens Before Vacuum Saturation at the End of UCS Test (From Left to Right: Raw, Lime, CFA, CKD)

Figure F 8: Lomill Specimens After Vacuum Saturation at the End of UCS Test (From Left to Right: Lime, CFA, CKD)