2008-05-17

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EVALUATION OF LABORATORY DURABILITY TESTS FOR STABILIZED SUBGRADE SOILS

by

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A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil and Environmental Engineering

Brigham Young University

August 2008

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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ABSTRACT

EVALUATION OF LABORATORY DURABILITY TESTS FOR STABILIZED SUBGRADE SOILS

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Department of Civil and Environmental Engineering

Master of Science

The Portland Cement Association commissioned a research project at Brigham Young University to compare selected laboratory durability tests available for assessing stabilized subgrade materials. Improved understanding of these tests is needed to enable more objective selection of durability tests by design engineers and to facilitate more meaningful comparisons of data obtained for different stabilizer treatments using different evaluation procedures. The laboratory research associated with this project involved two subgrade materials, four stabilizers at three concentrations each, and three durability tests in a full-factorial experimental design. The two subgrade soils used were a silty sand and a lean clay, while the four stabilizer types included Class C fly ash, lime-fly ash, lime, and Type I/II portland cement. The three tests used in this comparative study were the freeze-thaw test, the vacuum saturation test, and the tube suction test.

On average, to achieve the same 7-day unconfined compressive strength (UCS) values, the sand required 4.4 times more Class C fly ash than cement, 3.6 times more lime-fly ash than cement, and 6.0 times more lime than cement. Likewise, the clay

required 10 times more Class C fly ash than cement, 7.5 times more lime-fly ash than cement, and 1.8 times more lime than cement. Analyses of the test results indicated that the UCS and retained UCS were higher for specimens tested by vacuum saturation than the corresponding values associated with freeze-thaw cycling. This observation suggests that the freeze-thaw test is more severe than the vacuum saturation test for these particular fine-grained materials. Testing also suggested that specimens with 7-day UCS values below 200 psi will generally not survive freeze-thaw cycling.

After both freeze-thaw and vacuum saturation testing, the sand specimens treated with lime-fly ash had significantly higher UCS and retained UCS than specimens treated with Class C fly ash, lime, or cement. Similarly, the clay specimens treated with Class C fly ash or lime-fly ash had significantly higher UCS values than specimens treated with cement or lime; however, clay specimens treated with Class C fly ash and lime-fly ash were not significantly different. None of the four stabilizer types were significantly different from each other with respect to retained UCS after vacuum saturation testing.

Dielectric values measured in tube suction testing 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 dielectric value of sand specimens to a “marginal” rating, while no stabilizer reduced the moisture susceptibility of the clay to a satisfactory level.

A strong correlation was identified between UCS after the freeze-thaw test and UCS after the vacuum saturation test, while very weak correlations were observed between the final dielectric value after tube suction testing and all other response variables. Differences in variability between test results were determined to be statistically insignificant in an analysis of the CVs associated with data collected in this research.

Although the freeze-thaw test utilized in this research was determined to be more severe than the vacuum saturation test for materials similar to those tested in this study, the vacuum saturation test is recommended over both the freeze-thaw and tube suction tests because of the shorter test duration, usability for specimens with 7-day UCS values even below 200 psi, and lack of a need for daily specimen monitoring.

ACKNOWLEDGEMENTS

The author thanks Dr. Spencer Guthrie for his assistance with the experimental design and analysis of results. Funding for this project was provided by the Portland Cement Association under the direction of Dr. David Luhr. Dr. Dennis Eggett of the Brigham Young University (BYU) Center for Collaborative Research and Statistical Consulting is acknowledged for his assistance with the statistical analysis. The author acknowledges Clearwater Industries for donating the Class C fly ash, Burningham Enterprises for donating the Class F fly ash, and Holcim US for donating the portland cement used in the project. BYU undergraduate students Paul Dixon, Erica Tanner, and Wendy Thompson are acknowledged for their significant assistance with the specimen preparation and testing. The author thanks Matthew Roper, previously a BYU graduate student, for providing extensive consultation about the testing procedures and for providing significant assistance with the literature review and writing associated with this report. Most importantly, the author thanks Julia, his wife, for the long, unflinching support she offered throughout the project.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Soil stabilization is defined as the modification of native soil or aggregate in an effort to improve its engineering properties (*1*). While stabilization techniques have been used to modify soil for thousands of years, modern stabilization utilizing laboratory experimentation began around 1930. Since then, a variety of stabilizers have been investigated, including lime, portland cement, fly ash, blast furnace slag, lime-fly ash, bituminous products in various forms, road tar, calcium chloride and other salts, and several non-traditional additives (*2*, *3*).

As the popularity of each group of stabilizers has increased through time, various organizations have been created to promote particular stabilizers and to establish procedures for their use. These organizations have also created stabilizer-specific conditioning methods to predict performance in the adverse conditions unique to cold regions. For example, the durability of cement-treated materials is determined using a sequence of freezing and thawing or wetting and drying cycles following American Society for Testing and Materials (ASTM) D 560 (Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures) or ASTM D 559 (Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures), respectively. The durability of materials treated with fly ash, lime-fly ash, and lime, however, is determined using vacuum saturation according to ASTM C 593 (Standard Specification for Fly Ash and Other Pozzolans for Use with Lime). Since these durability tests exhibit varying degrees of severity, where severity is defined as the loss of specimen strength, a comparative evaluation of the durability of different stabilizers is difficult at best. For this reason, the Portland Cement Association (PCA) commissioned a research project at Brigham Young University (BYU) to compare selected laboratory durability tests available for assessing stabilized materials. Improved understanding of these tests is needed to enable more objective selection of durability tests by design engineers and to facilitate more meaningful comparisons of data obtained for different stabilizer treatments using different evaluation procedures.

1.2 SCOPE

The laboratory research associated with this project involved two subgrade soils, a silty sand and a lean clay; four stabilizers at three concentrations each; and three durability tests in a full-factorial experimental design. Three replicate specimens were created for each unique combination, yielding a total of 234 test specimens. The sand material was obtained from a site near St. George Boulevard in the center of St. George, Utah. The clay was collected from a construction site in West Valley City, Utah.

The four stabilizers used in the laboratory research included Class C fly ash, lime-fly ash, lime, and Type I/II portland cement. The Class C fly ash was obtained from the Dave Johnson Power Plant located near Casper, Wyoming. The lime-fly ash was prepared with a lime-to-fly ash ratio of 1:4. Hydrated lime was obtained from a local supplier. The fly ash used in conjunction with lime was a Class F fly ash originating from the Jim Bridger Power Plant near Rock Springs, Wyoming. The portland cement was obtained from Holcim US. Concentrations of each stabilizer were selected to achieve target 7-day compressive strengths of 100, 200, and 300 psi with the sand and 100, 125, and 150 psi with the clay.

The durability tests included the freeze-thaw test, the vacuum saturation test, and the tube suction test. The durability of the treated materials and the relative severity of the tests were evaluated from the collected laboratory data. Correlations between test results and variability in test responses were also examined.

1.3 OUTLINE OF REPORT

This report consists of five chapters. This chapter presents an introduction and explains the scope of the research project. Chapter 2 contains the results of a literature review focused on pertinent laboratory durability tests and stabilizer types. In Chapter 3, the material characterization, specimen preparation, specimen testing, and data analysis procedures are presented. The testing results are included in Chapter 4, while Chapter 5 contains a summary of the testing, research findings, and recommendations.

CHAPTER 2

BACKGROUND

2.1 OVERVIEW

The following sections include the results of a literature review conducted for this research. A description of pertinent laboratory durability tests is presented first, followed by a discussion of stabilizer types.

2.2 LABORATORY DURABILITY TESTS

The durability of stabilized materials is a major concern in cold regions, due to both frost heave and freeze-thaw cycling. Frost heave occurs as water is drawn upwards into freezing subgrade or base materials, often forming ice lenses. During times of temperate weather, the ice lenses thaw, and the structural capacity of the roadway may be dramatically reduced (*4*). Freeze-thaw cycling occurs as the depth of frost in the ground varies with changing ambient air temperatures. The mechanisms associated with freeze-thaw cycling are very similar to those associated with frost heave but occur on a smaller scale. Instead of forming large ice lenses between soil and/or aggregate particles, the integrity of the roadway substructure is deteriorated by the freezing and thawing of water within the pore spaces of the soil or aggregate matrix. In an effort to prevent roadway deterioration due to frost heave and freeze-thaw cycling, agencies have developed many different protocols to evaluate the durability of stabilized materials. The three laboratory tests of particular interest in this research include freeze-thaw cycling, vacuum saturation, and tube suction.

2.2.1 Freeze-Thaw Cycling

The freeze-thaw cycling procedures outlined in ASTM D 560 are recommended for durability testing of cement-treated soils. This protocol requires compaction of specimens at optimum moisture content (OMC) into molds using either standard or modified Proctor compaction effort immediately after mixing, followed by curing for 7 days in a fog room. After curing, specimens undergo 12 cycles of freezing and thawing. Freeze-thaw cycles consist of freezing specimens at a temperature no warmer than -10°F for 24 hours, followed by thawing specimens in a fog room at a temperature of 70°F for 23 hours. Water should be made available for absorption by the specimens during thawing. After thawing, specimens are brushed on all sides with a wire brush. Specimen durability is measured in terms of percent mass loss. As a result of the variability associated with the brushing process, many agencies omit the brushing portion of the test and replace it with unconfined compressive strength (UCS) testing after completion of all 12 cycles (*5*).

2.2.2 Vacuum Saturation

The vacuum saturation test outlined in ASTM C 593 is the durability test specified for Class C fly ash, lime-fly ash, and lime-stabilized soils. Specimens are compacted at OMC into molds using either standard or modified Proctor compaction effort immediately after mixing, placed in sealed containers, and then cured for 7 days at 100°F. After curing, specimens are removed from the curing environment and given 2 hours to reach equilibrium with room temperature. Specimens are then placed in a vacuum chamber that is subsequently evacuated to a pressure of 24 in. Hg (11.8 psi). After 30 minutes, the chamber is flooded with distilled water, and the vacuum is removed. The specimens are allowed to soak for 1 hour and are then tested for UCS.

2.2.3 Tube Suction

Another procedure being considered for use in durability testing of stabilized materials is the tube suction test. The tube suction test, described in Texas Department of Transportation Test Method Tex-144-E (Tube Suction Test), is a relatively new test developed by the Finnish National Road Administration and the Texas Transportation Institute (*6*). In recent years, tube suction test results have been correlated with bearing capacity, frost heave, and several other parameters (*7, 8, 9, 10, 11*). The tube suction test prescribes that samples be compacted at OMC into pre-drilled molds using standard or modified Proctor compaction effort as appropriate and then cured according to project specifications. Four 1/16-in.-diameter holes are drilled into the bottom of each mold, with each hole in a separate quadrant. Additional 1/16-in.-diameter holes spaced about 1/2-in. apart are also drilled in a line around the mold about 1/4 in. from the bottom. Following curing, specimens are dried at 140°F for 3 days and then placed in a 1/2-in.-deep bath of distilled water for 10 days. Each day the dielectric readings of the specimens are measured using a surface dielectric probe. Five surface readings are taken around the perimeter of the specimen, and a sixth is taken in the center. The highest and lowest values are discarded, and the average of the remaining four values is reported. Specimens having final dielectric readings 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. Specimens with final dielectric values between 10 and 16 are expected to exhibit marginal long-term durability (*6*).

2.3 STABILIZERS

As stated previously, modern stabilization utilizing laboratory experimentation began around 1930. Since then, many stabilizers have been investigated, including fly ash, lime-fly ash, lime, portland cement, asphalt in various forms, road tar, calcium chloride and other salts, and several non-traditional additives (*2, 3*). The current research is limited in scope to Class C fly ash, lime-fly ash, lime, and portland cement. A discussion of each of these stabilizers is given in the following sections.

2.3.1 Class C Fly Ash

Fly ash is a by-product of the coal industry. As coal is burned in power plants, fly ash is collected from the flue gases. Each year over 250 million tons of fly ash is produced in the United States alone (*12*). Fly ash may be characterized as one of two classes depending on the type and composition of the coal. Class F fly ash is produced from bituminous and subbituminous coals typically found east of the Mississippi River, while Class C fly ash comes from the lignitic coals usually found in the western United States. ASTM C 593 is commonly used to determine the suitability of a particular fly ash for soil stabilization.

The high levels of calcium oxide, or lime, present in Class C fly ash allow this material to be self-cementing (*12*). In other words, all of the mineral compounds necessary for cementation to occur are contained within the fly ash particles. The principle mechanism for stabilization is pozzolanic reactivity, which usually occurs over an extended period of time (*13*). For example, some Class C fly ash has been known to continue gaining strength for an entire year after placement (*14, 15*). With water present, the free lime within the fly ash reacts with the silica and alumina also contained within the fly ash (*14*). This reaction results in the formation of cementitious gels such as calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) (*14, 16*). Although these cementitious materials have hydration properties similar to those of portland cement, pozzolanic reactions occur at varying rates that depend largely on the composition of the fly ash (*14*). As a result of this variability, determining the percentage of the ultimate strength that will be achieved after a 7- or 14-day cure is not usually possible.

Unlike other stabilizers, Class C fly ash is not yet subject to any standard procedures established for specimen preparation. The literature suggests that two primary concerns exist relative to design procedures involving Class C fly ash. The first concern is the rapid rate at which the Class C fly ash hydrates with the introduction of water. Several researchers have found that compaction delay has a deleterious effect on specimen strength (*14, 17, 18*). A 1-hour delay between mixing and compaction may yield a decrease in maximum dry density (MDD) from 4 to 10 pcf (*18*). A decrease in MDD generally results in a corresponding decrease in strength. As a result of such findings, researchers have recommended that compaction occur immediately after the water, aggregate, and fly ash are mixed. In some cases, maximum compaction delays of 2 hours have been allowed (*14*). The second concern associated with Class C fly ash is the influence of moisture content on strength. The OMC for maximum strength has been found to be as much as 8 percent below the OMC for MDD, depending on soil type. Soils stabilized with fly ash generally have a discrepancy of 1 to 3 percent between the OMC associated with maximum strength and the OMC associated with maximum density (*14, 17, 18*).

Although no standard procedures for specimen preparation have been created for specimens treated with Class C fly ash, ASTM C 593 is typically used as a guide. Class C fly ash concentrations are generally determined as a percentage of the weight of dry aggregate and typically range from 12 to 25 percent (*13*, *18*). Two different curing environments for Class C fly ash-treated materials were identified in the literature. The first involved 7 days sealed in a bag in an oven at 100ºF, while the second consisted of 7 days at room temperature and a relative humidity of 90 percent or greater (*18, 19*). These two environments are consistent with the curing environments used for lime and lime-fly ash-treated soils and portland cement-treated soils, respectively. The strength of Class C fly ash-treated specimens is determined using UCS testing. Soaking fly ash-treated specimens for 4 hours prior to compressive strength testing is occasionally specified to simulate saturated field conditions; however, no standard practice has been set and the UCS test is often performed without prior soaking (*14, 16, 17, 18, 19, 20, 21*).

The use of Class C fly ash as a stabilizer is relatively new when compared with other paving materials. For this reason, the literature is void of information about the durability of in-situ Class C fly ash-treated materials. However, plans for future durability testing have been established for recently constructed full-depth reclamation and cold in-place recycled projects using Class C fly ash (*15, 22*).

2.3.2 Lime-Fly Ash

In this research, the fly ash used in conjunction with lime was a Class F fly ash exhibiting little or no self-cementing properties. The mechanisms associated with lime-fly ash stabilization are very similar to those of lime. In lime stabilization, the silica and alumina needed to react with the lime are provided by the soil medium. When the necessary silica and alumina are not present in the soil, a pozzolan, such as fly ash, needs to be added to facilitate the reaction with lime (*13*). Important soil-lime reactions include cation exchange and pozzolanic reactivity. Cation exchange occurs as monovalent cations present in the native soil are exchanged with cations of higher valences, primarily calcium ions contained in the lime, resulting in flocculation of the treated soil. Since cation exchange occurs only in cohesive soils, the primary mechanism associated with the stabilization of granular material is pozzolanic reactivity (*14, 23, 24*). Pozzolanic reactions begin as the addition of lime increases the pH of the soil and allows the silica and alumina present in fly ash to become soluble. Once the silica and alumina become available, calcium hydroxide (CH) combines with silica, alumina, and water to form C-S-H and C-A-H, the compounds primarily responsible for strength gain (*21*). Ettringite and low-sulfate sulfoaluminate may also be products of lime-fly ash reactions (*25*).

Design procedures for lime-fly ash are complicated by the multivariable nature of the mixture. The two variables associated with design are the total amount of lime-plus-fly ash and the lime-to-fly ash ratio. Lime-to-fly ash ratios specified in the literature range from 1:10 to 1:2, with ratios of 1:3 or 1:4 being most common (*25, 26*). The most efficient method for determining mixture proportions is to first establish appropriate lime-plus-fly ash concentrations using constant lime-to-fly ash ratios and then optimize lime-to-fly ash ratios. Appropriate concentrations and ratios can be selected using results from UCS testing (*25*). The literature indicates that strength depends more on the lime-plus-fly ash content than on the lime-to-fly ash ratio (*25*).

Specimen preparation methods for lime-fly ash-stabilized soils are outlined in ASTM C 593. The strength of lime-fly ash-treated soil or aggregate is most often determined using the UCS test following a 7-day cure in a sealed container at 100°F. Samples tested for UCS are soaked for 4 hours prior to testing.

As with the use of Class C fly ash, utilization of lime-fly ash for stabilization is a relatively new technique. As such, documented long-term performance of this material is not available (*25*). However, in a study comparing lime-fly ash and cement-treated base after 5 years of service life, researchers noted that the cement-treated sections cracked sooner and more severely than did the lime-fly ash treated sections (*27*). Thus, lime-fly ash seems less likely to exhibit shrinkage cracking than cement-stabilized base.

2.3.3 Lime

A common stabilizer used to treat clayey soils is lime. Lime is produced from limestone or dolomite mined from the earth. Once the raw materials have been purified, the newly created lime can be modified into a variety of forms. Hydrated high-calcium lime ($Ca(OH)_2$ (or CH)), monohydrated dolomitic lime ($Ca(OH)_2 \cdot MgO$), calcitic quicklime (CaO), and dolomitic quicklime ($CaO \cdot MgO$) are the most common types of lime (*28*). The majority of lime stabilization in the United States utilizes hydrated lime, although quicklime has become increasingly common in the past 20 years (*23*).

Lime is particularly effective for improving clayey soils because of the high content of silica and alumina within the clay. Adding a sufficient amount of lime raises the pH of the soil-lime mixture, which in turn increases the solubility of the silica and alumina. Silica and alumina from the soil dissolve in the presence of water and react with calcium ions from the lime to form C-S-H and C-A-H, respectively (*29*). In addition, cation exchange processes cause the clay particles to flocculate, resulting in an immediate change in the clay texture. This mechanism is especially beneficial in treating soft, moist subgrade soils that would otherwise inhibit construction equipment from operating. When used appropriately, lime can improve the plasticity, workability, and volume stability of clayey soils, although improvements in strength, stiffness, and fatigue life may not be achieved in all soils (*23*).

Current mixture design procedures for lime vary regionally within the United States; however, two main ideas appear in the literature. Eades and Grim developed a procedure based on their theory that soil-lime pozzolanic reactions occur when the mixture has a pH of 12.4 (*29*). Thus, the reaction will continue as long as sufficient lime exists in the mixture to maintain the elevated pH. ASTM D 6276 (Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization) should be used to determine the proper amount of lime a particular soil needs to obtain a mixture pH of 12.4. In this procedure, several soil samples are mixed with distilled water and varying percentages of lime. The solutions are stirred for specific intervals of time over a 1-hour period, after which time the pH is measured. The amount of lime required for stabilization is the lowest concentration that produces a pH of 12.4.

The other methodology common in the literature involves determinations of UCS for the soil when mixed with different concentrations of lime. Samples are prepared with varying proportions of lime. After mixing, but prior to compaction, the mixture is typically allowed to mellow. Mellowing is accomplished in the laboratory by allowing the specimen to sit undisturbed while being covered to prevent moisture loss; this conditioning allows the initial cation exchange processes to occur. The specified amount of time for mellowing varies greatly throughout the literature. Some researchers have used 1 hour (*30, 31*) or 3 hours (*32, 33*), while others have used 24 hours (*34, 35*) and even 72 hours (*31*); a mellowing period of 1 hour appears to be most commonly specified. After mellowing, the samples are compacted and cured for a specific amount of time. The curing duration can vary depending on the objective of the research; however, 7, 28, and 90 days are most common according to ASTM D 5102 (Standard Test Method for Unconfined Compressive Strength of Compacted Soil-Lime Mixtures). The curing temperature also varies from one study to another. For example, even though ASTM D 5102 specifies wrapping specimens in air-tight, moisture-proof containers and curing at 73.4°F, higher temperatures are sometimes utilized to achieve higher strengths in shorter curing times. Elevated curing temperatures should be used with caution since temperatures above 120°F have been shown to produce pozzolanic reactions uncommon in field curing conditions (*23*).

Although lime is commonly used for achieving immediate improvements in the engineering properties of soil, it can also provide long-term strength gains in reactive soil. Lime-soil mixtures develop strength at a slow rate in comparison with other stabilizers such as Class C fly ash or cement; however, curing times of 56 and 75 days have been shown to produce UCS values of up to 650 and 1580 psi, respectively (*23*). Field data document significant strength gains after 13 years (*28*). One major concern with lime treatment is the effect of leaching on the soils. Cyclic wetting and drying on lime-soil mixtures can alter the soil through dissolution of chemical bonds, cation exchange, or other processes (*28*). The effects of leaching can be mitigated by adding the lime content corresponding to the optimum strength in the mixture design process (*28*).

2.3.4 Portland Cement

Modern portland cement, a compound containing calcium, silica, alumina, and iron, was first developed in the early- to mid-1800s (*12, 21*). Since then, many advances have been made in the production of portland cement, making it readily available in most areas of the world. In the United States, portland cement is classified into five subgroups depending on composition and fineness. Types I and II are the most common, while Types III through V are primarily used for specialty projects.

Mechanisms of cement stabilization are well documented in the literature. The two basic reactions occurring in cement stabilization are hydration reactions and pozzolanic reactions. Hydration reactions, which occur with the introduction of water, involve the combination of calcium, silica, and water, resulting in the formation of C-S-H and excess CH. During subsequent but slower pozzolanic reactions, excess CH from the hydration reaction combines with water and silica or alumina, depending on their availability, resulting in the formation of additional C-S-H or C-A-H, respectively. Since these cementitious products are responsible for the strength gain of cement-treated materials, both the hydration and pozzolanic reactions contribute to the overall strength of a specimen.

Of all the stabilizers, portland cement has the most defined design procedure. Mixture procedures specify that cement be added as a percentage of the weight of dry aggregate, with concentrations between 2 and 13 percent cement being common (*36*). Specimens are usually cured at room temperature and 100 percent relative humidity for 7 days. Other common curing times include 28 and 56 days. Tests that have been used to quantify the strength of cement-treated materials include UCS and California bearing ratio (*1, 36, 37, 38*). Specimens tested for UCS are usually soaked for 4 hours prior to testing (*1, 5, 36*).

While substantial research has been performed to investigate the effects of treating base materials with cement, the effects of treating subgrade soil with cement has been studied far less. However, the literature does include examples where cement-treated soils have sustained substantial gains in bearing capacity for long periods of time (*39*). Also, a long-term study showed how cement can effectively reduce the plasticity index of fine-grained soils (*40*).

2.4 SUMMARY

In an effort to prevent the deleterious effects of frost heave and freeze-thaw cycling in pavements, engineers have conducted significant research to establish procedures for laboratory durability testing of stabilized materials, many of which have been standardized by ASTM. Although curing conditions differ by stabilizer type, preparation procedures are similar for specimens stabilized with Class C fly ash, lime-fly ash, lime, and cement. Also, using UCS to determine stabilizer concentrations is common for specimens treated with Class C fly ash, lime-fly ash, lime, and cement. The long-term field performance of lime- and cement-treated materials has been well established, while the literature is absent of information regarding the long-term performance of materials treated with Class C fly ash and lime-fly ash.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 OVERVIEW

In this research, a full-factorial laboratory experiment including two subgrade soils and three concentrations of each of four different stabilizers, with three replicates of each possible combination, was performed. Three untreated specimens of each soil were also prepared as control samples, and all of the treatments were subjected to three separate tests, requiring preparation and testing of 234 specimens. This chapter presents the procedures and protocols used during the research project, including material characterization, specimen preparation and testing, and data analyses.

3.2 MATERIAL CHARACTERIZATION

Two subgrade soils were used for this research project. A sand and a clay were chosen to represent two typical subgrade materials commonly stabilized for road construction. The reddish sand was sampled near St. George Boulevard in the center of St. George, Utah, in the summer of 2004. The clay was collected from a construction site in West Valley City, Utah, in the summer of 2007. These particular subgrade materials were selected for use in this research because of their close proximity to BYU.

Samples of the sand and clay materials were transported to the BYU Highway and Materials Laboratory in bulk and were dried at 140°F. Following drying, the sand was separated over the 3/8-in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200 sieves; the material retained on the 3/8-in. sieve was then discarded. After the entire sample was sieved, a particle-size distribution was established to facilitate reconstruction of replicate samples with identical gradations.

Due to the extremely fine gradation of the clay, which prohibited separation of the material over several sieves in a time frame acceptable to the research schedule, a modified approach to sieving was followed. After drying, the clay clumps were pulverized in a Los Angeles abrasion machine and subsequently sieved through the No. 40 sieve. The material was processed in this manner until a sufficient quantity of clay passing the No. 40 sieve was obtained to fill 20 five-gallon buckets. After all the necessary material was pulverized, a sample of approximately 0.5 lb was taken from buckets 1 and 2 to make a single 1-lb sample, which was then separated over the No. 50, No. 100, and No. 200 sieves. This procedure was followed for buckets 3 and 4, 5 and 6, and so on until each bucket had been sampled. Variability among the resulting 10 gradations was evaluated by computing the standard deviation associated with the percent retained on each sieve and on the pan. With the standard deviations all below 4 percent, the material was considered acceptably uniform throughout all the buckets, and the particle-size distribution was then determined for the bulk material.

Washed sieve analyses and liquid and plastic limit tests were then performed to classify the sand and clay according to the American Association of State Highway and Transportation Officials (AASHTO) and Unified Soil Classification systems.

3.3 SPECIMEN PREPARATION

After the sand and clay were processed, three to five samples with varying moisture contents were prepared following the pre-determined gradations to determine the OMC and MDD for each untreated material. The coarse fraction of the sand, retained on the No. 4 sieve, was soaked in de-ionized water for 24 hours prior to compaction. Just before compaction, the dry fine fraction, passing the No. 4 sieve, was mixed and added to the coarse fraction. The combined material was then mixed until it was uniform in color and texture. For the clay, de-ionized water was applied directly to the dry material and mixed until it was uniform in color and texture. Each sample was then compacted into a mold using standard Proctor compaction effort in accordance with ASTM D 698 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort) Method A. The standard Proctor procedure requires compaction of the specimen in three lifts, with each lift consisting of 25 blows of a 5.5-lb hammer dropped from a height of 12 inches. The mold has a height of 4.58 in. and a 4-in. diameter. Following compaction, an additional five blows were applied with a finishing tool to level the specimen surface. Figure 3.1 shows the finishing tool in operation with the compaction apparatus used for the research in the background. After leveling was complete, the combined weight of the specimen, cylinder, and base plate was measured. The height of the specimen relative to the top of the cylinder was then measured. The specimen was then extruded from the mold. The specimen was subsequently dried to constant weight in an oven at 230°F to facilitate calculation of gravimetric moisture content and dry density. These values were plotted to determine the OMC and MDD for each untreated material.

Once the OMC and MDD were determined, three replicates of each untreated material were prepared at OMC for UCS testing. Specimens were compacted to a target height of 4.58 in. using the standard Proctor procedure as described previously. The specimens were then capped with a high-strength gypsum compound to provide a flat surface on each end necessary to ensure uniform load distribution during testing. Immediately after the specimens were capped, they were tested for UCS at a constant strain rate of 0.05 in./minute using a screw-type press with a floating base as shown in

Figure 3.1 Compaction apparatus and finishing tool.

Figure 3.2. The maximum load was divided by the cross-sectional area to obtain the compressive strength.

An initial concentration of each stabilizer was selected for each soil based on information in the literature. Moisture-density curves were then created for each material treated with the specified concentrations of Class C fly ash, lime-fly ash, lime, and portland cement. A lime-to-fly ash ratio of 1:4 was used for all testing in this research. Three to five specimens were prepared at varying water contents for each moisture-density curve as described previously for Class C fly ash, lime-fly ash, and lime. The specimens stabilized with lime only differed from the other stabilizers in that a 1-hour mellowing period was provided immediately prior to compaction. The OMC values for the cement-treated specimens were estimated from the OMC values associated with the untreated specimens by adding 0.3 percentage points of water for every 1.0 percent cement added to the aggregate (*41*). That is, for a specimen stabilized with 2.0 percent cement, for example, the OMC of the untreated material would be increased by 0.6 percent as an estimation of the OMC of the cement-treated material.

Figure 3.2 UCS test machine.

As noted earlier, the sand contained a coarse fraction that was retained on the No. 4 sieve. This fraction was soaked for 24 hours before it was added to the fine fraction to ensure the larger particles contained adequate moisture. The clay contained no coarse fraction and therefore required no soaking prior to compaction.

Following compaction, specimen heights and weights were measured, after which the specimens were extruded and placed in an oven at 230°F until dried to constant weight. Once moisture contents and dry densities were computed and plotted, the OMC and MDD were determined for each treated material. Additional specimens were then prepared at the corresponding OMC, cured for a 7-day period, and tested for UCS under various conditions as prescribed by the practices identified for each stabilizer in the literature review. A minimum of two replicate specimens were tested at each concentration. For this research project, a 7-day cure was utilized for all treated specimens.

For UCS testing, specimens stabilized with either Class C fly ash or lime were sealed in air-tight plastic bags following extrusion to prevent moisture loss during the curing period. As depicted in Figure 3.3, curing occurred in an oven at 100°F for 7 days. After the curing period, specimens were immediately capped with gypsum and subjected to UCS testing as described previously.

Figure 3.3 Curing conditions for specimens treated with fly ash and/or lime.

Lime-fly ash-treated specimens were cured and tested in a similar fashion as those treated with Class C fly ash or lime; however, following curing, lime-fly ash-treated specimens were soaked underwater for 4 hours as prescribed by ASTM C 593. Figure 3.4 shows a sample soaking in preparation for UCS testing.

Specimens treated with portland cement were cured at room temperature in a fog room with 100 percent relative humidity. The tops of the specimens were protected from dripping water during the 7-day curing period. Afterwards, specimens were soaked underwater for 4 hours following PCA guidelines (*37*). Specimens were then capped with gypsum and subjected to UCS testing.

The initial UCS test results from each stabilizer were evaluated to select additional stabilizer concentrations within a target 7-day UCS range of 100 to 300 psi. Previous research on aggregate base materials used high, medium, and low concentrations corresponding to 200, 400, and 600 psi, respectively (*42*); however, early in this project, which is focused on subgrade soils, the researchers concluded that strengths of 400 and 600 psi would be unattainable for most of the stabilizers within an acceptable range of concentrations used in construction practice. Because of this limitation and in consideration of the reduced stresses experienced by the subgrade in comparison to the base layer, lower target UCS values were selected for investigation.

Figure 3.4 Specimen soaking prior to UCS testing.

Thus, the low, medium, and high concentrations were adjusted to correspond to UCS values of 100, 200, and 300 psi, respectively, for the sand and 100, 125, and 150 psi for the clay.

Once additional stabilizer concentrations were selected, values for OMC, MDD, and 7-day UCS were then obtained for each material-stabilizer combination. Following testing, plots of UCS versus stabilizer concentration were created for each combination of material and stabilizer type. Low, medium, and high stabilizer concentrations were then selected from these plots using interpolation. In some instances, the target maximum strength could not be reached even at very high stabilizer concentrations. In these cases, the high stabilizer concentration was selected by adding the difference between the low and medium concentrations to the medium concentration. Values of OMC and MDD associated with each selected concentration were similarly determined by interpolating between points on plots of OMC and MDD versus stabilizer concentration.

3.4 SPECIMEN TESTING

Specimens were tested for durability using the freeze-thaw test, the vacuum saturation test, and the tube suction test. The freeze-thaw and vacuum saturation tests were performed in general accordance with ASTM D 560 and ASTM C 593, respectively, while the tube suction test was performed in general accordance with Texas Department of Transportation Test Method Tex-144-E, with slight modification to the specimen size.

For freeze-thaw testing, three replicates of each material treated with each stabilizer concentration were prepared, compacted, extruded, and cured as described in Section 3.3. After the 7-day cure, specimens were submerged in de-ionized water for a 4-hour period and then placed in a chest freezer at -20°F. Following the freezing period, specimens were removed from the chest freezer and weighed. Specimens were then thawed at room temperature for 20 hours and subsequently soaked underwater for 4 hours. This process of freezing, thawing, and soaking comprised one freeze-thaw cycle. Figure 3.5 through Figure 3.7 depict the freezing, thawing, and soaking configurations, respectively, for freeze-thaw testing. As prescribed in ASTM D 560, specimens were

Figure 3.5 Freezing configuration for freeze-thaw testing.

Figure 3.6 Thawing configuration for freeze-thaw testing.

Figure 3.7 Soaking configuration for freeze-thaw testing.

subjected to 12 freeze thaw-cycles in total. During each soaking period, care was taken to place specimens treated with the same stabilizer together in order to prevent cross contamination of stabilizers in the event that leaching occurred. After 12 cycles were completed, the circumference of each specimen visibly damaged by the testing was measured, if possible, and then all surviving specimens were capped and subjected to UCS testing as described previously. The actual cross-sectional area was then utilized to compute the UCS of each specimen. Following testing, the caps were removed, and the specimens were oven-dried at 230°F to constant weight so moisture contents could be determined.

The vacuum saturation test was also performed on three replicates of each material treated with each stabilizer concentration. Specimens were prepared, compacted, extruded, and cured as described in Section 3.3. Following the curing period, specimens were weighed and placed upright inside a vacuum chamber. The vacuum chamber lid was then replaced, the chamber was evacuated, and the vacuum was sustained for 30 minutes following ASTM C 593. After the de-airing period, the chamber was flooded with de-aired, de-ionized water as depicted in Figure 3.8. The vacuum was then removed, and the specimens were soaked at atmospheric pressure for 1 hour. Following the soaking period, specimens were removed from the vacuum

Figure 3.8 Vacuum saturation test configuration.

chamber, weighed, and capped with gypsum. After capping, specimens were subjected to UCS testing, following which all capping materials were removed to facilitate determination of specimen moisture contents by oven-drying at 230°F.

For the tube suction test, specimens were compacted into 4-in.-diameter pre-prepared plastic molds. Four 1/16-in.-diameter holes were drilled into the bottom of each mold, with each hole in a separate quadrant. Additional 1/16-in.-diameter holes spaced about 1/2 in. apart were also drilled in a line around the mold about 1/4 in. from the bottom as shown in Figure 3.9. The mold was also trimmed to about 5 in. in height. Specimens were prepared, compacted, and cured as described in Section 3.3, except that the specimens remained in the plastic molds in which they were compacted. A metal sleeve was placed around each mold during compaction to prevent the sides of the mold from buckling. After curing, specimens were dried for 72 hours at 104°F, following which the weight of each dry specimen and mold was measured. Initial dielectric readings were then obtained using a surface dielectric probe as displayed in Figure 3.10. According to the protocol given in Section 2.2.3, dielectric readings were measured daily at six locations on each specimen surface for the next 10 days. Final dielectric values were measured 240 hours after the specimens were placed in the water bath. Following testing, each of the specimens was weighed in the wet condition, oven-dried to constant weight at 230°F, and weighed again to facilitate computation of moisture content and dry density.

Figure 3.9 Plastic mold used for tube suction test.

Figure 3.10 Tube suction test configuration.

3.5 DATA ANALYSES

The test results were evaluated using a fixed effects analysis of variance (ANOVA). The null hypothesis of an ANOVA is that the population means of all the treatments are equal. The alternative hypothesis is that at least one population mean is significantly different from the others. The typical Type I error rate of 0.05 was used throughout the analysis. Thus, when the level of significance, or *p*-value, was less than or equal to 0.05, the null hypothesis was rejected, and the alternative hypothesis was accepted. When the *p*-value was greater than 0.05, insufficient evidence existed to reject the null hypothesis. The response variables associated with this research included UCS after the freeze-thaw test, percent UCS retained after the freeze-thaw test, UCS after the vacuum saturation test, percent UCS retained after the vacuum saturation test, and final dielectric value after the tube suction test. Because the target strengths for the UCS test were different for the sand and the clay, the two materials were treated separately in the statistical analyses. In each case, factors included stabilizer type, stabilizer concentration level, and the interaction of these two variables. Initially, a full model was created using the two factors and their interaction. A reduced model was then created using a Type I error rate of 0.15 commonly specified for this purpose; only factors with *p*-values less than or equal to 0.15 were included in the reduced model. When the fixed effects ANOVA indicated that treatments were significantly different, Tukey's mean separation procedure was used to identify the differences.

In addition to the ANOVA test, correlations between the different test results were evaluated with plots, linear regression, and the corresponding coefficients of determination (R^2 values) associated with the computed trend lines. Also, the coefficient of variation (CV) was calculated for each set of test results, and an ANOVA was performed on the CVs in order to determine if one test was more repeatable than the others in this research.

3.6 SUMMARY

A full-factorial experimental design was utilized to evaluate the durability of specimens treated with various stabilizers and the relative severity of various laboratory durability tests. Sand and clay soils were stabilized with Class C fly ash, lime-fly ash, lime, and portland cement in three concentrations each. Specimens were compacted using standard Proctor effort and cured for 7 days either in a fog room at room temperature and 100 percent relative humidity or sealed in a plastic bag in an oven at 100°F. Following curing, specimens were subjected to freeze-thaw, vacuum saturation, or tube suction testing. The test results were evaluated using an ANOVA and Tukey's mean separation procedure. Correlations between the different test results were evaluated, and the CV for each test was calculated.

CHAPTER 4

RESULTS

4.1 OVERVIEW

The following sections present the results of material characterization, stabilizer concentration evaluations, and freeze-thaw, vacuum saturation, and tube suction testing. The results of statistical analyses performed on the data are also reported.

4.2 MATERIAL CHARACTERIZATION

Both the sand and clay materials were characterized using washed sieve analyses and liquid and plastic limit tests. Particle-size distributions determined from washed sieve analyses are presented in Table 4.1 and Figure 4.1. The sand was non-plastic; therefore, the liquid and plastic limits could not be measured. The liquid and plastic limits for the clay were 38 and 22, respectively. According to the AASHTO and Unified soil classification procedures, the sand material was classified as A-2-4 and SM (silty sand), respectively, while the clay material was classified as A-6 and CL (lean clay), respectively.

Table 4.1 Particle-Size Distributions

Sieve Size	Percent Passing (%)	
	Sand	Clay
3/8 in.	100.0	100.0
No. 4	97.6	100.0
No. 8	92.0	100.0
No. 16	86.7	100.0
No. 30	82.0	100.0
No. 50	67.2	99.8
No. 100	57.3	98.1
No. 200	34.7	89.0

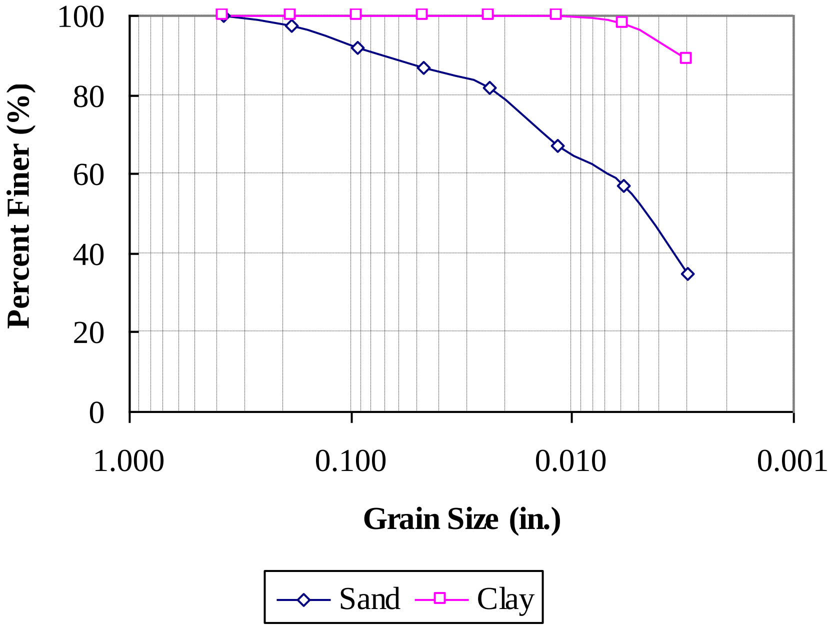

Figure 4.1 Particle-size distributions.

4.3 STABILIZER CONCENTRATIONS

Plots of stabilizer concentration versus 7-day UCS are shown in Figure 4.2 through Figure 4.5 for Class C fly ash, lime-fly ash, lime, and portland cement, respectively. The OMC, MDD, and UCS data associated with the trial stabilizer concentrations represented in these figures are presented in Appendix A. Table 4.2 summarizes the stabilizer concentrations and values of OMC and MDD selected for both the sand and the clay. In Table 4.2, concentration levels of low, medium, and high for the sand correspond to target 7-day UCS values of 100, 200, and 300 psi, respectively, while concentration levels of low, medium, and high for the clay correspond to target 7-day UCS values of 100, 125, and 150 psi, respectively. On average, to achieve the same 7-day USC values, the sand required 4.4 times more Class C fly ash than cement, 3.6 times more lime-fly ash than cement, and 6 times more lime than cement. Likewise, the clay required 10 times more Class C fly ash than cement, 7.5 times more lime-fly ash than cement, and 1.8 times more lime than cement. Stabilizer concentrations are reported as percentages of the weight of dry soil, while OMC is reported in each case as the percentage of the total weight of the dry soil and stabilizer.

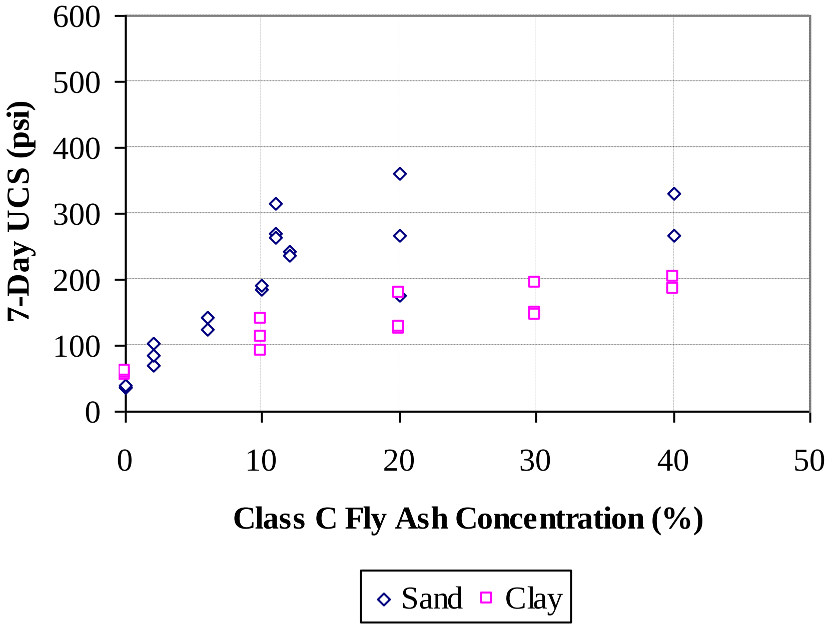

Figure 4.2 UCS data for materials treated with Class C fly ash.

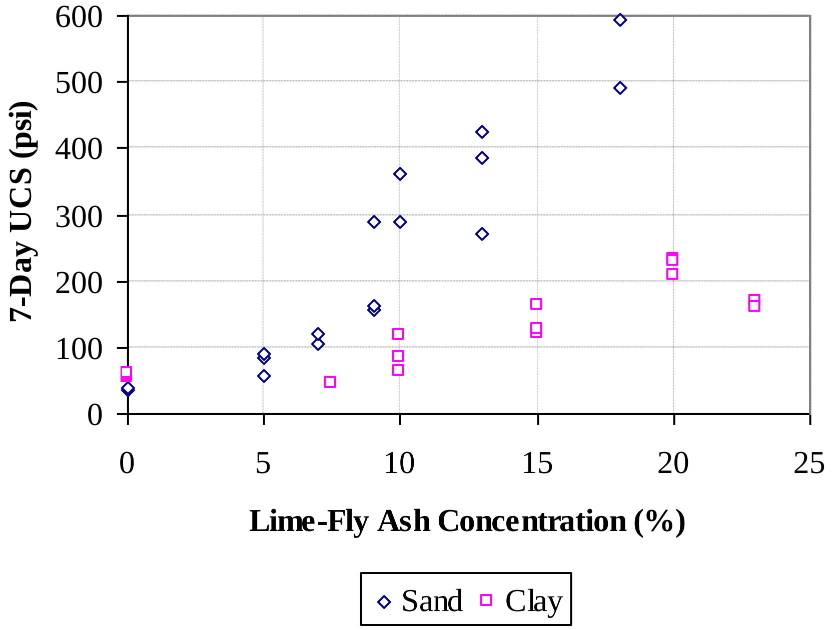

Figure 4.3 UCS data for materials treated with lime-fly ash.

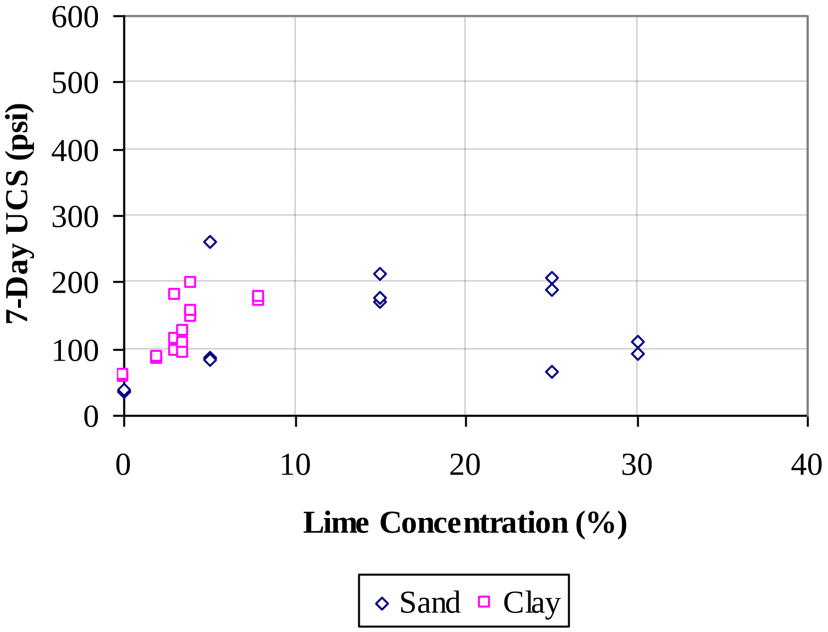

Figure 4.4 UCS data for materials treated with lime.

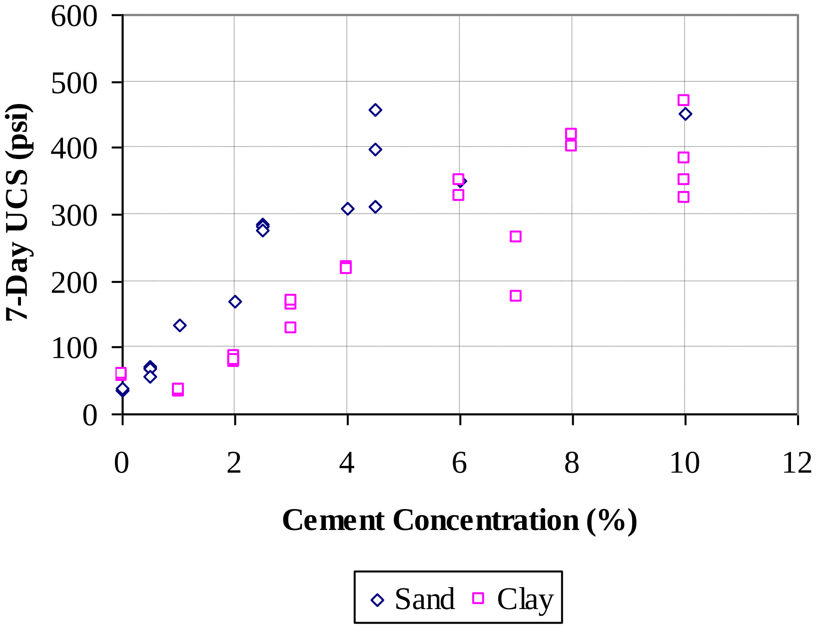

Figure 4.5 UCS data for materials treated with cement.

As displayed in Figure 4.2 through Figure 4.5, the sand was capable of attaining greater strength at lower concentrations than the clay when Class C fly ash, lime-fly ash, or cement was added; however, the lime performed better at lower concentrations when added to clay than when added to sand. As mentioned in Section 2.3.3, lime will always perform better when applied to materials containing soluble silica and alumina, such as clay, due to the reaction of calcium with the silica and alumina within the clay to form C-S-H and C-A-H; when silica and alumina are not present, the lime does not have the necessary components to form pozzolanic products.

The MDD values shown in Table 4.2 for cement-treated materials are the same as those listed for untreated materials for both the sand and the clay because the effect of cement on the compaction characteristics was assumed to be negligible due to the low cement concentrations.

Table 4.2 Stabilizer Concentrations Used for Testing

Aggregate Type	Stabilizer Type	Concentration Level	Stabilizer Concentration (%)	OMC (%)	MDD (pcf)
Sand	Untreated	-	-	12.0	120.4
	Class C Fly Ash	Low	2	9.8	112.6
		Medium	11	12.2	113.5
		High	20	16.0	114.5
	Lime-Fly Ash	Low	5	12.8	116.2
		Medium	9	12.6	116.3
		High	13	12.5	116.0
	Lime	Low	5	13.8	114.5
		Medium	15	15.6	110.3
		High	25	17.8	104.9
	Cement	Low	0.5	12.2	120.4
		Medium	2.5	12.8	120.4
		High	4.5	13.4	120.4
Clay	Untreated	-	-	22.5	100.8
	Class C Fly Ash	Low	10	19.5	99.8
		Medium	20	20.0	102.2
		High	30	17.8	98.0
	Lime-Fly Ash	Low	10	21.5	96.9
		Medium	15	21.4	96.6
		High	20	21.3	96.3
	Lime	Low	3	21.7	96.2
		Medium	3.5	22.5	95.0
		High	4	23.0	94.1
	Cement	Low	1	22.8	100.8
		Medium	2	23.1	100.8
		High	3	23.4	100.8

4.4 FREEZE-THAW TEST

Table 4.3 and Figure 4.6 present the data collected during the freeze-thaw test performed on the sand. Hyphens in the table and the absence of some bars in the figure represent data that were not measured due to specimen deterioration. In cases in which the specimens deteriorated to the point that the UCS test could not be performed, the strengths of the specimens were assumed to be negligible. Since the untreated specimens failed during the initial soaking period required before the commencement of the first freeze-thaw cycle, the strength and final moisture content of those specimens

Table 4.3 Sand Freeze-Thaw Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	UCS (psi)	Final Moisture (%)
Untreated	-	1	123.5	-	-
		2	123.0	-	-
		3	123.5	-	-
Class C Fly Ash	Low	1	116.0	-	-
		2	115.3	-	-
		3	114.9	-	-
	Medium	1	117.3	145	10.8
		2	119.0	130	10.7
		3	116.7	125	11.2
	High	1	113.0	194	12.3
		2	113.1	177	12.8
		3	113.4	180	12.8
Lime-Fly Ash	Low	1	118.2	-	17.8
		2	118.2	-	18.0
		3	118.4	-	19.2
	Medium	1	116.9	221	13.1
		2	117.6	236	12.7
		3	117.5	253	12.6
	High	1	117.1	375	12.7
		2	116.3	450	12.6
		3	116.8	431	12.4
Lime	Low	1	116.4	52	15.0
		2	115.3	90	14.1
		3	115.6	47	14.7
	Medium	1	107.8	-	22.6
		2	109.4	-	23.2
		3	110.9	-	25.3
	High	1	105.1	-	-
		2	104.3	-	-
		3	104.7	-	-
Cement	Low	1	121.4	-	-
		2	122.2	-	-
		3	122.1	-	-
	Medium	1	119.9	145	12.0
		2	119.2	123	12.1
		3	119.5	99	12.5
	High	1	115.8	282	11.6
		2	116.5	297	11.5
		3	116.6	292	11.5

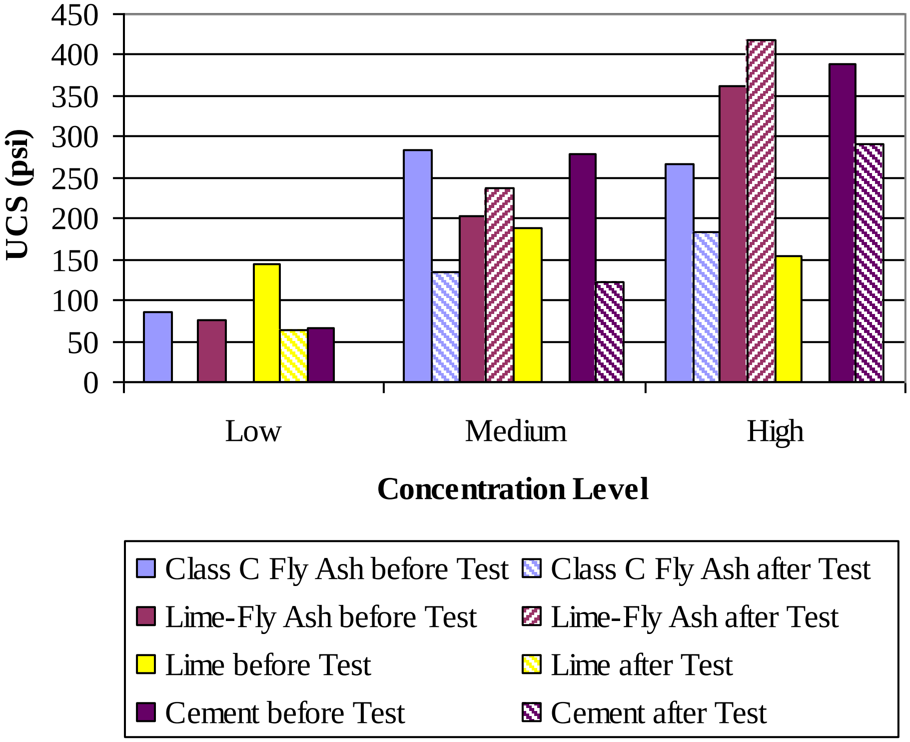

Figure 4.6 Sand freeze-thaw test results.

could not be measured. This was also the case for the specimens treated with the low concentrations of Class C fly ash and cement and the high concentration of lime. The specimens treated with a low concentration of lime-fly ash and a medium concentration of lime deteriorated to the point that a UCS test could not be performed; however, enough remained for the final moisture content to be determined. The higher the concentration of lime within the sand specimens, the more quickly they disintegrated during the testing. Among the lime-treated specimens, only specimens prepared at the low concentration could be tested for strength at the conclusion of freeze-thaw cycling, and these sustained significant strength loss compared to the treated control specimens tested at 7 days.

The final moisture contents of the sand specimens, as shown in Table 4.3, can be compared to the OMCs at which the specimens were originally prepared, which are displayed in Table 4.2. During freeze-thaw testing, the average water content of the sand specimens treated with lime-fly ash and lime increased by 1.9 and 4.4 percentage points, respectively, while the average water content of the sand specimens treated with Class C fly ash and cement actually decreased by 2.4 and 1.3 percentage points, respectively.

Figure 4.6 shows that, in general, most of the sand specimens lost strength during testing compared to the treated control specimens tested at 7 days. The only exceptions to this trend were the specimens treated with medium and high concentrations of lime-fly ash, which gained 17 and 16 percent strength, respectively. This strength gain may be in part attributable to the relatively long duration of the test. The pozzolanic reaction occurring between the lime and fly ash might have continued throughout the 5 weeks required to complete the freeze-thaw test, resulting in the observed strength gain. The lime-treated specimens lost all strength at the medium and high levels and nearly all strength at the low concentration. The cement-treated samples performed well at high concentration levels but lost significant strength at the low and medium levels. At the low concentration, all of the stabilizers except lime failed to strengthen the sand sufficiently to endure the freeze-thaw testing regime; although they lost significant strength, specimens treated with the low concentration of lime were still able to be tested for UCS at the conclusion of the freeze-thaw cycling.

Table 4.4 and Figure 4.7 present the data collected during the freeze-thaw test performed on the clay. All clay samples failed during the test, deteriorating to the point that neither UCS nor final moisture content could be obtained. Therefore, Table 4.4 instead reports the number of cycles until failure. Failure in each case was defined as the point at which the specimen completely disintegrated. In the case of the untreated clay, the specimens completely disintegrated during the 4-hour soaking period prior to the first freeze. Though number of cycles to failure is not an official criterion for measuring the performance of specimens in the freeze-thaw test, this was the only response variable available for comparing the relative performance of the 39 clay specimens tested in this research. As displayed in Figure 4.7, the high concentration level gave comparable results for each stabilizer, while the low and medium concentrations gave mixed results. While specimens treated at the low concentration of Class C fly ash performed poorly, specimens treated at the medium and high concentrations performed relatively well. For all stabilizers, specimens exhibited improved durability as the stabilizer concentration

Table 4.4 Clay Freeze-Thaw Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	Cycles to Failure
Untreated	-	1	105.1	0
		2	105.5	0
		3	105.7	0
Class C Fly Ash	Low	1	101.5	4
		2	99.2	3
		3	99.7	4
	Medium	1	101.3	11
		2	100.4	11
		3	100.7	11
	High	1	94.3	11
		2	95.2	11
		3	94.4	11
Lime-Fly Ash	Low	1	98.7	7
		2	97.7	7
		3	98.8	7
	Medium	1	98.3	11
		2	96.8	11
		3	96.0	11
	High	1	96.5	11
		2	95.6	11
		3	99.0	11
Lime	Low	1	94.2	8
		2	94.7	7
		3	94.5	8
	Medium	1	92.6	9
		2	98.2	9
		3	95.4	9
	High	1	92.1	11
		2	92.5	11
		3	91.7	11
Cement	Low	1	100.8	1
		2	101.3	1
		3	102.1	1
	Medium	1	98.0	6
		2	98.4	6
		3	97.4	6
	High	1	94.0	11
		2	93.7	11
		3	96.2	11

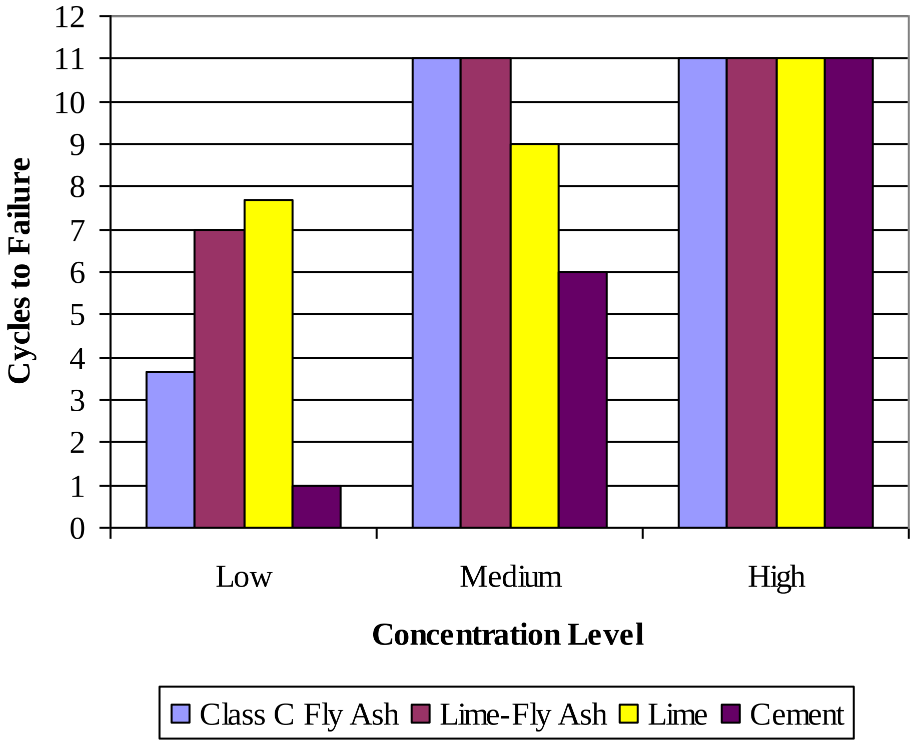

Figure 4.7 Clay freeze-thaw test results.

increased; however, an apparent ceiling exists with Class C fly ash and lime-fly ash, shown by the fact that durability was not improved as the concentration increased in each case from medium to high. This ceiling is not apparent with lime or cement within the ranges in concentrations used in this study.

Appendix A provides additional data collected for both the sand and clay materials during the freeze-thaw test, including weights measured during each freeze-thaw cycle and the final circumference of each surviving specimen. Appendix B displays photographs of each group of surviving specimens taken after curing but before testing and after 6 and 12 cycles of freezing and thawing.

4.5 VACUUM SATURATION TEST

Data collected during vacuum saturation testing on the sand specimens are shown in Table 4.5 and Figure 4.8. The untreated material deteriorated during the soaking stage and could not be tested for either UCS or final moisture content. All of the treated sand

Table 4.5 Sand Vacuum Saturation Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	UCS (psi)	Final Moisture (%)
Untreated	-	1	118.9	-	-
		2	119.3	-	-
		3	119.4	-	-
Class C Fly Ash	Low	1	120.1	37	14.5
		2	120.7	37	14.0
		3	119.4	33	15.1
	Medium	1	118.5	170	15.8
		2	119.1	178	15.7
		3	118.6	201	15.5
	High	1	113.0	114	18.8
		2	113.1	110	18.8
		3	113.5	125	18.7
Lime-Fly Ash	Low	1	119.9	103	15.5
		2	119.6	119	15.4
		3	118.6	115	15.3
	Medium	1	118.5	305	15.5
		2	118.3	337	15.5
		3	115.4	105	15.6
	High	1	117.6	475	15.8
		2	117.6	551	15.7
		3	118.0	383	15.4
Lime	Low	1	117.0	110	16.4
		2	116.9	97	16.3
		3	116.7	111	18.7
	Medium	1	110.4	82	18.7
		2	111.0	89	18.6
		3	110.9	92	18.6
	High	1	104.7	72	21.5
		2	104.5	73	21.5
		3	104.4	77	21.4
Cement	Low	1	118.9	60	14.4
		2	118.8	55	14.3
		3	118.4	57	14.7
	Medium	1	119.4	233	14.0
		2	119.1	241	14.5
		3	119.2	236	13.8
	High	1	118.8	228	14.5
		2	118.9	249	14.6
		3	118.7	236	14.3

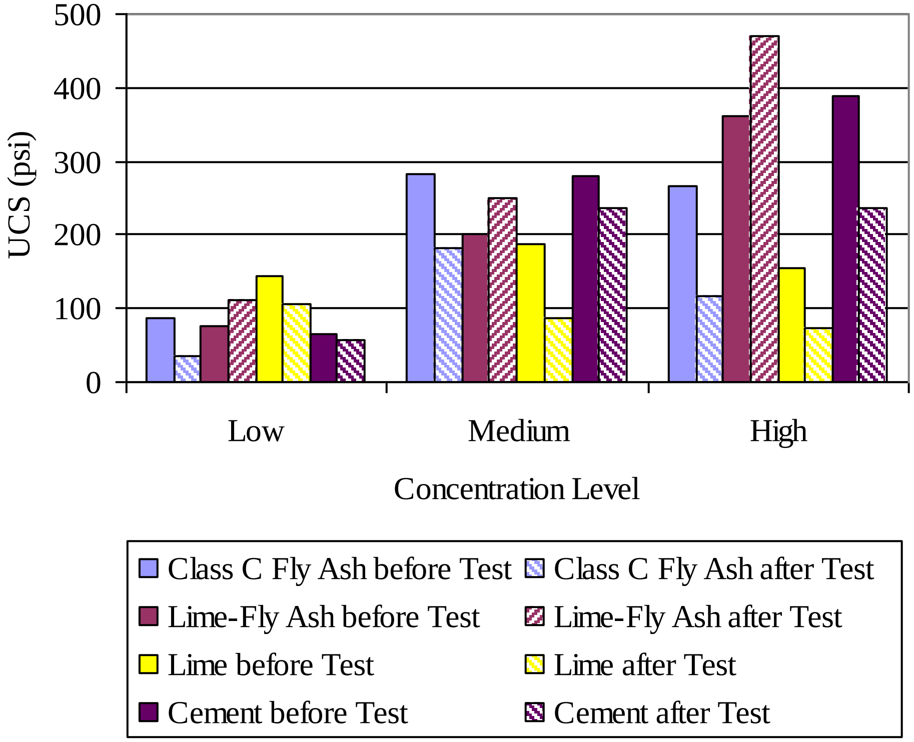

Figure 4.8 Sand vacuum saturation test results.

specimens lost strength compared to the control specimens tested at 7 days, with the exception of those treated at low, medium, and high concentrations of lime-fly ash, which experienced strength gains of 46, 23, and 30 percent, respectively. These strength gains cannot be attributed to prolonged pozzolanic activity, as the vacuum saturation test requires less than three hours to perform. Determining the reason for the observed strength gains in these particular specimens is beyond the scope of the current study and requires further investigation.

The final moisture contents of the sand specimens, as shown in Table 4.5, can be compared to the OMCs at which the specimens were originally prepared, which are displayed in Table 4.2. During vacuum saturation testing, the average water content of the sand specimens increased by an average of 2.8 percentage points.

Table 4.6 and Figure 4.9 present the data collected during the vacuum saturation testing on the clay material. The untreated material deteriorated during the soaking stage and could not be tested for UCS; however, a sufficient sample remained to enable

Table 4.6 Clay Vacuum Saturation Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	UCS (psi)	Final Moisture (%)
Untreated	-	1	99.2	-	25.8
		2	100.1	-	25.1
		3	100.9	-	24.0
Class C Fly Ash	Low	1	101.7	46	18.8
		2	100.4	48	20.7
		3	98.9	49	21.6
	Medium	1	98.7	82	22.6
		2	99.2	91	22.4
		3	100.6	106	21.3
	High	1	100.7	109	25.2
		2	101.1	120	25.0
		3	100.8	129	25.0
Lime-Fly Ash	Low	1	102.7	105	19.4
		2	102.6	48	19.4
		3	102.6	49	19.8
	Medium	1	100.8	82	20.7
		2	101.1	91	20.1
		3	100.3	106	20.9
	High	1	100.5	109	20.2
		2	100.9	120	20.0
		3	101.4	129	19.9
Lime	Low	1	94.0	65	25.7
		2	94.5	64	25.4
		3	94.9	60	25.1
	Medium	1	94.4	76	25.6
		2	94.3	76	25.7
		3	92.6	76	26.8
	High	1	90.9	91	28.6
		2	91.9	94	28.1
		3	92.0	87	28.2
Cement	Low	1	108.7	-	-
		2	108.7	-	-
		3	108.2	-	-
	Medium	1	107.5	88	14.5
		2	109.3	92	14.4
		3	108.6	99	13.9
	High	1	98.6	94	21.9
		2	99.8	119	21.4
		3	100.7	108	20.8

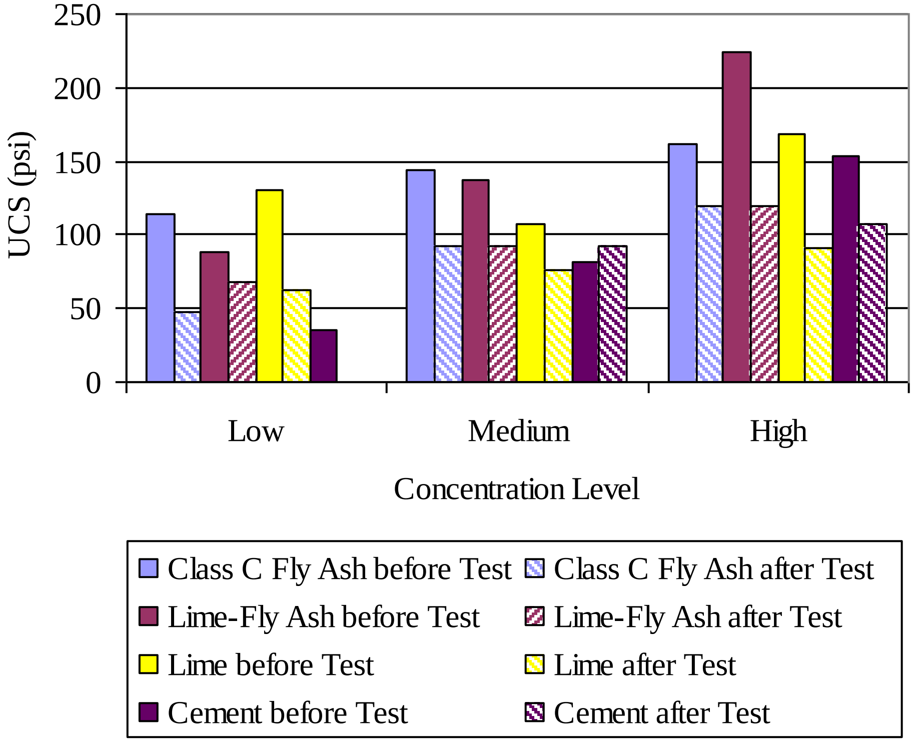

Figure 4.9 Clay vacuum saturation test results.

determination of the final moisture content. All of the treated clay specimens lost strength, with the exception of those treated at the medium concentration of cement, which gained 13 percent in strength. This relatively small discrepancy can probably be attributed to the variability inherent in specimen preparation and UCS testing; Figure 4.9 illustrates the variability in UCS between replicate specimens stabilized with cement. Specimens treated with a low concentration of cement deteriorated during the soaking stage and could not be tested for either UCS or final moisture content.

The final moisture contents of the clay specimens, as shown in Table 4.6, can be compared to the OMCs at which the specimens were originally prepared, which are displayed in Table 4.2. During vacuum saturation testing, the average water content of the clay specimens treated with Class C fly ash and lime increased by an average of 3.4 and 4.2 percentage points, respectively, while the average water content of the clay specimens treated with lime-fly ash and cement actually decreased by 1.3 and 5.5 percentage points, respectively.

4.6 TUBE SUCTION TEST

Table 4.7 and Figure 4.10 present results from tube suction testing on the sand. Without the addition of a stabilizer, the sand was “poor” with respect to moisture susceptibility, having an average final dielectric value of 22.3. As displayed in Figure 4.10, all stabilizers at all levels successfully reduced the dielectric value, with the medium concentration of cement giving the lowest value at 10.3 and the low concentration of Class C fly ash giving the highest value at 21.2. Dielectric values of specimens treated at all of the Class C fly ash concentrations, the low concentrations of both lime-fly ash and cement, and the high concentration of lime remained above 16, warranting moisture susceptibility ratings of “poor.” The moisture susceptibility ratings of all the other specimens are “marginal.”

The tube suction test did not cause significant water ingress in the sand specimens. In fact, on average, the sand specimens completed the test with an average water content 7.6 percentage points less than the respective OMCs at which they were compacted.

The results of the tube suction tests on clay are shown in Table 4.8 and Figure 4.11. Without the addition of a stabilizer, the clay was “poor” with respect to moisture susceptibility, having an average final dielectric value of 29.9. The high concentration of cement produced the lowest average dielectric value of 18.8, while the medium concentration of lime-fly ash produced the highest average dielectric value of 31.9. Thus, different than the trend observed for the sand specimens, not all of the average dielectric values of the treated clay specimens were lower than the average dielectric value of the untreated specimens. Furthermore, no stabilizer at any concentration was successful in reducing the moisture susceptibility of the clay from the “poor” rating according to the tube suction test criteria, although Figure 4.11 shows that stabilizing the clay with increasing amounts of Class C fly ash or cement does result in monotonically decreasing dielectric values within the ranges of concentrations evaluated in this study.

For the clay material, the tube suction test did cause significant water ingress. The specimens completed the test with an average water content 7.8 percentage points higher than the respective OMCs at which they were compacted.

Table 4.7 Sand Tube Suction Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	Final Dielectric Value	Final Moisture (%)
Untreated	-	1	121.9	23.1	9.5
		2	121.6	20.0	9.3
		3	118.1	23.8	10.9
Class C Fly Ash	Low	1	119.9	21.0	9.3
		2	121.0	22.4	8.8
		3	120.6	20.4	8.8
	Medium	1	119.5	14.8	7.7
		2	121.2	17.1	7.2
		3	121.1	16.3	7.3
	High	1	113.3	16.5	7.8
		2	114.0	14.9	7.9
		3	113.1	18.1	7.9
Lime-Fly Ash	Low	1	114.2	20.6	7.3
		2	118.6	15.7	5.6
		3	119.4	18.3	5.6
	Medium	1	118.6	17.0	4.4
		2	119.5	15.2	4.6
		3	119.3	15.4	4.1
	High	1	118.5	11.1	2.8
		2	119.1	10.8	2.6
		3	120.1	10.6	2.1
Lime	Low	1	117.7	15.7	5.3
		2	116.4	13.9	5.2
		3	117.4	14.3	5.2
	Medium	1	108.8	17.2	8.0
		2	110.4	14.0	7.7
		3	110.1	16.5	7.9
	High	1	103.8	21.6	10.3
		2	105.8	19.0	10.1
		3	104.9	20.0	9.9
Cement	Low	1	120.9	20.5	5.7
		2	120.6	16.9	5.1
		3	120.8	19.6	5.2
	Medium	1	120.0	8.8	0.5
		2	120.4	10.3	1.8
		3	120.3	12.0	1.9
	High	1	119.3	14.7	3.2
		2	120.2	13.5	3.0
		3	120.3	13.0	2.6

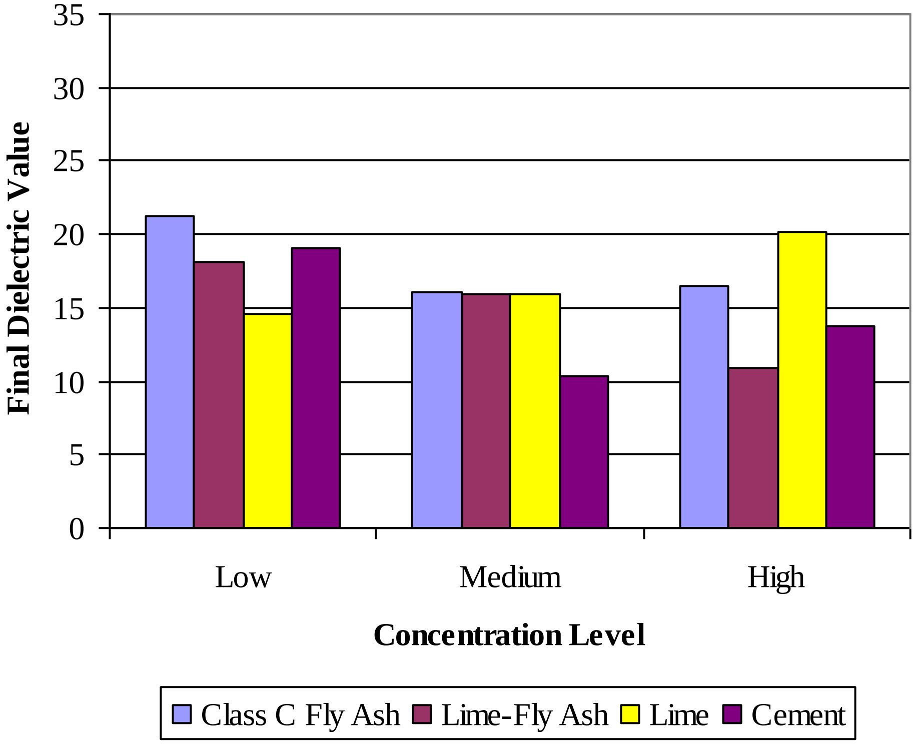

Figure 4.10 Sand tube suction test results.

Appendix A provides each dielectric value recorded daily during the testing, including the highest and lowest dielectric values that were excluded in the analyses of the tube suction test results.

Table 4.8 Clay Tube Suction Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	Final Dielectric Value	Final Moisture (%)
Untreated	-	1	107.9	30.3	13.7
		2	110.3	28.3	14.7
		3	103.9	31.3	18.5
Class C Fly Ash	Low	1	102.0	32.1	27.9
		2	100.8	22.9	28.1
		3	100.6	32.5	28.2
	Medium	1	101.8	25.3	26.2
		2	103.1	18.6	25.6
		3	104.3	25.3	25.3
	High	1	96.6	20.0	26.3
		2	95.9	17.5	26.8
		3	95.3	21.1	27.2
Lime-Fly Ash	Low	1	101.4	29.7	28.1
		2	96.9	32.7	30.9
		3	97.3	31.3	30.6
	Medium	1	95.8	30.6	31.3
		2	96.3	32.2	31.0
		3	95.8	32.8	31.5
	High	1	96.5	29.9	30.8
		2	95.5	28.5	31.5
		3	97.9	26.0	29.8
Lime	Low	1	94.8	28.0	31.4
		2	96.1	29.7	31.3
		3	96.0	31.0	31.1
	Medium	1	95.1	29.7	30.7
		2	95.3	27.6	29.9
		3	94.7	30.8	31.7
	High	1	92.8	30.7	31.2
		2	93.8	28.2	30.5
		3	93.8	31.6	31.0
Cement	Low	1	103.5	26.8	28.4
		2	102.6	25.0	29.1
		3	102.5	27.5	29.5
	Medium	1	100.7	28.0	29.2
		2	102.8	22.1	27.8
		3	100.0	20.9	29.8
	High	1	100.7	17.7	28.1
		2	101.1	19.9	28.1
		3	101.0	18.8	28.4

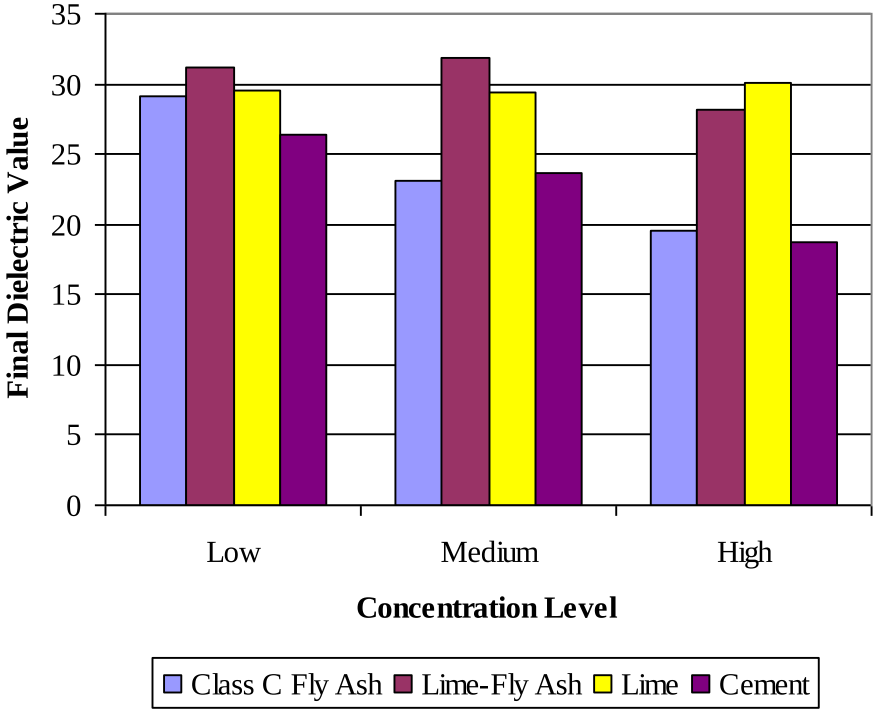

Figure 4.11 Clay tube suction test results.

4.7 STATISTICAL ANALYSES

Due to the different target strengths used for each material, statistical analyses of the sand and clay specimens were performed separately. Table 4.9 and Table 4.10 show the *p*-values computed in the ANOVA for each factor, including main effects and interactions, for the sand and clay, respectively. The tables show the significance levels associated with the reduced model in each case. As described in Section 3.5, only

Table 4.9 Significance Levels for Main Effects and Interactions for Sand

Factor	*p* -values				
	Freeze-Thaw Test		Vacuum Saturation Test		Tube Suction Test
	UCS	Retained UCS	UCS	Retained UCS	Dielectric Value
Stabilizer Type	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Concentration Level	<0.0001	<0.0001	<0.0001	-	<0.0001
Stabilizer Type * Concentration Level	<0.0001	<0.0001	<0.0001	-	<0.0001

Table 4.10 Significance Levels for Main Effects and Interactions for Clay

Factor	*p* -values		
	Vacuum Saturation Test		Tube Suction Test
	UCS	Retained UCS	Dielectric Value
Stabilizer Type	0.0006	0.529	<0.0001
Concentration Level	<0.0001	<0.0001	0.0004
Stabilizer Type * Concentration Level	<0.0001	<0.0001	0.0371

factors having *p*-values less than or equal to 0.15 have been included; the hyphens in the table indicate that the *p*-values in those cases exceeded 0.15. Because every clay specimen failed during freeze-thaw testing, all freeze-thaw data collected on clay specimens were omitted from the analyses. In Table 4.10, the *p*-value associated with stabilizer type for retained UCS after vacuum saturation testing is greater than 0.15; this factor was included in the analysis because the interaction involving stabilizer type and concentration level is significant, as indicated by a *p*-value equal to or less than 0.05. A discussion of the statistical analyses relating to the main effects and interactions is given in the following sections.

4.7.1 Main Effects

Table 4.11 contains the least square mean values associated with the main effects of stabilizer type for the sand material. The least square mean is the best estimate of the subpopulation mean for a given level of a given factor (*43*). In a balanced experiment such as the one conducted in this study, the least square mean equals the arithmetic mean

Table 4.11 Least Square Means for Main Effects of Stabilizer Type for Sand

Test	Response Variable	Class C Fly Ash	Lime-Fly Ash	Lime	Cement
Freeze-Thaw	UCS (psi)	106	218	21	137
	Retained UCS (%)	39	78	15	39
Vacuum Saturation	UCS (psi)	112	277	89	177
	Retained UCS (%)	50	120	56	78
Tube Suction	Dielectric Value	18	15	17	14

for each subpopulation. With respect to comparing the different stabilizers investigated in this research, the results of Tukey’s mean separation procedure indicated that UCS values after freeze-thaw cycling are significantly different for each stabilizer. Likewise, each stabilizer yielded a significantly different percentage of retained strength after freeze-thaw cycling, with the exception of Class C fly ash and cement, which were not determined to be significantly different. Although Table 4.11 displays some differences in values obtained from vacuum saturation testing on specimens treated with Class C fly ash and lime, Tukey’s mean separation procedure showed that these stabilizer types are not significantly different from each other with respect to UCS. Similarly, lime is not significantly different than Class C fly ash or cement with respect to retained UCS after vacuum saturation testing; however, Class C fly ash and cement are significantly different from one another. The two lowest dielectric values, given by lime-fly ash and cement, are not significantly different from one another but are significantly lower than the values given by either Class C fly ash or lime. This indicates that lime-fly ash and cement were effective at reducing the moisture susceptibility of the sand from “poor” to “marginal,” while Class C fly ash and lime were not successful at reducing the moisture susceptibility of the sand.

Table 4.11 also shows that, on average, the UCS and retained UCS were higher for specimens tested in vacuum saturation than the corresponding values associated with freeze-thaw testing. This observation suggests that, for sand being treated at target 7-day UCS values within the range of 100 to 300 psi, the freeze-thaw test is more severe than the vacuum saturation test. Furthermore, the fact that no clay specimens survived freeze-thaw cycling, while the majority were able to be tested after vacuum saturation, indicates that the freeze-thaw test is more severe than the vacuum saturation test for the materials evaluated in this research. The severity of the freeze-thaw test may be attributed to the high moisture susceptibility of the sand and the clay, which, during each soaking period, draw in significant amounts of water that then expands during the freezing cycle as it changes to ice. The expansion of absorbed water upon freezing causes worse deterioration of the specimens than that induced by vacuum saturation, in which the specimens are subjected to higher moisture contents but not to freezing. Also, the relatively low target strengths of 100, 125, and 150 psi used for the clay may not be sufficient to effectively combat freeze-thaw damage in this clay, regardless of the stabilizer type.

Table 4.12 contains the least square mean values associated with the main effects of concentration level for the sand material. Both UCS and retained UCS after the freeze-thaw test increase with increasing concentrations. According to the results of Tukey's mean separation procedure, the UCS values of the medium and high concentrations after the vacuum saturation test are not significantly different, but they are both significantly higher than that of the low concentration. Similarly, the dielectric values of the medium and high concentrations in the tube suction test are not significantly different, but they are both significantly higher than that of the low concentration. The percent of retained UCS after the vacuum saturation test was not significantly affected by the concentration level.

The least square mean values associated with the main effects of stabilizer type and concentration level for the clay material are presented in Table 4.13 and Table 4.14, respectively. With respect to UCS after vacuum saturation testing, the results of Tukey's mean separation procedure indicate that lime-fly ash and Class C fly ash are not significantly different, Class C fly ash and lime are not significantly different, and lime

Table 4.12 Least Square Means for Main Effects of Concentration Level for Sand

Test	Response Variable	Low	Medium	High
Freeze-Thaw	UCS (psi)	16	123	223
	Retained UCS (%)	11	52	65
Vacuum Saturation	UCS (psi)	78	189	224
Tube Suction	Dielectric Value	18	15	15

Table 4.13 Least Square Means for Main Effects of Stabilizer Type for Clay

Test	Response Variable	Class C Fly Ash	Lime-Fly Ash	Lime	Cement
Vacuum Saturation	UCS (psi)	87	93	77	67
	Retained UCS (%)	60	66	58	61
Tube Suction	Dielectric Value	24	30	30	23

Table 4.14 Least Square Means for Main Effects of Concentration Level for Clay

Test	Response Variable	Low	Medium	High
Vacuum Saturation	UCS (psi)	44	89	109
	Retained UCS (%)	42	79	63
Tube Suction	Dielectric Value	29	27	24

and cement are not significantly different. However, the UCS associated with cement is significantly lower than the corresponding values of both Class C fly ash and lime fly ash, and the UCS associated with lime is significantly lower than that of lime-fly ash. With respect to UCS retained after vacuum saturation testing, no stabilizer was determined to be significantly different from another. With respect to the dielectric value, lime-fly ash and lime are not significantly different from one another, nor are the Class C fly ash and cement significantly different from one another; however, the dielectric values associated with Class C fly ash and cement are both significantly lower than those of lime-fly ash and lime.

As shown in Table 4.14, increasing the concentration level increased the UCS and retained UCS after the vacuum saturation test. With respect to the dielectric value, Tukey’s mean separation procedure showed that the low and medium concentrations were not significantly different from one another, but both had dielectric values significantly higher than the high concentration.

4.7.2 Interactions

ANOVA results indicate that the two-way interaction between stabilizer type and concentration level was significant in one or more of the tests. Table 4.15 lists the least square mean values for this interaction for the sand material, while Figure 4.12 through Figure 4.15 show the extent to which the effects of stabilizer type depend on concentration level for each response variable included in the research. Data relating to UCS retained after vacuum saturation testing are missing from Table 4.15 because the interaction between stabilizer type and concentration level was not significant for this particular response variable. Missing bars in the figures indicate a least square mean value of zero.

Table 4.15 Least Square Means for Interactions between Stabilizer Type and Concentration Level for Sand

Stabilizer Type	Concentration Level	Freeze-Thaw Test		Vacuum Saturation Test	Tube Suction Test
		UCS (psi)	Retained UCS (%)	UCS (psi)	Dielectric Value
Class C Fly Ash	Low	0	0	36	21
	Medium	133	47	183	16
	High	184	69	470	17
Lime-Fly Ash	Low	0	0	113	18
	Medium	237	117	249	16
	High	418	116	470	11
Lime	Low	63	0	106	15
	Medium	0	44	87	16
	High	0	0	74	20
Cement	Low	0	0	58	19
	Medium	122	44	237	10
	High	290	75	238	14

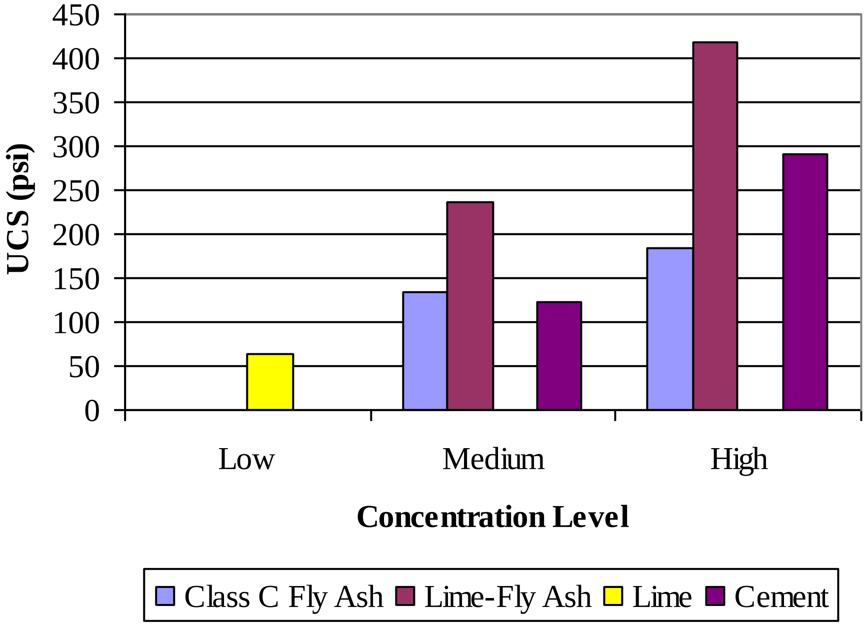

Figure 4.12 Interaction between stabilizer type and concentration type for UCS after the freeze-thaw testing of sand.

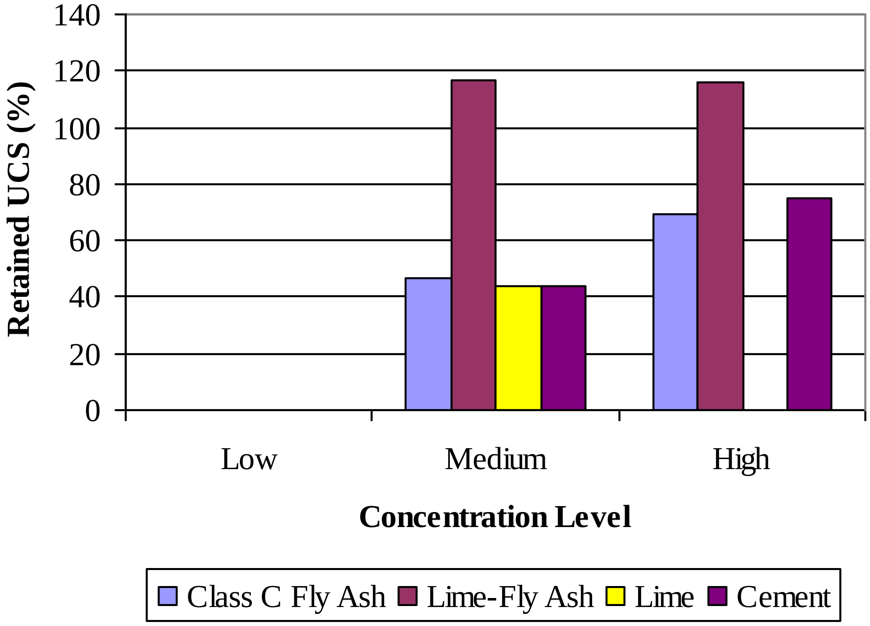

Figure 4.13 Interaction between stabilizer type and concentration type for retained UCS after the freeze-thaw testing of sand.

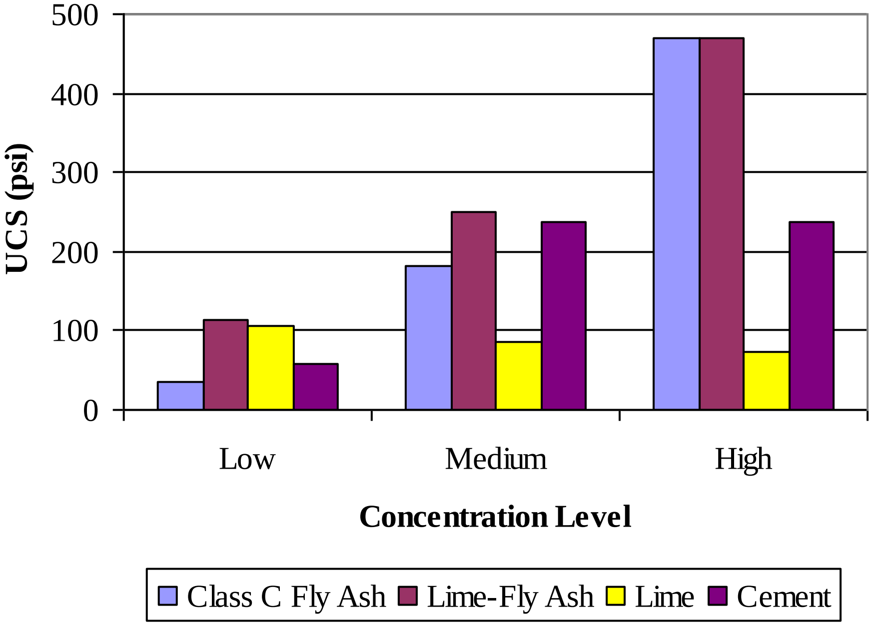

Figure 4.14 Interaction between stabilizer type and concentration type for UCS after the vacuum saturation testing of sand.

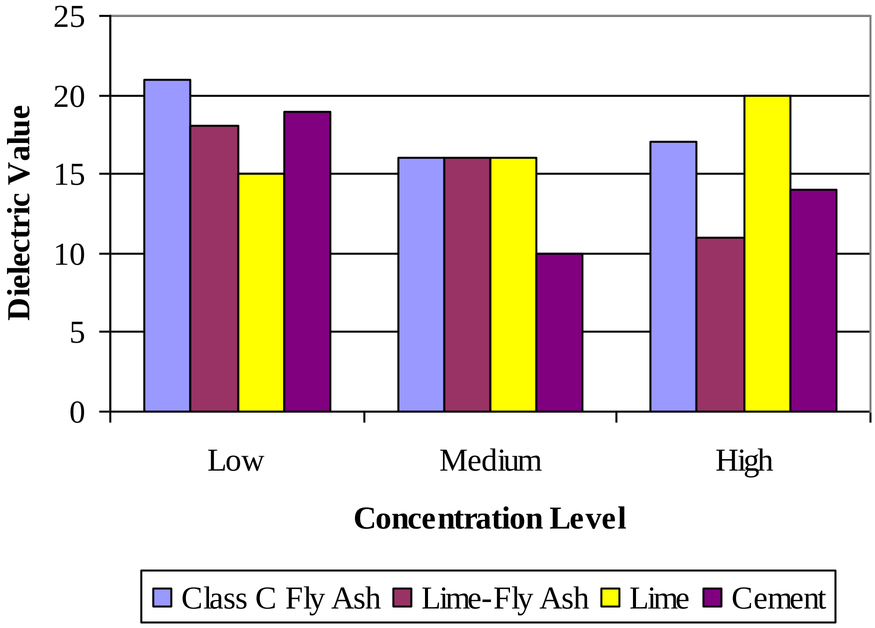

Figure 4.15 Interaction between stabilizer type and concentration type for dielectric value after the tube suction testing of sand.

Table 4.16 contains the least square mean values for interactions between stabilizer type and concentration level for the clay, while Figure 4.16 throughFigure 4.18 show the extent to which the effects of stabilizer type depend on concentration level for each response variable.

Table 4.16 Least Square Means for Interactions between Stabilizer Type and Concentration Level for Clay

Stabilizer Type	Concentration Level	Vacuum Saturation Test		Tube Suction Test
		UCS (psi)	Retained UCS (%)	Dielectric Value
Class C Fly Ash	Low	48	42	29
	Medium	93	64	23
	High	119	74	20
Lime-Fly Ash	Low	67	77	31
	Medium	93	68	32
	High	119	53	28
Lime	Low	90	48	30
	Medium	76	71	29
	High	90	54	30
Cement	Low	0	0	26
	Medium	93	114	24
	High	107	70	19

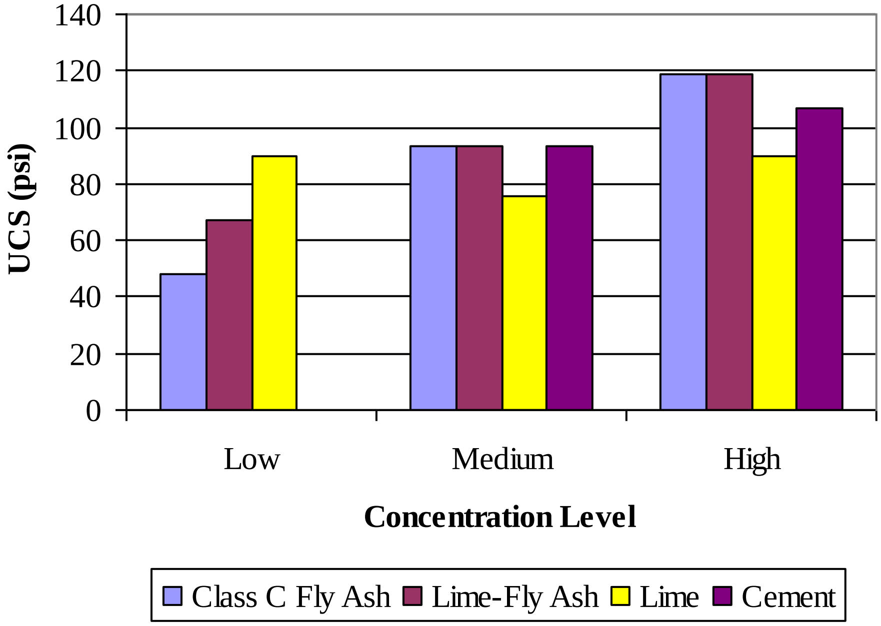

Figure 4.16 Interaction between stabilizer type and concentration level for UCS after the vacuum saturation testing of clay.

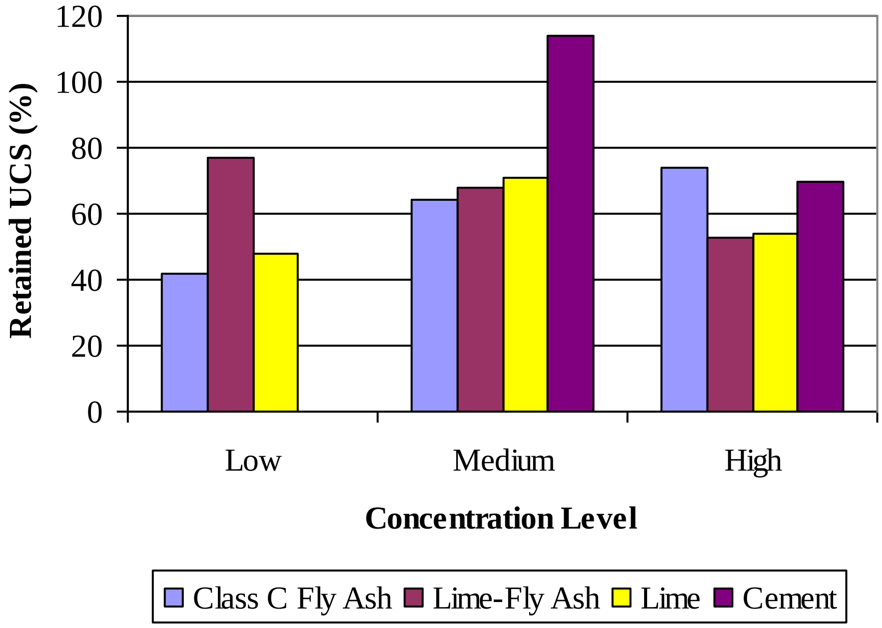

Figure 4.17 Interaction between stabilizer type and concentration level for retained UCS after the vacuum saturation testing of clay.

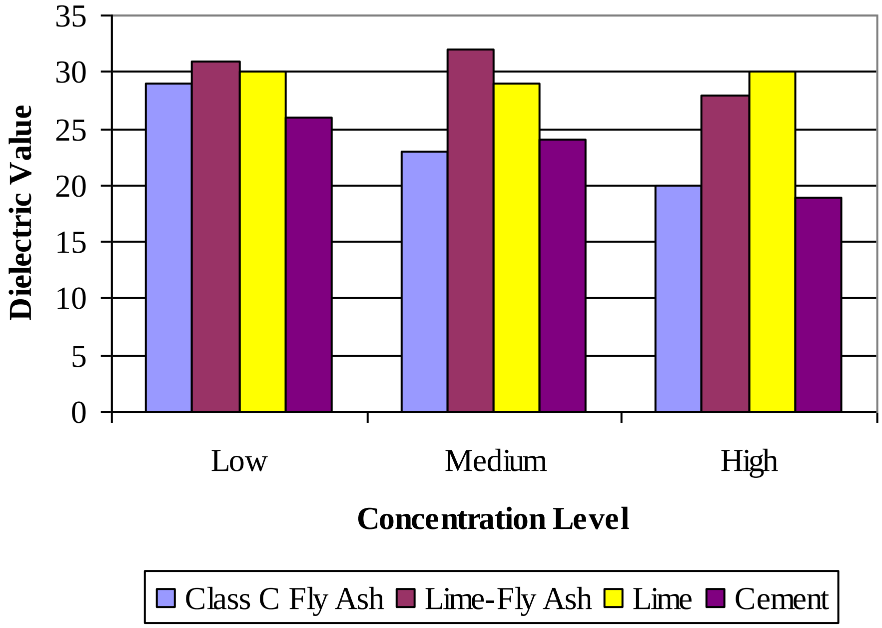

Figure 4.18 Interaction between stabilizer type and concentration level for dielectric value after the tube suction testing of clay.

4.7.3 Correlations

Figure 4.19 to Figure 4.23 present correlations between the results of freeze-thaw, vacuum saturation, and tube suction tests. Because UCS data associated with freeze-thaw testing could not be collected for the clay material, the figures report only the data collected for the sand material where freeze-thaw data are applicable; otherwise, sand and clay data are presented together. Each figure includes the trend line representing the results of linear regression performed to examine the relationship between the two variables displayed in each plot. Figure 4.19 shows a plot of UCS after freeze-thaw cycling versus UCS after vacuum saturation. The R^2 value associated with this correlation is comparatively high at 0.8337. Figure 4.20 is a plot of UCS after freeze-thaw cycling versus final dielectric value. The corresponding R^2 value associated with this correlation is 0.5061. Figure 4.21 is a plot of UCS after the vacuum saturation test versus final dielectric value. The corresponding R^2 value associated with this correlation is 0.4183. Retained UCS after freeze-thaw cycling is compared with final dielectric value in the tube suction test in Figure 4.22, while retained UCS after vacuum saturation

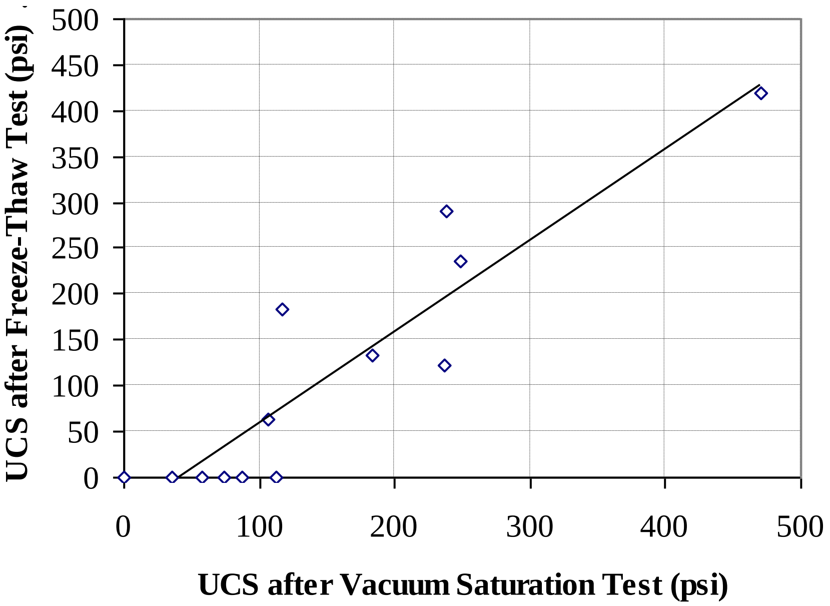

Figure 4.19 Correlation between UCS after the freeze-thaw test and UCS after the vacuum saturation test.

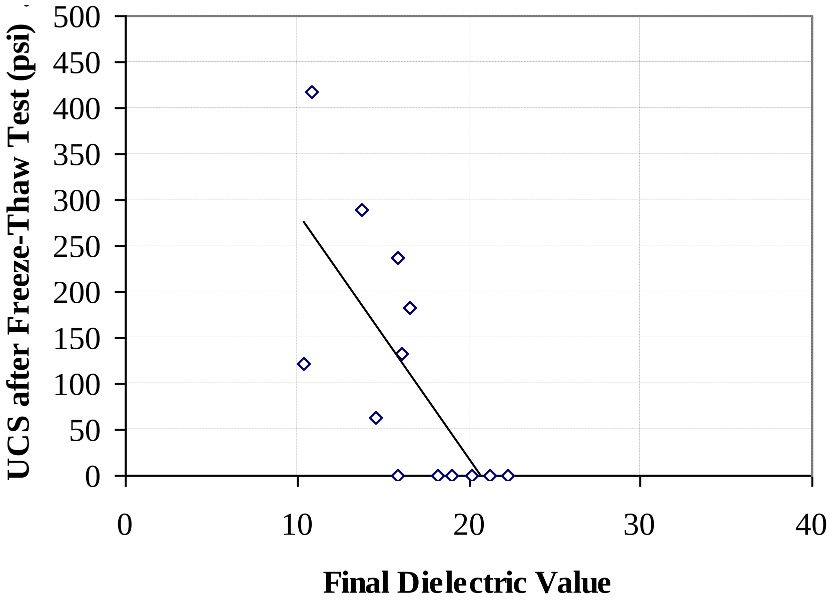

Figure 4.20 Correlation between UCS after the freeze-thaw test and final dielectric value in the tube suction test.

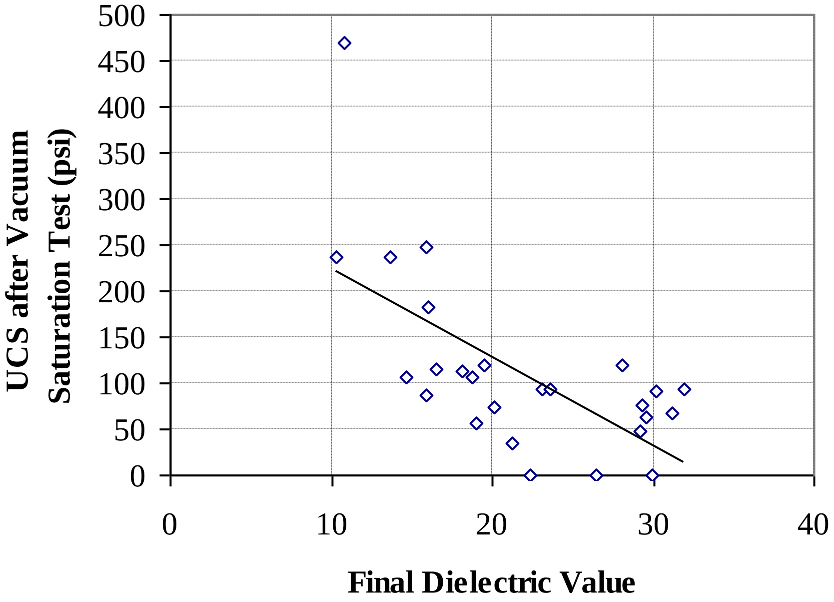

Figure 4.21 Correlation between UCS after the vacuum saturation test and final dielectric value in the tube suction test.

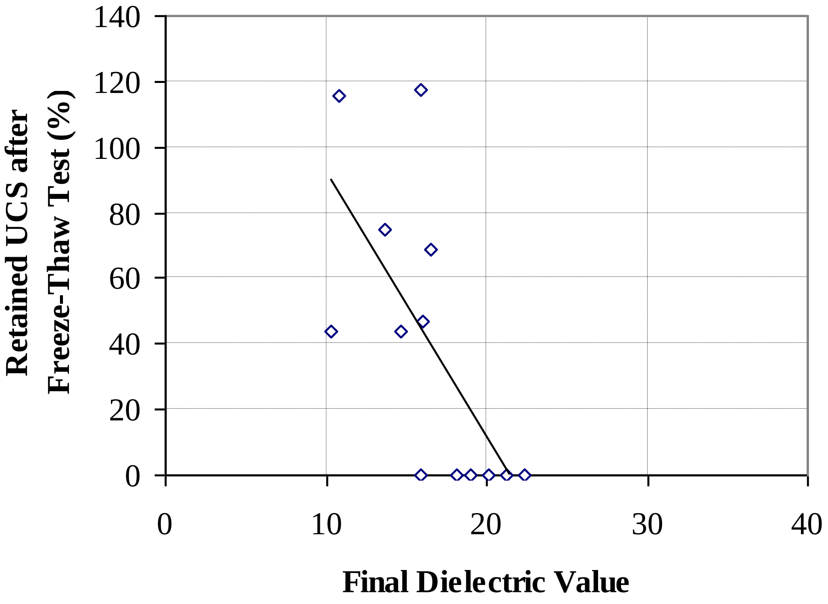

Figure 4.22 Correlation between retained UCS after the freeze-thaw test and final dielectric value in the tube suction test.

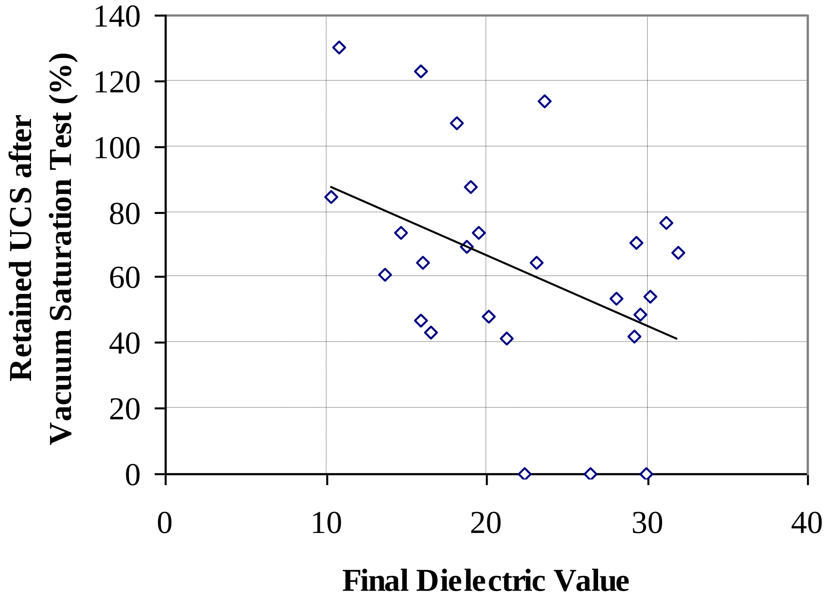

Figure 4.23 Correlation between retained UCS after the vacuum saturation test and final dielectric value in the tube suction test.

is compared with final dielectric value in the tube suction test in Figure 4.23. The corresponding R^2 values for these relationships are 0.4319 and 0.1780, respectively.

4.7.4 Coefficient of Variation

The CV is a measure of the variability among replicate samples and is computed by dividing the standard deviation associated with a particular set of measurements by the mean of the same distribution (*43*). For this research, three replicate specimens were created for each unique combination of aggregate type, stabilizer type, and stabilizer concentration level. The computed means, standard deviations, and CVs for each unique combination are shown in Table 4.17. Hyphens in the table represent specimens that failed during testing. For all sand and clay specimens, the average CVs for UCS after freeze-thaw cycling, UCS after vacuum saturation, and dielectric value after tube suction testing are 12.5, 10.7, and 8.3 percent, respectively. An ANOVA was performed to determine if differences between population means were present, where the CV data for a given test type represented a single population. The null hypothesis of the ANOVA was that the CV population means were all equal, while the alternative hypothesis was that at least one population mean was significantly different from the others. Since the analysis yielded a *p*-value of 0.517, insufficient evidence exists to claim that the differences in the computed CVs are statistically significant, or that any one of the tests is more repeatable than another.

Table 4.17 Means, Standard Deviations, and Coefficients of Variation

Aggregate Type	Stabilizer Type	Concentration Level	Freeze-Thaw Test			Vacuum Saturation Test			Tube Suction Test		
			Mean UCS (psi)	St. Dev.	CV (%)	Mean UCS (psi)	St. Dev.	CV (%)	Mean Dielectric Value	St. Dev.	CV (%)
Sand	Untreated	-	-	-	-	-	-	-	22.3	2.0	9.0
	Class C Fly Ash	Low	-	-	-	36	2.1	5.9	21.2	1.0	4.8
		Medium	133	10.3	7.8	183	16.1	8.8	16.1	1.2	7.5
		High	184	9.3	5.1	116	7.8	6.7	16.5	1.6	9.7
	Lime-Fly Ash	Low	-	-	-	113	8.3	7.3	18.2	2.4	13.4
		Medium	237	15.9	6.7	249	125.5	50.4	15.9	1.0	6.1
		High	418	38.9	9.3	470	84.5	18.0	10.8	0.3	2.4
	Lime	Low	63	23.5	37.2	106	7.9	7.4	14.6	0.9	6.5
		Medium	-	-	-	88	5.3	6.0	15.9	1.7	10.5
		High	-	-	-	74	2.9	3.9	20.2	1.3	6.4
	Cement	Low	-	-	-	58	2.8	4.9	19.0	1.9	9.8
		Medium	122	22.7	18.5	237	4.0	1.7	10.3	1.6	15.6
		High	290	7.7	2.7	238	10.8	4.5	13.7	0.9	6.5
Clay	Untreated	-	-	-	-	-	-	-	29.9	1.5	5.0
	Class C Fly Ash	Low	-	-	-	48	1.6	3.3	29.2	5.4	18.7
		Medium	-	-	-	93	12.1	13.0	23.1	3.8	16.7
		High	-	-	-	119	10.0	8.4	19.5	1.8	9.3
	Lime-Fly Ash	Low	-	-	-	67	32.6	48.4	31.2	1.5	4.8
		Medium	-	-	-	93	12.1	13.0	31.9	1.1	3.6
		High	-	-	-	119	10.0	8.4	28.1	2.0	7.0
	Lime	Low	-	-	-	63	2.9	4.6	29.6	1.5	5.0
		Medium	-	-	-	76	0.0	0.0	29.4	1.7	5.6
		High	-	-	-	90	3.6	4.0	30.1	1.8	5.9
	Cement	Low	-	-	-	-	-	-	26.4	1.3	5.0
		Medium	-	-	-	93	5.6	6.0	23.7	3.8	16.0
		High	-	-	-	107	12.8	11.9	18.8	1.1	5.8

4.8 SUMMARY

Results from freeze-thaw cycling and vacuum saturation testing indicate that nearly all the sand specimens lost strength during testing in comparison with the treated control specimens tested at 7 days. The sand specimens treated with medium and high concentrations of lime-fly ash tested in freeze-thaw cycling were exceptions to this trend; in these cases, the specimens gained appreciable strength during testing, probably due to continuing pozzolanic reactivity. The magnitude of strength loss for all other sand specimens depended on stabilizer type, concentration level, and test type. All stabilizers were able to reduce the moisture susceptibility of the sand material in the tube suction test with varying degrees of success, with the medium concentration of cement producing the best results.

The clay material failed the freeze-thaw test in every instance. Clay specimens treated at all concentrations of all stabilizers lost strength during the vacuum saturation test with the exception of the medium concentration of cement, which gained minor strength. No stabilizer at any concentration was successful in reducing the moisture susceptibility of the clay from the “poor” rating according to the criteria given in the tube suction test.

Following data collection, an ANOVA was performed on the sand and clay data separately. For both the sand and clay materials, the ANOVA showed that the main effects of stabilizer type and concentration level, as well as the interaction between these two variables, were significant for all measured response variables except retained UCS after vacuum saturation testing. In the case of the sand, neither the concentration level nor the interaction between stabilizer type and concentration level were significant. For the clay, stabilizer type was not significant but was included in the analysis because the interaction between stabilizer type and concentration level was significant.

A comparatively strong correlation between freeze-thaw cycling and vacuum saturation data was identified, but the tube suction test data did not correlate well with either the freeze-thaw or the vacuum saturation test data. Differences in variability between test results were determined to be statistically insignificant in an analysis of the CVs associated with data collected in this research.

CHAPTER 5

CONCLUSION

5.1 SUMMARY

PCA commissioned a research project at BYU to compare selected laboratory durability tests available for assessing stabilized subgrade materials. Improved understanding of these tests is needed to enable more objective selection of durability tests by design engineers and to facilitate more meaningful comparisons of data obtained for different stabilizer treatments using different evaluation procedures. The laboratory research associated with this project involved two subgrade materials, four stabilizers at three concentrations each, and three durability tests in a full-factorial experimental design. The two subgrade soils used were a silty sand and a lean clay, while the four stabilizer types included Class C fly ash, lime-fly ash, lime, and Type I/II portland cement. The three tests used in this comparative study were the freeze-thaw test, the vacuum saturation test, and the tube suction test.

5.2 FINDINGS

On average, to achieve the same 7-day UCS values, the sand required 4.4 times more Class C fly ash than cement, 3.6 times more lime-fly ash than cement, and 6.0 times more lime than cement. Likewise, the clay required 10 times more Class C fly ash than cement, 7.5 times more lime-fly ash than cement, and 1.8 times more lime than cement. Analyses of the test results indicated that the UCS and retained UCS were higher for specimens tested by vacuum saturation than the corresponding values associated with freeze-thaw cycling. This observation suggests that the freeze-thaw test is more severe than the vacuum saturation test for these particular fine-grained materials. Testing also suggested that specimens exhibiting 7-day UCS values below 200 psi will generally not survive freeze-thaw cycling.

After both freeze-thaw and vacuum saturation testing, the sand specimens treated with lime-fly ash had significantly higher UCS and retained UCS than specimens treated with Class C fly ash, lime, or cement. Similarly, the clay specimens treated with Class C fly ash or lime-fly ash had significantly higher UCS values than specimens treated with cement or lime; however, clay specimens treated with Class C fly ash and lime-fly ash were not significantly different. None of the four stabilizer types were significantly different from each other with respect to retained UCS after vacuum saturation testing.

Dielectric values measured in tube suction testing 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 dielectric value of sand specimens to a "marginal" rating, while no stabilizer reduced the moisture susceptibility of the clay to a satisfactory level.

A strong correlation was identified between UCS after the freeze-thaw test and UCS after the vacuum saturation test, while very weak correlations were observed between the final dielectric value after tube suction testing and all other response variables. Differences in variability between test results were determined to be statistically insignificant in an analysis of the CVs associated with data collected in this research.

5.3 RECOMMENDATIONS

Although the freeze-thaw test utilized in this research was determined to be more severe than the vacuum saturation test for materials similar to those tested in this study, the vacuum saturation test is recommended over both the freeze-thaw and tube suction tests because of the shorter test duration, usability for specimens with 7-day UCS values even below 200 psi, and lack of a need for daily specimen monitoring. Although the lime-fly ash used in this research performed well, further investigation of various sources of fly ash for use with lime in treating subgrade soils is recommended because of the variability inherent in fly ash composition. Further research should also be performed on other types of soils. Research related to long-term field performance of stabilized materials should be conducted to develop appropriate thresholds for laboratory UCS values in conjunction with vacuum saturation testing.

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APPENDIX A:
ADDITIONAL TEST RESULTS

Table A.1 Sand OMC and MDD Values

Stabilizer Type	Stabilizer Concentration (%)	Moisture Content (%)	Dry Density (pcf)	OMC (%)	MDD (pcf)
Untreated	-	7.5	112.3	12.0	120.4
		10.2	118.1		
		12.2	120.4		
		14.2	116.4		
		16.0	112.6		
Class C Fly Ash	10	8.5	110.9	11.0	113.2
		10.4	113.3		
		13.5	110.3		
	20	11.5	109.1	16.0	114.4
		15.2	114.4		
		17.7	111.6		
	40	12.3	107.0	15.8	110.3
		14.5	110.3		
		17.5	107.6		
Lime-Fly Ash	5	11.1	114.0	12.8	116.2
		13.1	116.2		
		14.7	114.1		
	10	11.7	113.6	12.6	116.4
		13.5	116.4		
		15.9	112.3		
	18	10.6	113.7	12.3	115.0
		12.0	114.9		
		13.9	114.5		
		16.4	111.0		
Lime	5	11.6	110.4	14.0	114.5
		13.3	112.9		
		14.8	114.4		
		18.9	107.5		
	15	14.4	108.6	15.6	110.3
		16.2	110.4		
		19.2	105.7		
	30	16.1	97.7	19.0	100.4
		18.9	100.3		
		21.6	99.4		
		22.3	98.5		

Table A.2 Clay OMC and MDD Values

Stabilizer Type	Stabilizer Concentration (%)	Moisture Content (%)	Dry Density (pcf)	OMC (%)	MDD (pcf)
Untreated	-	19.5	98.6	22.5	100.8
		22.8	100.4		
		25.6	95.5		
		38.7	72.2		
Class C Fly Ash	10	15.2	95.6	19.5	99.8
		19.3	99.9		
		25.3	96.2		
		28.0	91.9		
	20	18.3	99.9	20.0	102.2
		19.7	102.4		
		21.2	101.4		
		25.5	95.6		
	30	13.8	94.2	17.8	98.0
		16.3	97.1		
		18.3	97.9		
		20.0	94.9		
Lime-Fly Ash	7.5	20.2	95.6	21.5	97.0
		21.8	96.8		
		23.2	91.7		
		24.7	93.4		
		26.2	94.1		
		27.1	92.5		
	15	19.3	95.1	21.4	96.6
		21.4	96.6		
		23.1	94.0		
		26.0	92.3		
Lime	2	12.9	91.3	19.5	100.0
		20.4	99.3		
		33.3	80.0		
	4	20.7	88.6	23.0	94.1
		22.6	94.1		
		29.5	91.5		
	8	21.5	90.5	24.3	92.6
		24.0	92.5		
		26.7	92.0		

Table A.3 Sand 7-Day UCS Values

Stabilizer Type	Stabilizer Concentration (%)	Specimen	UCS (psi)
Untreated	-	1	37
		2	37
		3	39
Class C Fly Ash	2.0	1	71
		2	85
		3	103
	6.0	1	125
		2	143
	10.0	1	186
		2	192
	11.0	1	269
		2	265
		3	315
	12.0	1	242
		2	236
	20.0	1	360
		2	266
		3	176
	40.0	1	266
		2	329
Lime-Fly Ash	5.0	1	84
		2	89
		3	57
	7.0	1	104
		2	120
	9.0	1	156
		2	162
		3	288
	10.0	1	361
		2	289
	13.0	1	271
		2	387
		3	426
	18.0	1	493
		2	594
Lime	5.0	1	86
		2	84
		3	262
	15.0	1	170
		2	178
		3	214
	25.0	1	66
		2	208
		3	188
	30.0	1	111
		2	93
Cement	0.5	1	72
		2	67
		3	57
	1.0	1	134
	2.0	1	168
	2.5	1	285
		2	281
		3	275
	4.0	1	310
	4.5	1	311
		2	457
		3	399
	6.0	1	350
	10.0	1	453

Table A.4 Clay 7-Day UCS Values

Stabilizer Type	Stabilizer Concentration (%)	Specimen	UCS (psi)
Untreated	-	1	56
		2	57
		3	60
Class C Fly Ash	10.0	1	111
		2	90
		3	139
	20.0	1	126
		2	128
		3	179
	30.0	1	147
		2	144
		3	194
	40.0	1	186
		2	204
Lime-Fly Ash	7.5	1	45
		2	45
	10.0	1	84
		2	117
		3	62
	15.0	1	120
		2	127
		3	164
	20.0	1	209
		2	233
		3	229
	23.0	1	168
		2	159
Lime	2.0	1	85
		2	87
	3.0	1	97
		2	113
		3	179
	3.5	1	107
		2	93
		3	125
	4.0	1	147
		2	157
		3	199
	8.0	1	171
		2	176
Cement	1.0	1	36
		2	33
		3	36
	2.0	1	78
		2	86
		3	81
	3.0	1	165
		2	170
		3	128
	4.0	1	219
		2	217
	6.0	1	351
		2	325
	7.0	1	177
		2	264
	8.0	1	419
		2	401
	10.0	1	470
		2	384
		3	325
		4	349

Table A.5 Additional Sand Freeze-Thaw Test Results

Stabilizer	Stabilizer Concentration (%)	Specimen	Frozen Weight per Freeze-Thaw Cycle (lb)												Final Circumference (in.)
			1	2	3	4	5	6	7	8	9	10	11	12	
Untreated	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
		2	-	-	-	-	-	-	-	-	-	-	-	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-
Class C Fly Ash	2	1	4.010	-	-	-	-	-	-	-	-	-	-	-	-
		2	3.998	-	-	-	-	-	-	-	-	-	-	-	-
		3	3.960	-	-	-	-	-	-	-	-	-	-	-	-
	11	1	4.179	4.173	4.078	3.982	3.838	3.666	3.563	3.357	3.180	3.038	2.982	2.954	12.45
		2	4.197	4.190	4.124	4.051	3.985	3.944	3.857	3.743	3.619	3.546	3.522	3.481	12.57
		3	4.206	4.192	4.112	3.954	3.795	3.632	3.491	3.287	3.098	2.932	2.841	2.683	11.76
	20	1	4.308	4.305	4.302	4.303	4.301	4.304	4.305	4.394	4.291	4.289	4.286	4.286	12.57
		2	4.091	4.089	4.089	4.091	4.084	4.084	4.081	4.074	4.070	4.065	4.062	4.063	12.57
		3	4.014	4.011	4.006	4.006	4.000	4.000	3.993	3.985	3.980	3.972	3.969	3.971	12.57
Lime-Fly Ash	5	1	4.223	4.200	4.115	4.026	3.859	3.607	3.206	2.878	2.564	2.219	1.338	1.084	-
		2	4.197	4.184	4.100	4.040	3.833	3.610	3.233	2.894	2.626	2.337	2.001	1.634	-
		3	4.179	4.175	4.152	4.082	3.967	3.736	3.272	2.781	2.404	2.008	1.691	1.385	-
	9	1	4.210	4.212	4.208	4.212	4.190	4.161	4.108	4.079	4.042	4.006	3.979	3.935	12.57
		2	4.247	4.251	4.192	4.253	4.233	4.218	4.185	4.155	4.135	4.109	4.069	4.038	12.57
		3	4.186	4.193	4.205	4.192	4.176	4.166	4.149	4.134	4.115	4.104	4.070	4.059	12.57
	13	1	4.206	4.206	4.205	4.212	4.208	4.206	4.203	4.194	4.191	4.188	4.172	4.176	12.57
		2	4.254	4.258	4.258	4.237	4.259	4.257	4.256	4.253	4.251	4.246	4.232	4.234	12.57
		3	4.231	4.240	4.238	4.248	4.244	4.243	4.240	4.237	4.233	4.231	4.215	4.223	12.57
Lime	5	1	4.001	3.996	3.999	3.978	3.978	3.797	3.615	3.261	2.845	2.900	2.149	1.889	10.41
		2	4.089	4.009	4.088	4.048	4.024	3.870	3.649	3.228	2.842	2.337	2.081	1.851	9.88
		3	4.084	4.081	4.090	4.066	4.020	3.873	3.606	3.209	2.694	2.349	1.958	1.640	9.67
	15	1	4.229	4.201	4.102	3.829	3.829	2.942	2.435	1.779	1.253	1.003	0.798	0.583	-
		2	4.057	4.052	4.003	3.872	3.518	3.158	2.435	1.900	1.327	0.000	0.752	0.499	-
		3	3.926	3.926	3.940	3.915	3.740	3.223	2.766	2.218	1.560	1.036	0.714	0.473	-
	25	1	3.903	3.865	2.338	2.219	2.219	1.629	1.325	0.895	0.689	0.474	0.200	0.117	-
		2	3.969	3.903	3.812	3.442	2.199	1.900	1.498	1.128	0.778	0.000	0.464	0.274	-
		3	3.929	3.853	3.759	3.347	2.863	2.378	1.927	1.099	0.570	0.419	0.271	-	-
Cement	0.5	1	4.120	3.567	2.992	2.500	2.120	1.702	0.742	0.521	0.398	-	-	-	-
		2	4.105	3.790	3.346	2.790	2.374	1.912	1.465	0.561	0.438	0.144	-	-	-
		3	4.077	3.849	3.385	2.727	1.795	1.795	0.696	0.489	0.345	-	-	-	-
	2.5	1	4.116	4.098	4.103	4.094	4.036	4.062	4.038	4.018	3.972	3.926	3.876	3.818	12.57
		2	4.094	4.085	4.090	4.080	4.031	4.066	4.045	4.015	3.988	3.939	3.873	3.788	12.57
		3	4.073	4.080	4.085	4.065	4.034	4.034	4.003	3.953	3.915	3.791	3.616	3.499	12.57
	4.5	1	4.077	4.065	4.075	4.067	4.041	4.062	4.066	4.065	4.068	4.063	4.028	4.008	12.57
		2	4.050	4.060	4.067	4.063	4.039	4.059	4.059	4.064	4.070	4.068	4.072	4.068	12.57
		3	4.055	4.055	4.068	4.065	4.061	4.061	4.066	4.068	4.073	4.069	4.070	4.069	12.57

Table A.6 Additional Clay Freeze-Thaw Test Results

Stabilizer	Stabilizer Concentration (%)	Specimen	Frozen Weight per Freeze-Thaw Cycle (lb)												Final Circumference (in.)
			1	2	3	4	5	6	7	8	9	10	11	12	
Untreated	0	1	-	-	-	-	-	-	-	-	-	-	-	-	-
		2	-	-	-	-	-	-	-	-	-	-	-	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-
Class C Fly Ash	10	1	3.827	1.866	1.428	0.533	-	-	-	-	-	-	-	-	-
		2	3.801	2.698	1.108	-	-	-	-	-	-	-	-	-	-
		3	3.800	3.112	2.220	0.786	-	-	-	-	-	-	-	-	-
	20	1	4.036	3.556	3.032	2.024	1.241	0.443	0.310	0.217	0.174	0.135	0.089	-	-
		2	3.967	3.682	3.105	1.953	0.788	0.482	0.494	0.250	0.184	0.149	0.115	-	-
		3	3.968	3.744	3.151	2.000	1.357	0.703	0.267	0.187	0.149	0.100	0.070	-	-
	30	1	3.909	3.345	2.749	1.776	1.660	0.672	0.417	0.196	0.155	0.137	0.102	-	-
		2	3.887	3.463	2.937	2.017	1.303	0.700	0.402	0.279	0.212	0.149	0.109	-	-
		3	3.849	3.431	2.799	1.874	1.313	0.671	0.324	0.233	0.205	0.168	0.143	-	-
Lime-Fly Ash	10	1	3.784	3.445	2.824	2.082	1.325	0.682	0.235	-	-	-	-	-	-
		2	3.917	3.330	2.579	1.838	1.212	0.322	0.095	-	-	-	-	-	-
		3	3.751	3.437	2.949	2.386	1.788	1.003	0.538	-	-	-	-	-	-
	15	1	3.891	3.849	3.735	3.423	2.872	2.315	1.772	1.280	0.669	0.478	0.333	-	-
		2	3.808	3.671	3.458	2.385	2.485	1.282	1.003	0.775	0.539	0.346	0.249	-	-
		3	3.863	3.711	3.533	2.949	2.422	1.900	1.458	0.816	0.547	0.289	0.205	-	-
	20	1	3.843	3.650	3.521	3.097	2.724	2.096	1.636	1.210	0.601	0.416	0.326	-	-
		2	3.789	3.822	3.744	3.434	2.809	2.203	1.726	1.342	0.763	0.564	0.344	-	-
		3	3.815	3.791	3.684	3.284	2.870	2.212	1.772	1.407	1.125	0.721	0.571	-	-
Lime	3	1	3.812	3.701	3.354	2.656	2.656	1.547	0.000	0.216	-	-	-	-	-
		2	3.647	3.552	3.183	2.587	2.066	1.403	0.000	-	-	-	-	-	-
		3	3.725	3.650	3.330	2.912	2.360	1.749	0.000	0.701	-	-	-	-	-
	3.5	1	3.812	3.806	3.658	3.125	3.125	2.004	2.353	2.043	1.025	-	-	-	-
		2	3.671	3.689	3.688	3.570	3.211	2.781	1.438	1.198	0.757	0.000	-	-	-
		3	3.781	3.792	3.680	3.427	2.983	2.532	2.133	1.839	1.490	-	-	-	-
	4	1	3.727	3.754	3.712	3.204	3.204	2.220	1.787	1.391	1.234	0.239	0.115	-	-
		2	3.769	3.783	3.694	3.289	2.851	2.325	1.974	1.568	0.954	0.000	0.080	-	-
		3	3.704	3.714	3.600	3.165	2.735	2.141	1.779	1.498	1.187	0.417	0.177	-	-
Cement	1	1	3.789	-	-	-	-	-	-	-	-	-	-	-	-
		2	3.953	-	-	-	-	-	-	-	-	-	-	-	-
		3	3.902	-	-	-	-	-	-	-	-	-	-	-	-
	2	1	3.536	3.082	2.465	1.647	0.786	0.499	-	-	-	-	-	-	-
		2	3.936	3.421	2.557	1.842	1.340	0.262	-	-	-	-	-	-	-
		3	3.923	3.395	2.797	2.097	0.727	0.727	-	-	-	-	-	-	-
	3	1	3.812	3.674	3.525	3.221	2.922	2.329	2.080	1.654	1.379	0.572	0.416	-	-
		2	3.833	3.754	3.600	3.375	2.981	2.448	1.875	1.507	1.231	0.499	0.207	-	-
		3	3.728	3.728	3.660	3.383	2.387	2.387	1.109	0.903	0.745	0.359	0.219	-	-

Table A.7 Additional Sand Tube Suction Test Results

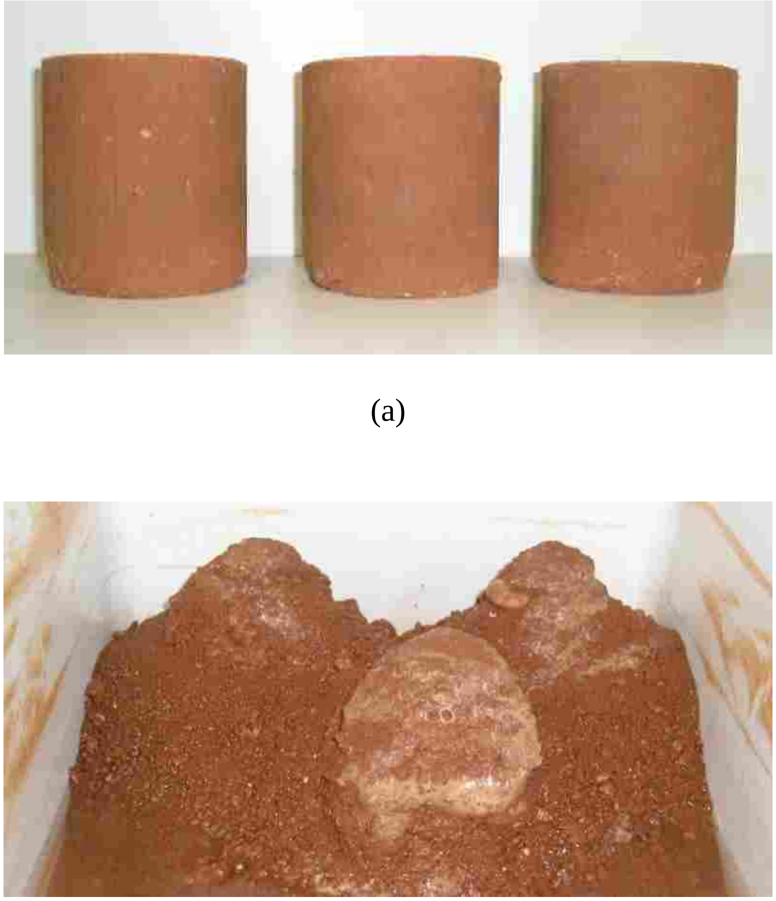
Stabilizer Type	Stabilizer Concentration (%)	Specimen	Dielectric Value per Day										
			0	1	2	3	4	5	6	7	8	9	10
Untreated	-	1	4.7	-	-	20.0	23.5	20.8	21.1	-	22.0	21.5	23.1
		2	4.7	-	-	18.3	19.0	17.9	15.3	-	19.3	19.8	20.0
		3	4.8	-	-	22.1	21.7	21.6	20.0	-	22.5	23.5	23.8
Class C Fly Ash	2	1	6.9	19.8	22.8	21.2	23.1	21.8	21.9	-	21.5	-	21.0
		2	4.6	16.9	22.4	22.7	22.7	23.8	23.1	-	22.5	-	22.4
		3	2.8	15.8	19.4	21.1	21.7	22.6	20.4	-	21.2	-	20.4
	11	1	2.4	11.0	14.0	15.0	15.9	15.5	15.4	-	15.8	-	14.8
		2	4.3	13.5	16.2	17.8	17.9	19.0	17.1	-	17.9	-	17.1
		3	8.4	11.4	13.5	16.4	14.2	17.3	14.8	-	16.1	-	16.3
	20	1	7.9	11.5	14.3	14.2	14.9	16.4	16.8	-	16.1	-	16.5
		2	8.6	12.4	12.0	15.5	15.7	14.9	15.5	-	15.4	-	14.9
		3	8.4	13.1	15.0	19.3	16.6	19.1	16.9	-	18.1	-	18.1
Lime-Fly Ash	5	1	5.4	16.1	18.8	22.6	22.1	19.0	-	21.3	-	22.8	20.6
		2	2.7	11.0	14.5	16.0	17.5	17.1	-	17.3	-	18.5	15.7
		3	1.9	11.6	16.0	16.6	17.6	16.1	-	17.6	-	19.0	18.3
	9	1	2.1	7.2	12.1	14.4	16.4	15.8	-	15.6	-	17.2	17.0
		2	1.9	6.0	11.9	14.4	14.6	14.1	-	14.9	-	16.8	15.2
		3	1.5	6.2	10.9	13.2	13.8	14.3	-	14.8	-	16.0	15.4
	13	1	1.0	5.7	7.6	8.1	8.4	9.1	-	10.3	-	11.3	11.1
		2	1.3	5.5	7.8	8.4	8.7	8.8	-	9.3	-	10.2	10.8
		3	1.0	6.1	8.2	8.6	8.6	8.5	-	9.5	-	10.3	10.6
Lime	5	1	5.0	8.2	10.2	14.0	13.2	-	16.2	-	14.2	13.1	15.7
		2	5.0	8.4	10.4	10.4	12.3	-	13.6	-	13.9	12.8	13.9
		3	5.8	9.7	12.0	15.9	15.9	-	17.5	-	17.5	16.0	14.3
	15	1	5.8	18.2	18.5	17.6	18.1	-	19.5	-	21.4	17.1	17.2
		2	5.4	13.6	14.9	14.9	16.4	-	18.7	-	19.3	14.3	14.0
		3	5.6	15.8	17.4	19.2	17.9	-	20.2	-	20.8	16.5	16.5
	25	1	6.3	19.8	23.8	22.2	20.6	-	21.2	-	22.8	20.3	21.6
		2	5.5	17.0	23.6	23.6	19.3	-	19.4	-	19.7	17.9	19.0
		3	6.0	18.8	17.4	22.7	20.8	-	21.0	-	20.4	18.9	20.0
Cement	0.5	1	8.3	-	16.8	17.6	19.8	17.3	16.4	-	20.9	21.1	20.5
		2	4.7	-	16.7	17.0	17.5	16.4	15.2	-	17.5	17.7	16.9
		3	7.7	-	18.1	19.1	18.8	17.7	13.3	-	19.7	19.8	19.6
	2.5	1	5.9	-	8.3	8.1	7.9	7.6	6.8	-	8.8	8.5	8.8
		2	0.0	-	8.6	8.5	8.6	8.2	7.2	-	9.7	9.7	10.3
		3	6.8	-	8.8	8.7	9.0	8.8	8.4	-	11.3	11.6	12.0
	4.5	1	7.7	-	9.8	11.3	13.7	12.3	10.5	-	14.1	14.3	14.7
		2	0.0	-	10.1	11.6	12.7	12.1	10.7	-	14.6	14.0	13.5
		3	6.7	-	8.9	9.5	11.1	11.7	10.8	-	12.6	12.1	13.0

Table A.8 Additional Clay Tube Suction Test Results

Stabilizer Type	Stabilizer Concentration (%)	Specimen	Dielectric Value per Day										
			0	1	2	3	4	5	6	7	8	9	10
Untreated	-	1	6.7	-	-	14.9	17.9	21.6	22.7	-	26.7	28.4	30.3
		2	6.1	-	-	10.7	11.7	12.9	16.5	-	22.9	26.7	28.3
		3	6.3	-	-	22.4	22.5	30.1	28.8	-	28.2	28.4	31.3
Class C Fly Ash	2	1	5.3	8.5	24.3	19.2	31.3	28.0	27.6	30.9	-	-	32.1
		2	4.8	16.9	20.3	14.5	23.4	21.6	20.9	23.5	-	-	22.9
		3	5.2	24.3	26.3	20.3	31.9	30.7	30.6	31.8	-	-	32.5
	11	1	5.1	7.9	17.7	15.2	24.6	25.9	25.1	24.8	-	-	25.3
		2	4.7	6.6	16.4	14.7	19.5	20.7	19.9	19.0	-	-	18.6
		3	5.1	7.6	16.8	17.6	25.4	26.0	28.6	25.7	-	-	25.3
	20	1	4.6	6.0	15.9	16.0	23.1	22.4	21.6	21.3	-	-	20.0
		2	4.4	6.0	16.8	15.2	18.9	19.1	18.9	18.6	-	-	17.5
		3	4.7	7.8	18.6	18.3	23.4	22.2	24.7	21.8	-	-	21.1
Lime-Fly Ash	5	1	4.9	9.8	19.7	19.8	25.1	28.9	29.4	29.1	-	-	29.7
		2	5.3	8.2	20.1	22.4	23.6	31.2	32.9	30.9	-	-	32.7
		3	5.0	9.6	17.1	17.4	25.7	26.3	28.3	26.9	-	-	31.3
	9	1	5.3	23.8	22.2	22.6	28.4	29.3	31.4	30.0	-	-	30.6
		2	5.2	8.1	20.9	24.3	27.6	31.6	32.0	31.6	-	-	32.2
		3	5.7	20.4	22.7	31.4	27.9	32.5	32.6	31.2	-	-	32.8
	13	1	5.0	7.5	24.6	24.1	29.7	27.5	29.9	27.7	-	-	29.9
		2	4.8	6.9	23.5	27.2	29.4	27.2	29.4	29.6	-	-	28.5
		3	4.8	6.4	17.6	23.0	26.4	26.5	31.4	25.5	-	-	26.0
Lime	5	1	4.7	11.8	20.2	22.9	26.8	26.2	28.9	22.5	-	-	28.0
		2	5.0	7.8	21.7	21.7	31.7	30.1	31.2	31.9	-	-	29.7
		3	5.4	9.4	19.6	30.6	31.6	32.7	31.9	31.3	-	-	31.0
	15	1	4.9	15.8	20.1	23.7	26.2	24.1	31.7	29.3	-	-	29.7
		2	5.0	7.5	18.6	18.6	28.9	22.3	30.7	28.7	-	-	27.6
		3	4.5	12.7	22.9	24.9	26.2	26.3	30.1	29.4	-	-	30.8
	25	1	5.2	9.5	22.7	27.5	31.2	26.5	31.4	29.9	-	-	30.7
		2	5.1	7.8	20.5	20.5	31.6	25.4	29.9	27.8	-	-	28.2
		3	5.0	7.4	19.4	24.7	28.6	23.9	31.4	26.7	-	-	31.6
Cement	0.5	1	4.7	8.5	15.2	22.9	27.5	25.0	28.1	24.6	-	-	26.8
		2	6.1	7.1	9.0	15.9	24.8	21.3	25.6	19.4	-	-	25.0
		3	5.4	9.7	14.4	23.1	30.6	28.9	30.1	29.6	-	-	27.5
	2.5	1	5.3	13.0	18.4	26.2	30.8	27.4	30.2	28.5	-	-	28.0
		2	0.0	17.6	17.2	21.6	30.8	23.3	26.5	21.4	-	-	22.1
		3	6.0	23.1	16.0	18.8	31.3	25.4	26.7	21.7	-	-	20.9
	4.5	1	5.3	16.7	15.4	17.9	30.5	17.8	22.7	18.9	-	-	17.7
		2	0.0	7.2	14.7	18.0	31.0	17.5	23.2	16.1	-	-	19.9
		3	5.1	7.4	12.6	17.4	31.1	17.5	26.5	20.2	-	-	18.8

APPENDIX B:

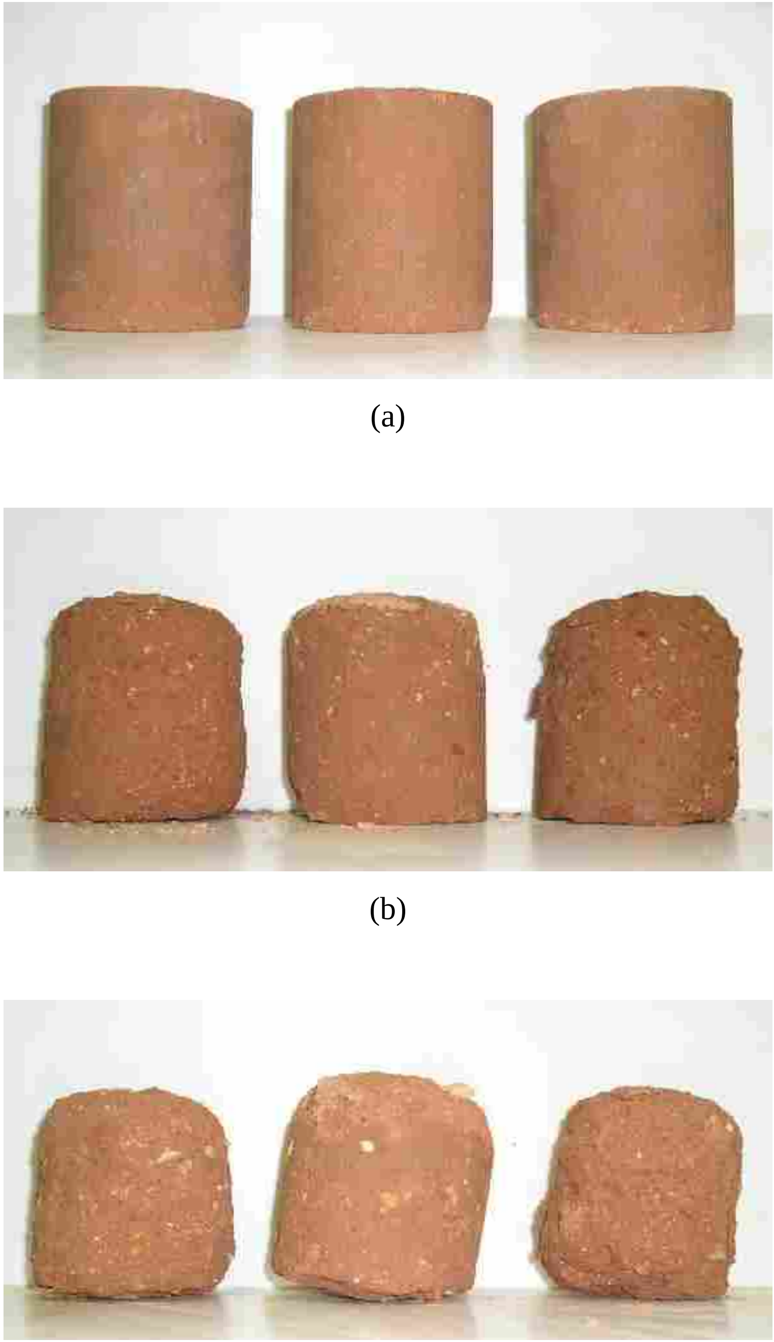
PICTORAL RESULTS OF FREEZE-THAW CYCLING



(a)

(b)

Figure B.1 Sand specimens treated with 2 percent Class C fly ash after (a) 0 cycles and (b) the first soak during freeze-thaw cycling.

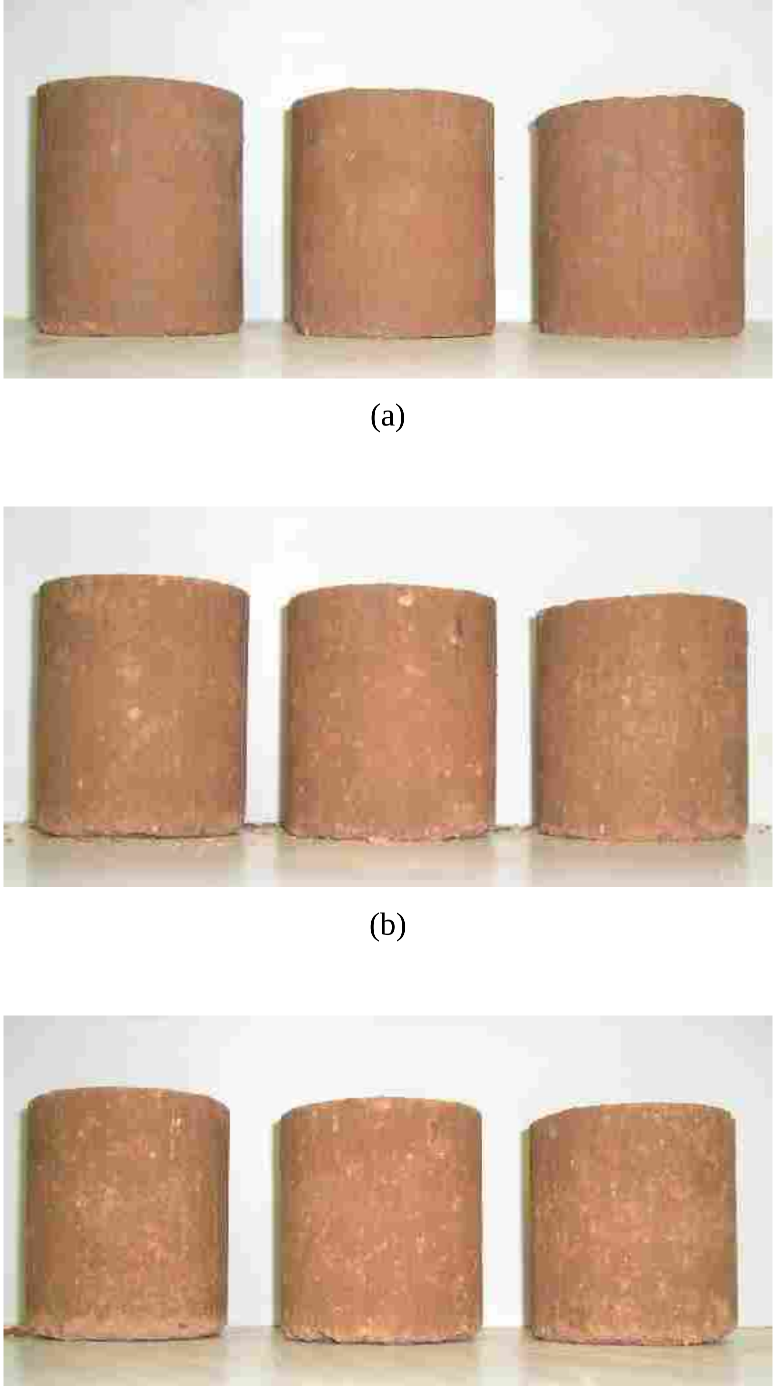


(a)

(b)

(c)

Figure B.2 Sand specimens treated with 11 percent Class C fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

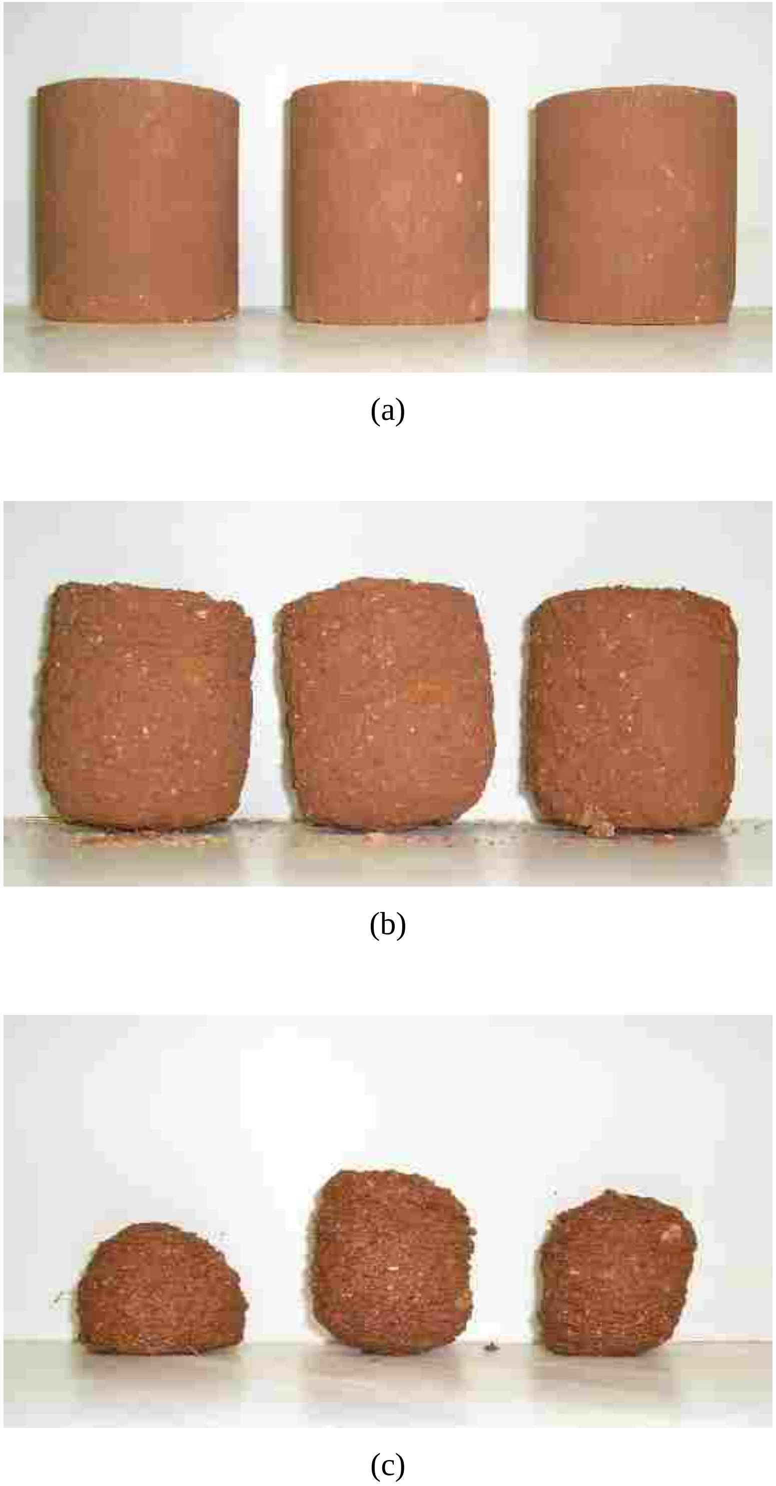


(a)

(b)

(c)

Figure B.3 Sand specimens treated with 20 percent Class C fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

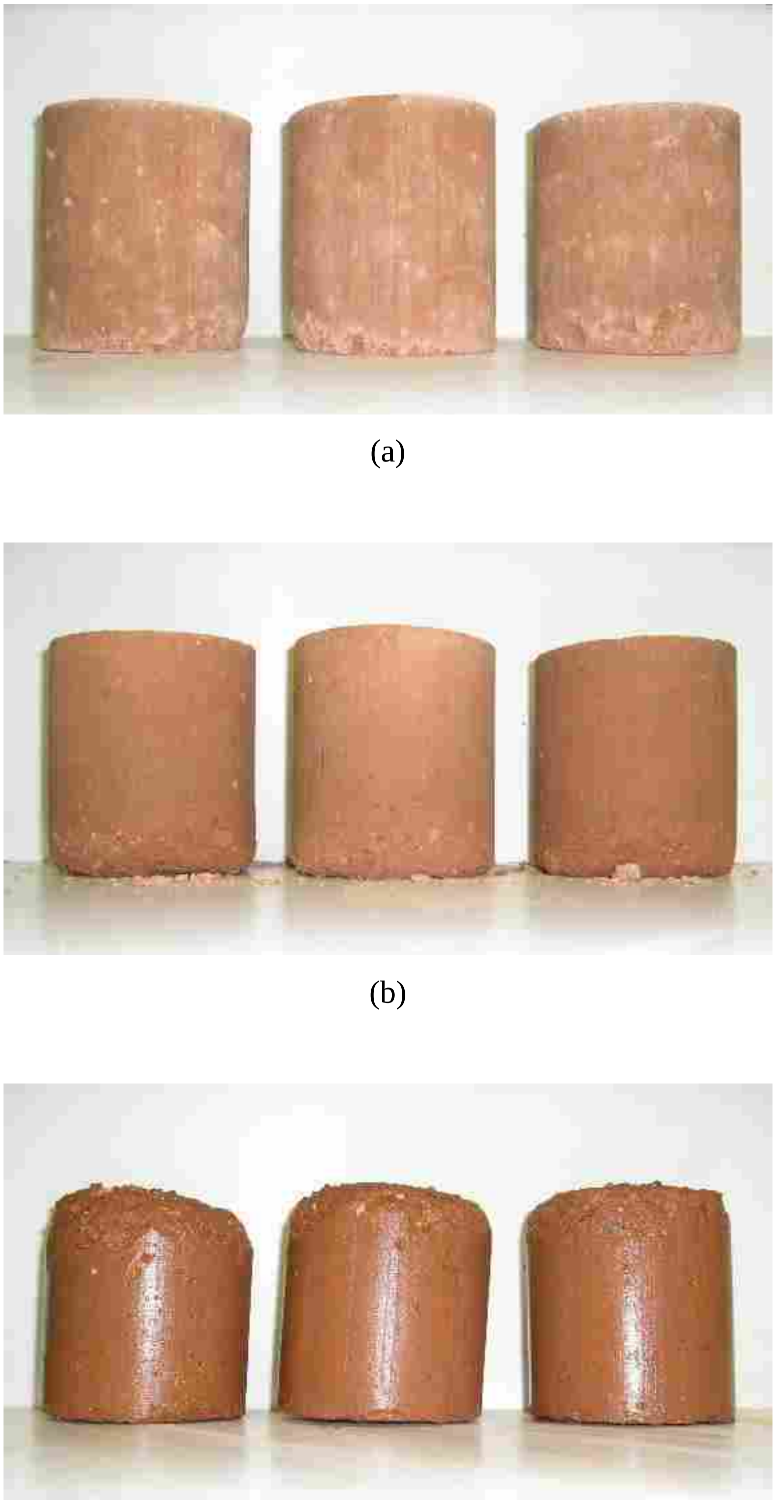


(a)

(b)

(c)

Figure B.4 Sand specimens treated with 5 percent lime-fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

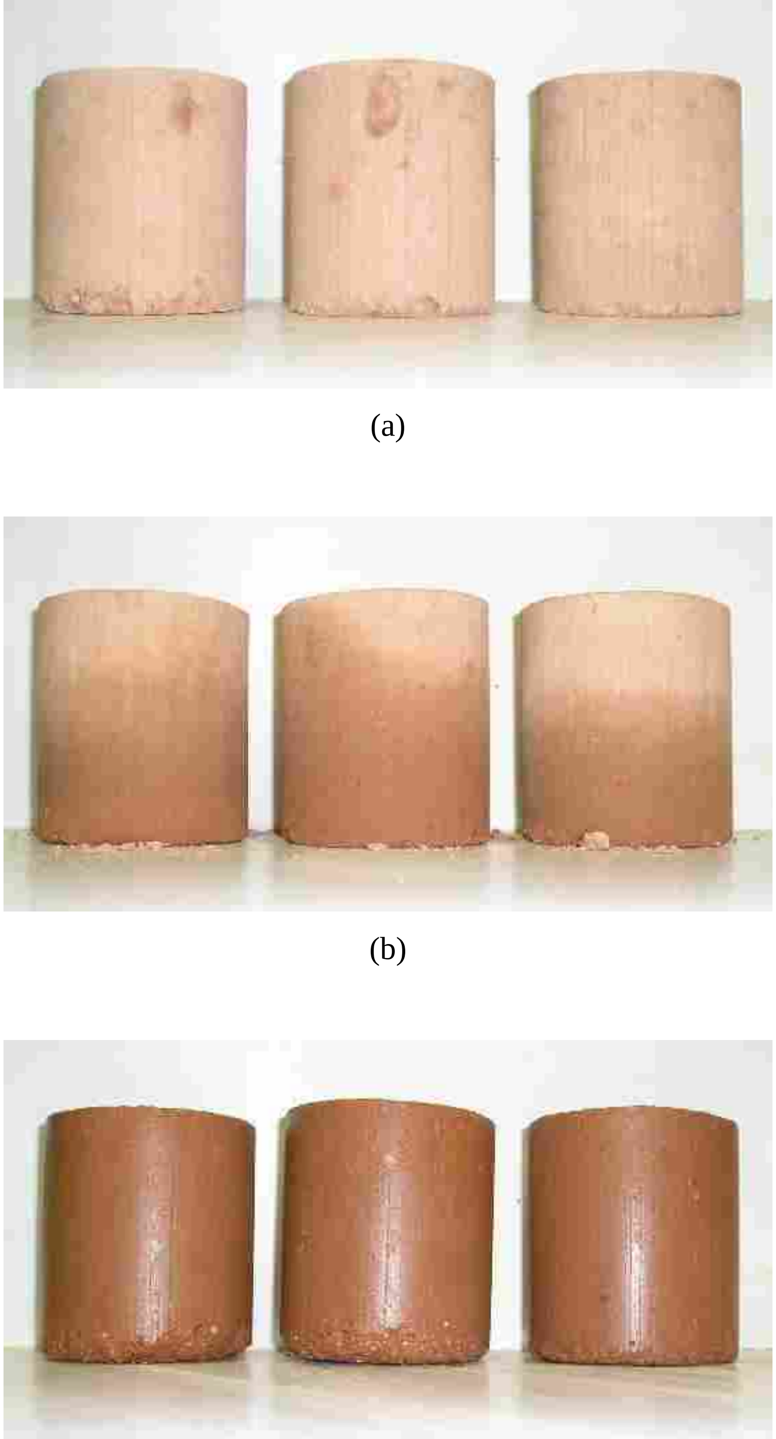


(a)

(b)

(c)

Figure B.5 Sand specimens treated with 9 percent lime-fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

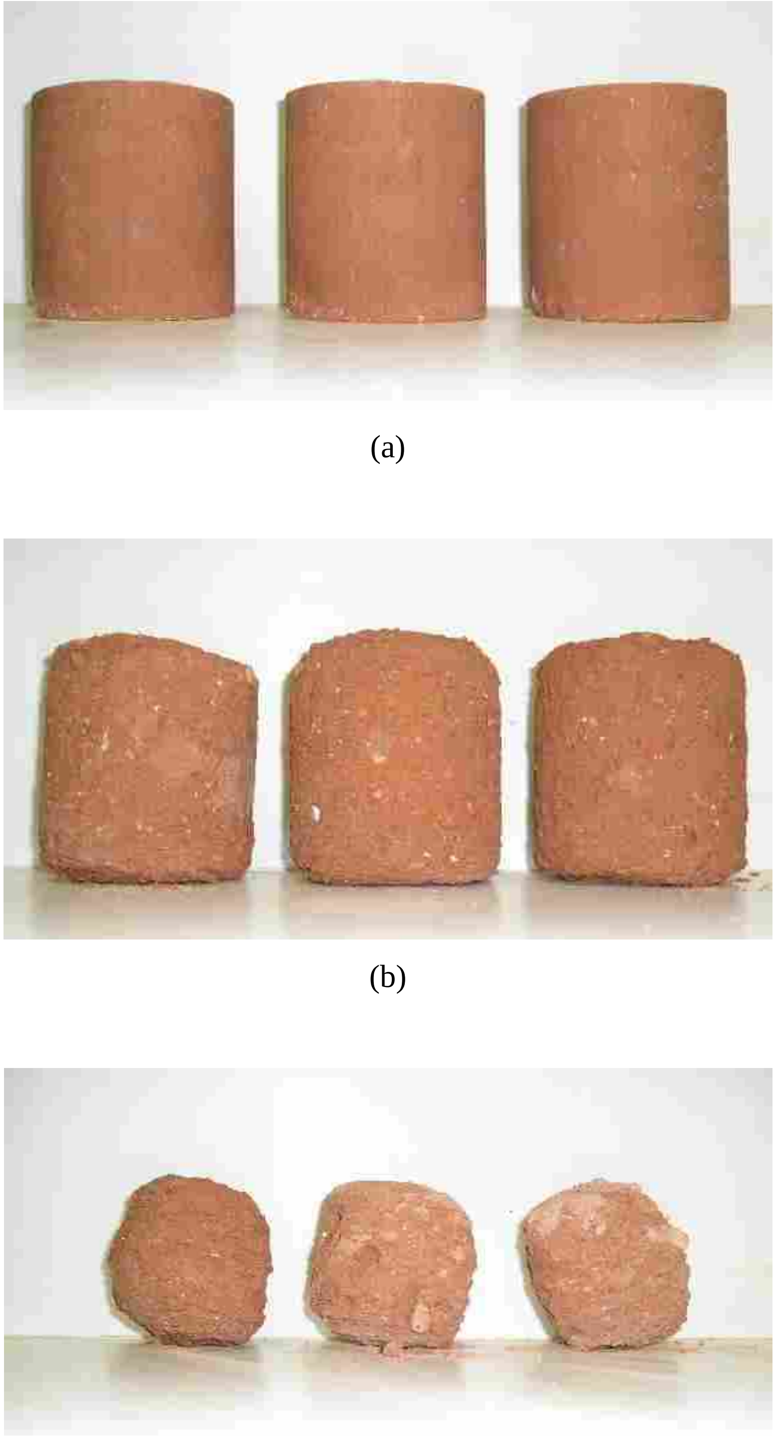


(a)

(b)

(c)

Figure B.6 Sand specimens treated with 13 percent lime-fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.



(a)

(b)

(c)

Figure B.7 Sand specimens treated with 5 percent lime after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

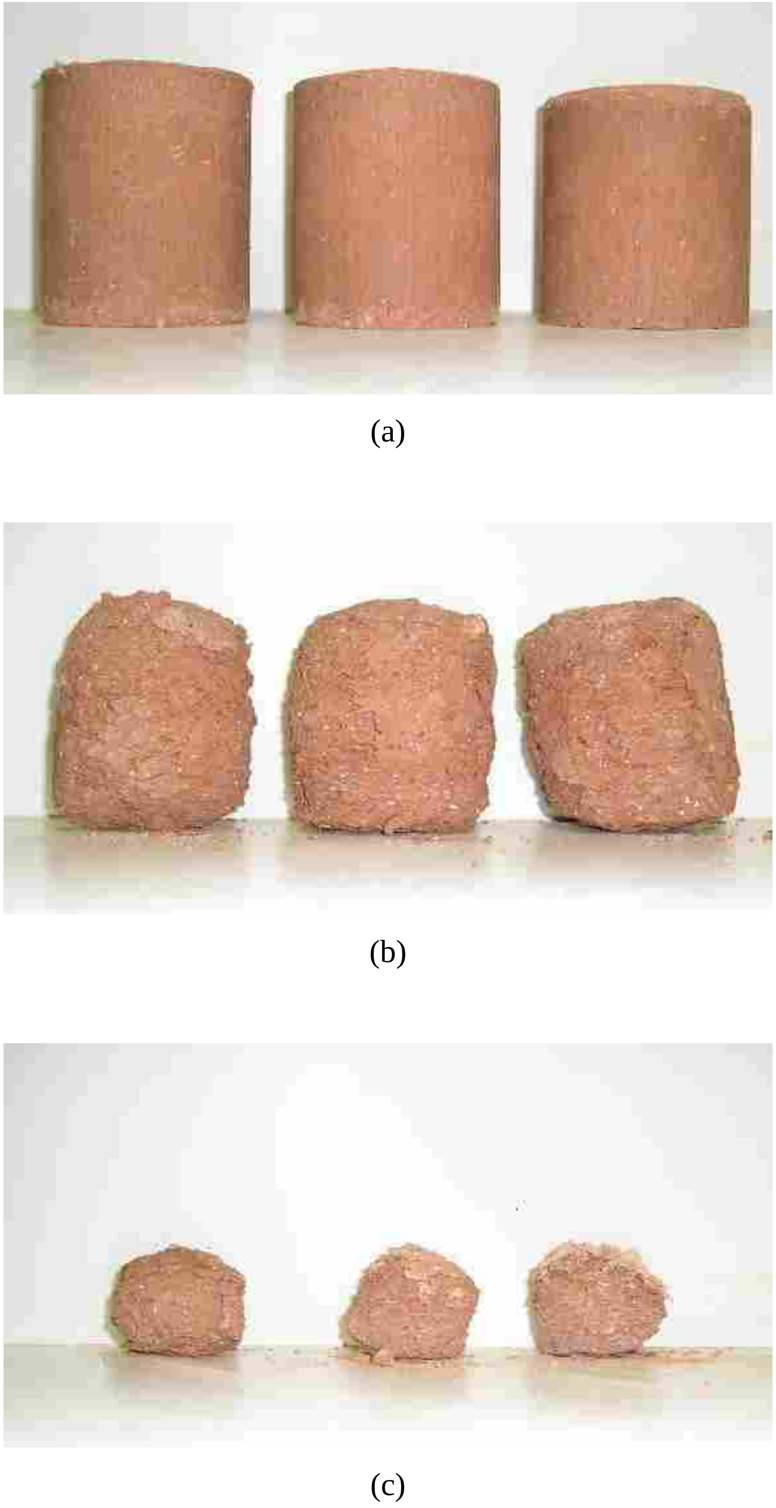


Figure B.8 Sand specimens treated with 15 percent lime after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

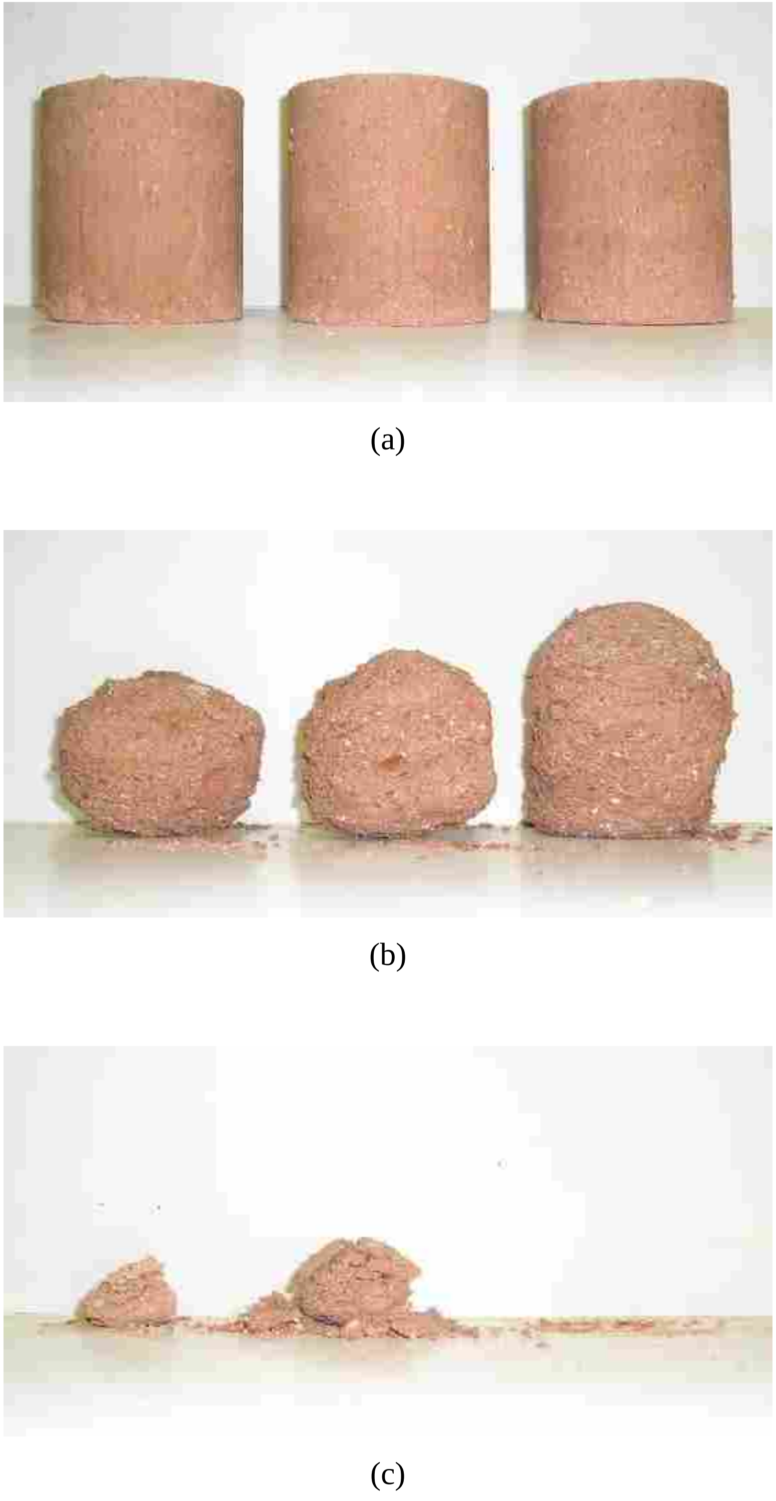
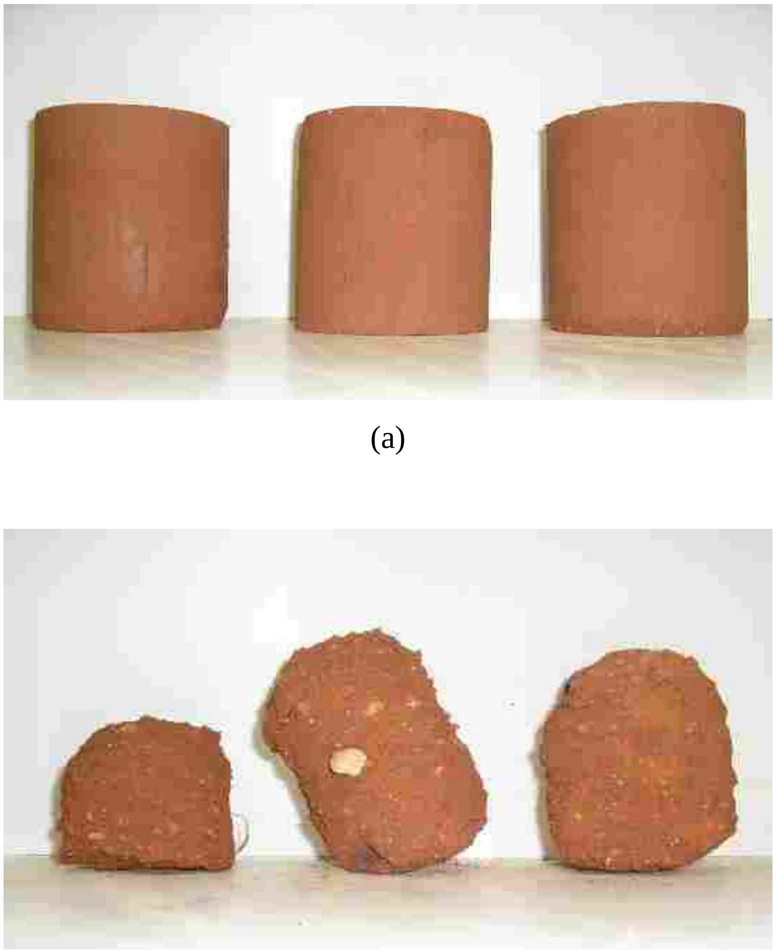


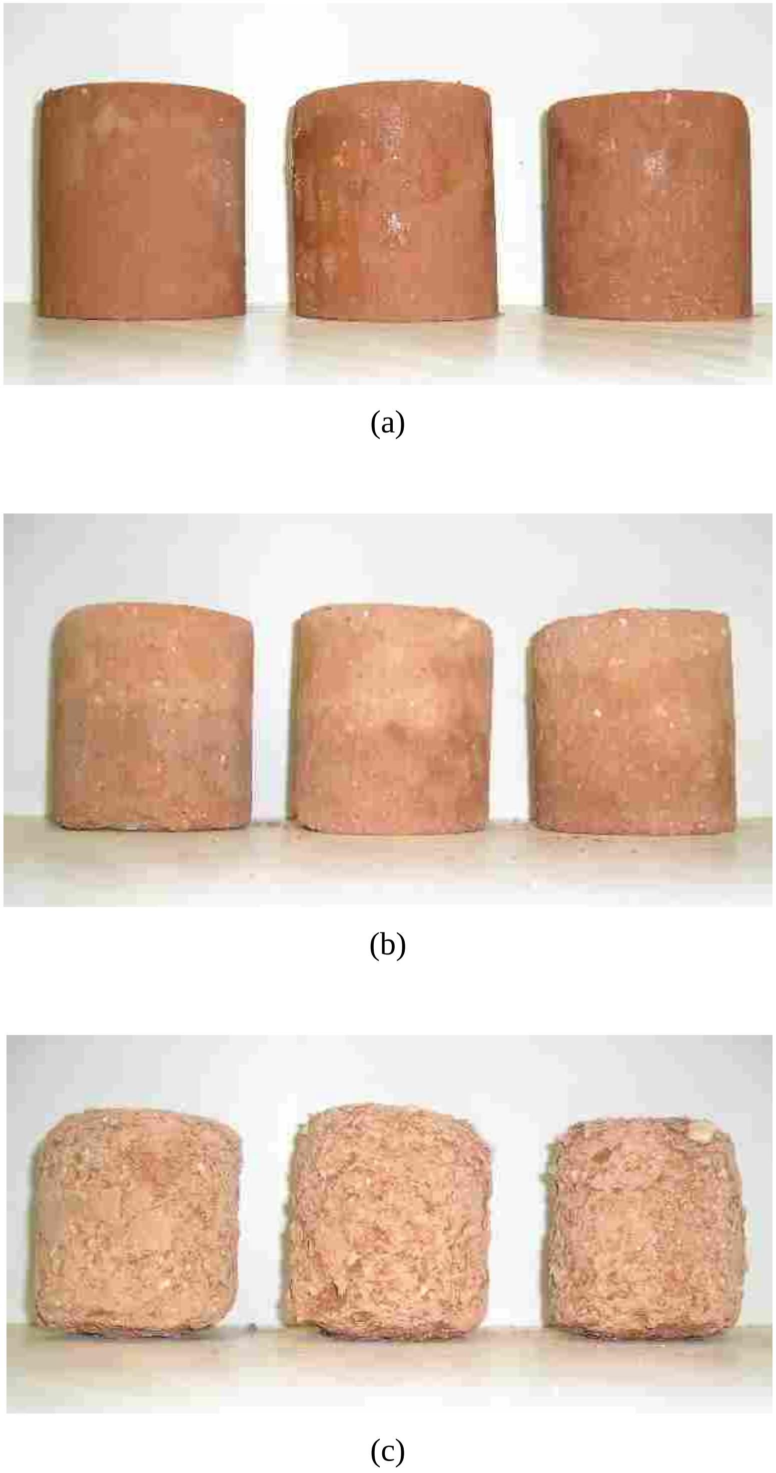
Figure B.9 Sand specimens treated with 25 percent lime after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.



(a)

(b)

Figure B.10 Sand specimens treated with 0.5 percent cement after (a) 0 cycles and (b) 6 cycles of freeze-thaw testing.

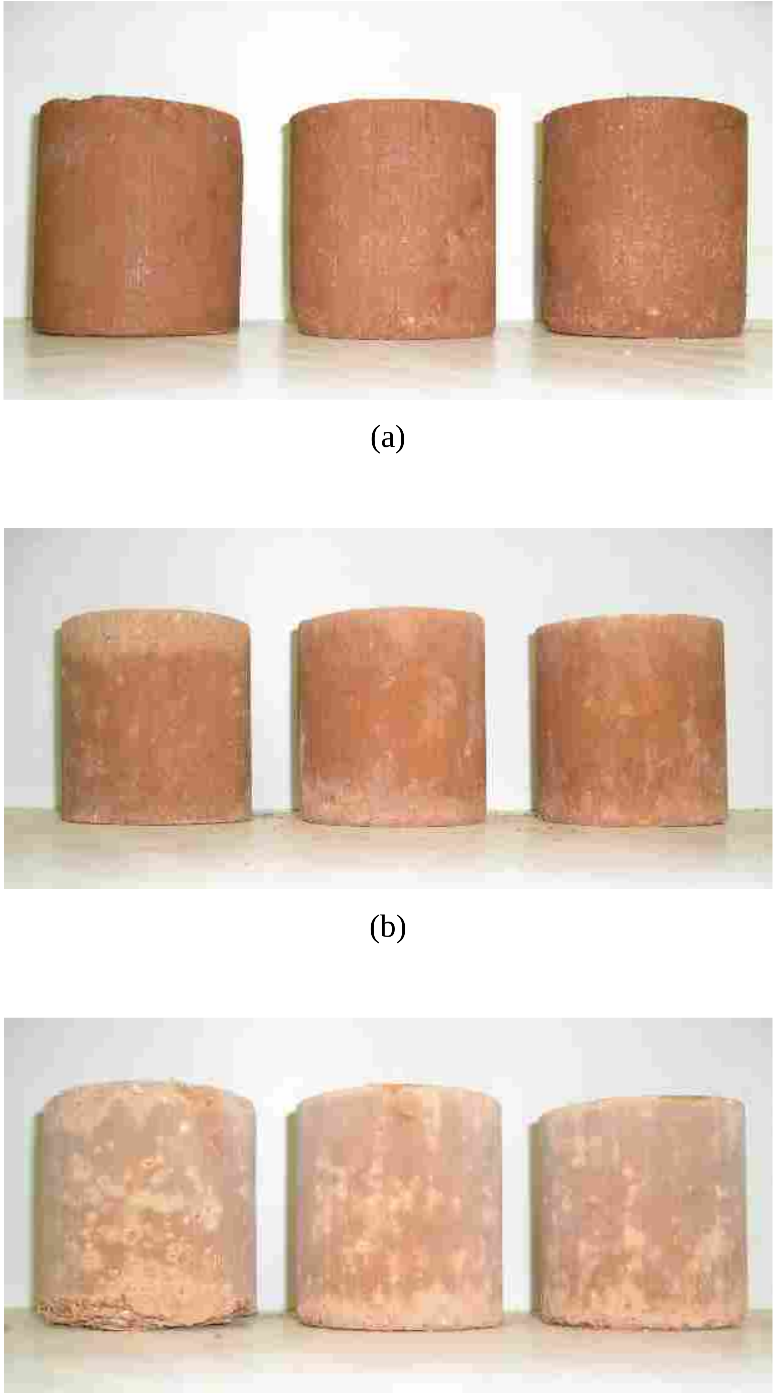


(a)

(b)

(c)

Figure B.11 Sand specimens treated with 2.5 percent cement after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.



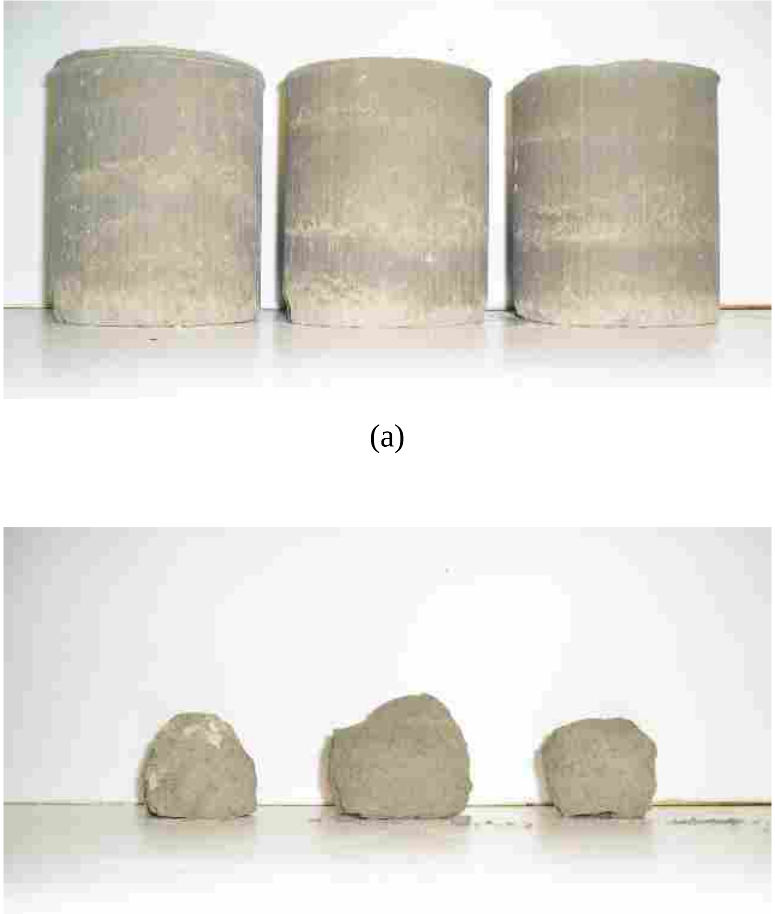
(a)

(b)

(c)

Figure B.12 Sand specimens treated with 4.5 percent cement after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

Figure B.13 Clay specimens treated with 10 percent Class C fly ash after 0 cycles of freeze-thaw testing.



(a)

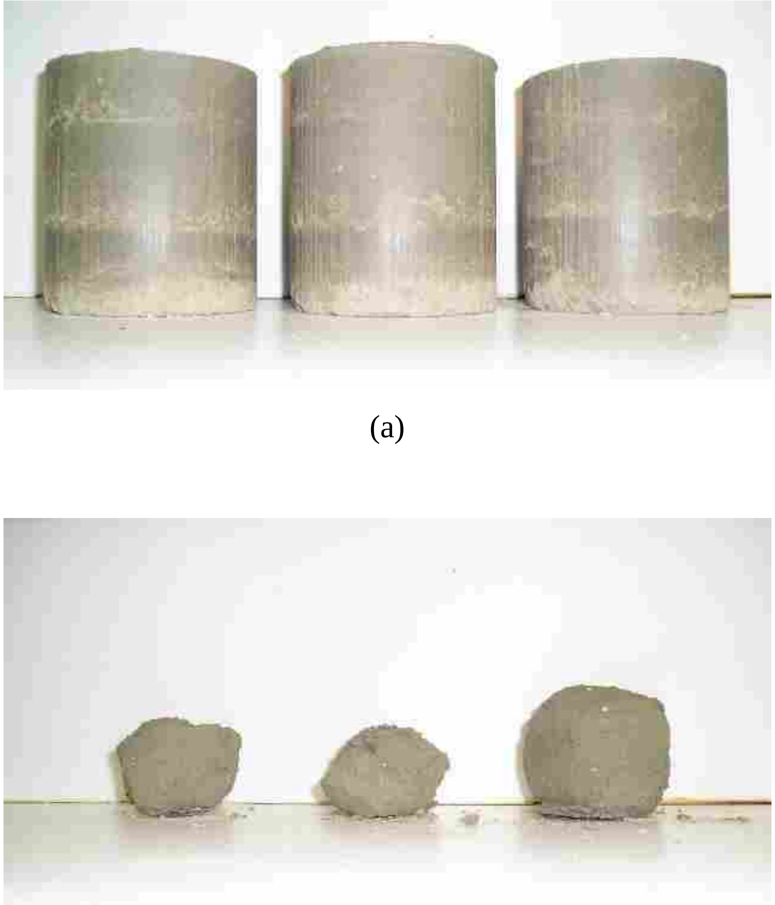
(b)

Figure B.14 Clay specimens treated with 20 percent Class C fly ash after (a) 0 cycles and (b) 6 cycles of freeze-thaw testing.

(a)

(b)

Figure B.15 Clay specimens treated with 30 percent Class C fly ash after (a) 0 cycles and (b) 6 cycles of freeze-thaw testing.



(a)

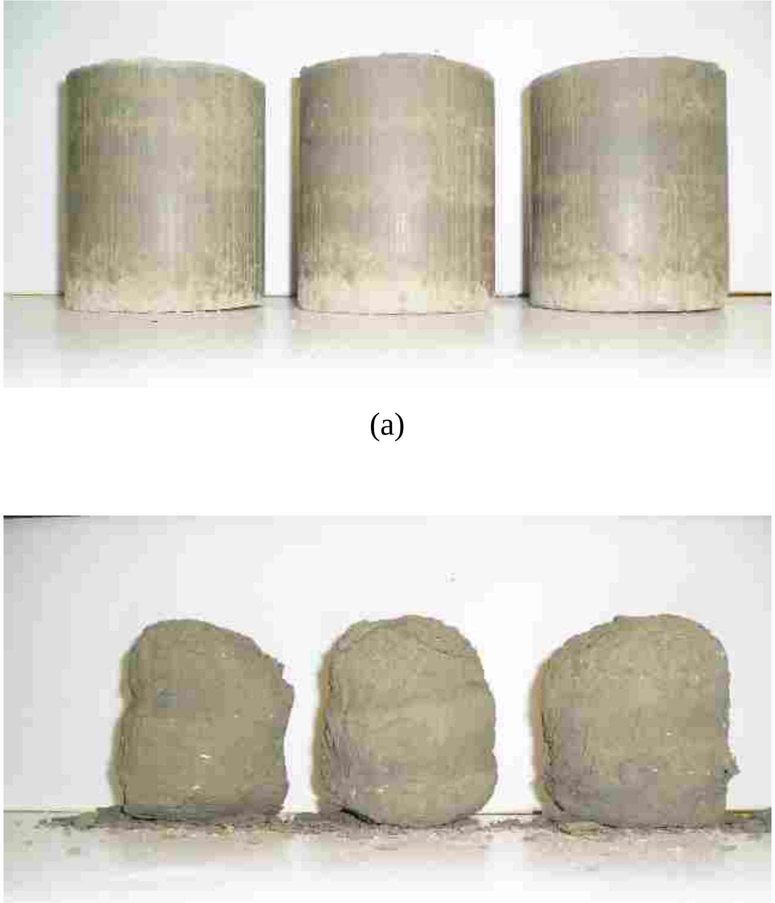
(b)

Figure B.16 Clay specimens treated with 10 percent lime-fly ash after (a) 0 cycles and (b) 6 cycles of freeze-thaw testing.

(a)

(b)

Figure B.17 Clay specimens treated with 15 percent lime-fly ash after (a) 0 cycles and (b) 6 cycles of freeze-thaw testing.



(a)

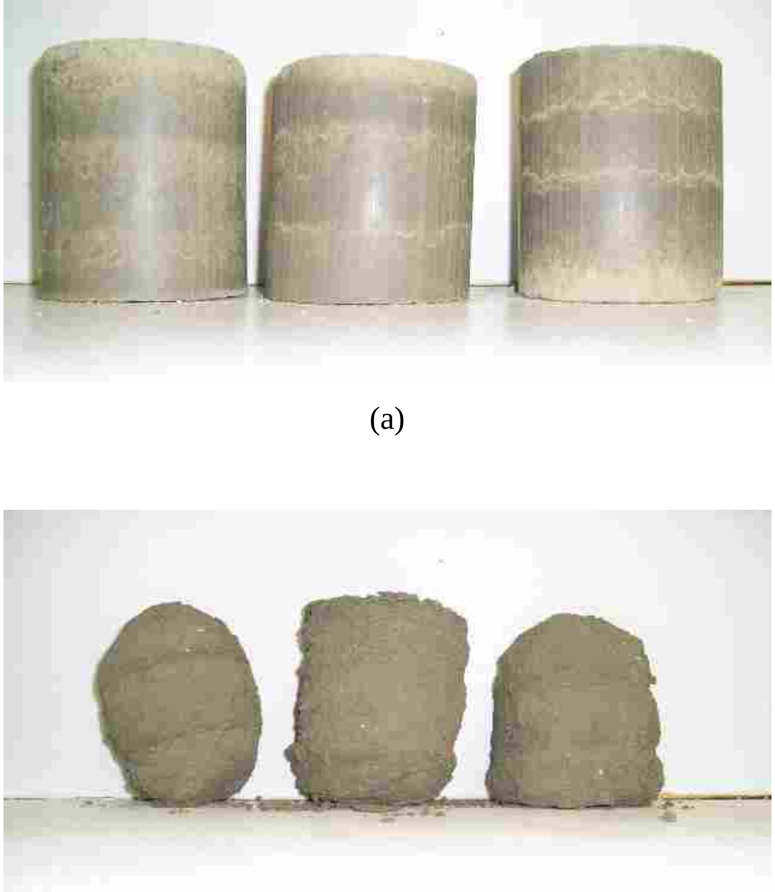
(b)

Figure B.18 Clay specimens treated with 20 percent lime-fly ash after (a) 0 cycles and (b) 6 cycles of freeze-thaw testing.

(a)

(b)

Figure B.19 Clay specimens treated with 3 percent lime after (a) 0 cycles and (b) 6 cycles of freeze-thaw testing.



(a)

(b)

Figure B.20 Clay specimens treated with 3.5 percent lime after (a) 0 cycles and (b) 6 cycles of freeze-thaw testing.

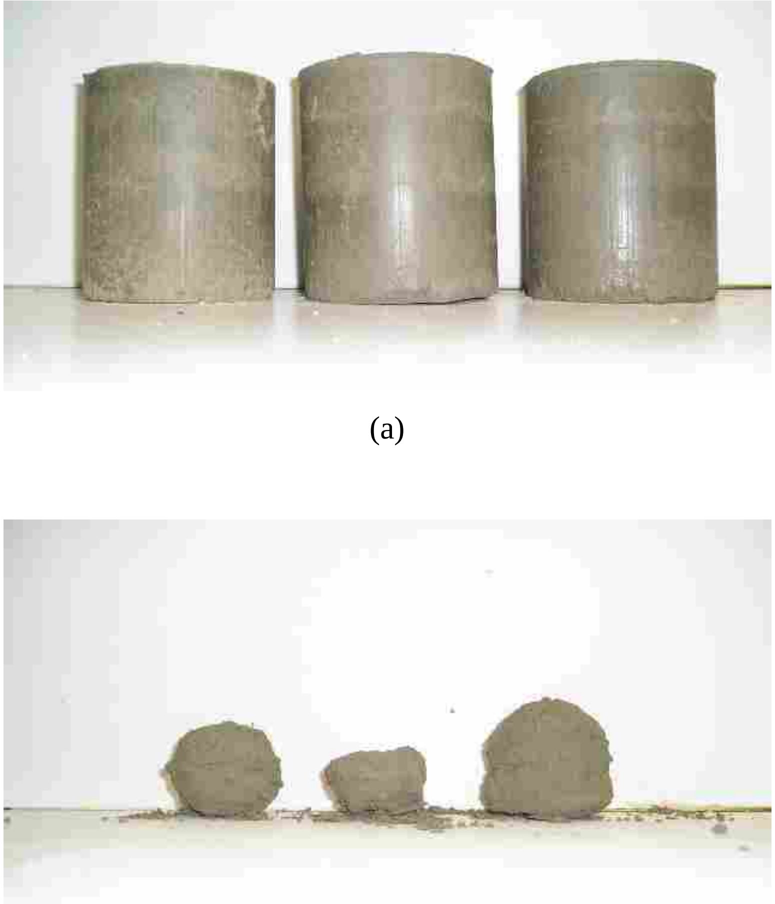
(a)

(b)

Figure B.21 Clay specimens treated with 4 percent lime after (a) 0 cycles and (b) 6 cycles of freeze-thaw testing.

(a)

Figure B.22 Clay specimens treated with 1 percent cement after 0 cycles of freeze-thaw testing.



(a)

(b)

Figure B.23 Clay specimens treated with 2 percent cement after (a) 0 cycles and (b) 6 cycles of freeze-thaw testing.

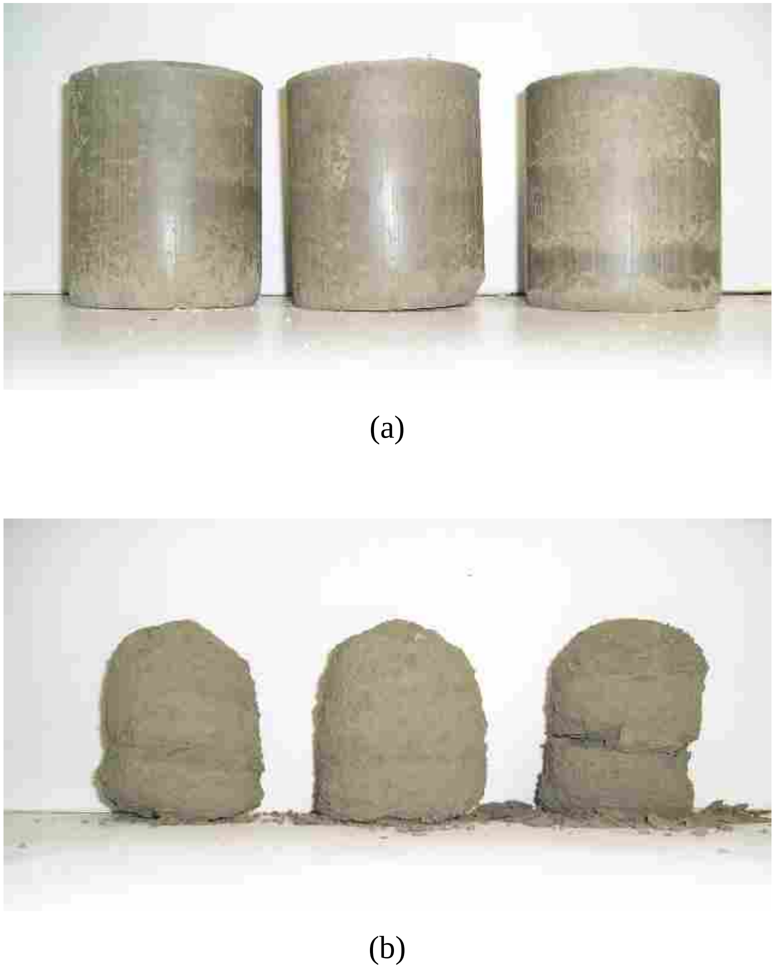


Figure B.24 Clay specimens treated with 3 percent cement after (a) 0 cycles and (b) 6 cycles of freeze-thaw testing.