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EVALUATION OF LABORATORY DURABILITY TESTS FOR STABILIZED AGGREGATE BASE MATERIALS

by

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GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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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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BRIGHAM YOUNG UNIVERSITY

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ABSTRACT

EVALUATION OF LABORATORY DURABILITY TESTS FOR STABILIZED AGGREGATE BASE MATERIALS

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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 aggregate base materials. The laboratory research associated with this project involved two granular base materials, three stabilizers at three concentration levels each, and three durability tests in a full-factorial experimental design. The granular base materials consisted of an aggregate-reclaimed asphalt pavement blend obtained from Interstate 84 (I-84) and a crushed limestone obtained from U.S. Highway 91 (US-91), while the three stabilizer types included Class C fly ash, lime-fly ash, and Type I/II Portland cement. Specimens were tested for durability using the freeze-thaw test, the vacuum saturation test, and the tube suction test.

Analyses of the test results indicated that the unconfined compressive strength (UCS) and retained UCS were higher for specimens tested in freeze-thaw cycling than the corresponding values associated with vacuum saturation testing. This observation suggests that the vacuum saturation test is more severe than the freeze-thaw test for materials similar to those evaluated in this research. The analyses also indicated that the

I-84 material retained more strength during freeze-thaw cycling and vacuum saturation and exhibited lower final dielectric values during tube suction testing than the US-91 material. Although the I-84 material performed better than the US-91 material, the I-84 material required higher stabilizer concentrations to reach the target 7-day UCS values specified in this research.

After freeze-thaw testing, the Class C fly-treated specimens were significantly stronger than both lime-fly ash- and cement-treated specimens. In the vacuum saturation test, none of the three stabilizer types were significantly different from each other with respect to either UCS or retained UCS. Dielectric values measured during tube suction testing were lowest for cement-treated specimens, indicating that cement performed better than other stabilizers in reducing the moisture/frost susceptibility of the treated materials. The results also show that, as the stabilizer concentration level increased from low to high, specimens performed better in nearly all cases.

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.

Engineers interested in specifying a comparatively severe laboratory durability test should consider vacuum saturation testing for specimens treated with stabilizers similar to those evaluated in this research. The vacuum saturation test is superior to both the freeze-thaw and tube suction tests because of the shorter duration and lack of a need for daily specimen monitoring. Although the Class C fly ash used in this research performed well, further investigation of various sources of Class C fly ash is recommended because of the variability inherent in that material. Similar research should be performed on subgrade soils, which are also routinely stabilized in pavement construction. 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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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 (*2*). 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 lime- and lime-fly ash-treated materials, 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, or cause varying degrees of specimen strength loss, a comparative evaluation of the durability of materials treated with 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 granular base materials, three stabilizers at three concentration levels each, and three durability tests in a full-factorial experimental design. Three replicate samples were prepared for each unique combination, yielding a total of 180 test specimens. The first granular base material was provided by the Utah Department of Transportation and was sampled from a full-depth reclamation project performed along Interstate 84 (I-84) in Weber Canyon near Morgan, Utah. The second granular base material was a crushed limestone collected during the summer of 2005 during a pavement reconstruction project along U.S. Highway 91 (US-91) near Richmond, Utah.

The three stabilizers used in the laboratory research included Class C fly ash, lime-fly ash, 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 from a local supplier was used in the testing. 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 strengths of 200, 400, and 600 psi.

The durability tests included the freeze-thaw test, vacuum saturation test, and 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

The 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 on the types and uses of laboratory durability tests, as well as properties of various stabilizers. In Chapter 3, the material characterization, specimen preparation and testing, and data analysis procedures are presented. The results of testing 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 followed by a discussion of stabilizer types.

2.2 LABORATORY DURABILITY TESTS

One major concern associated with cold-regions pavement engineering is the durability of stabilized materials in adverse environments. These durability concerns include both frost heave and freeze-thaw cycling. Frost heave occurs as water is drawn upwards into freezing base or subgrade materials, often forming ice lenses; upon thawing of the ice lenses, the structural capacity of the roadway may be dramatically reduced (*4*). Freeze-thaw cycling occurs as frost depths dynamically vary due to 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, engineers have developed many different protocols to evaluate the durability of stabilized materials. The three laboratory tests of particular interest in this research included freeze-thaw cycling, vacuum saturation, and tube suction testing.

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. Following 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. Following 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*).

The vacuum saturation test outlined in ASTM C 593 is the durability test specified for lime-fly ash- and Class C fly ash-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. Following 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 water, and the vacuum is removed. The specimens are allowed to soak for 1 hour and are then tested for UCS.

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 for assessing the moisture/frost susceptibility of aggregate base materials (*6*). In recent years, tube suction test results have been correlated with bearing capacity, frost heave, and several other material characteristics (*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. 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 0.5-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 satisfactory with respect to moisture/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, a variety of stabilizers have been investigated, including lime, Portland cement, fly ash, lime-fly ash, asphalt in various forms, road tar, calcium chloride and other salts, and several non-traditional additives (*2, 3*). This research was limited in scope to Class C fly ash, lime-fly ash, 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 U.S. 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*). Upon introduction of water, the free lime within the fly ash begins to react 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 final 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 upon 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) of 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 0 to 8 percent below the OMC for MDD, depending on soil type. Granular soils 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 usually 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. The literature contains mixed reviews about whether the fly ash-treated samples should be soaked for 4 hours prior to compressive strength testing (*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. Perhaps for this reason, no field data regarding the durability of Class C fly ash-treated materials could be identified in the literature review. Plans for future durability testing have been established, however, 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

Another common stabilizer used to treat base materials is a combination of lime and fly ash. 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 ($Ca(OH)_2$), monohydrated dolomitic lime ($Ca(OH)_2{\cdot}MgO$), calcitic quicklime (CaO), and dolomitic quicklime ($CaO{\cdot}MgO$) are the most common types of lime (*23*). A discussion regarding the types of fly ash is given in the previous section. 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*). Such soil-lime reactions include cation exchange, flocculation, and pozzolanic reactivity. Cation exchange and flocculation reactions occur as monovalent cations present in the native soil are exchanged with cations of higher valences, primarily calcium ions contained in the lime (*24*). Since cation exchange and flocculation reactions occur 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 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-plus-fly ash contents typically range from 12 to 30 percent by weight of dry aggregate, while lime-to-fly ash ratios 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 (*25*). 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 field 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 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. Since the early 1900s, more than 100,000 miles of cement-treated base has been constructed (*28*).

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 upon introduction of water, constitute the combination of calcium, silica, and water, resulting in the formation of C-S-H and excess calcium hydroxide. During subsequent but slower pozzolanic reactions, the excess calcium hydroxide 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, cement has the most defined design procedure. Mixture procedures specify that cement be added as a percentage of the dry weight of aggregate, with concentrations between 3 and 13 percent cement being common (*29*). 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, 28, 29, 30, 31*). Samples tested for UCS are usually soaked for 4 hours prior to testing (*1, 5, 29*).

A significant amount of research has been conducted on the durability of cement-treated base (*5, 27, 29, 30, 32, 33, 34, 35, 36*). Such research indicates that the primary concern with the durability of cement-treated base is the development of cracks in the base that may produce reflection cracking in the wearing course. The development of these cracks is attributable in many cases to self-desiccation associated with cement hydration (*27, 28, 32*). However, if proper construction practices are used, this effect can be minimized (*37*).

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, specimen preparation procedures and methods used to determine stabilizer concentrations are quite similar for Class C fly ash, lime-fly ash, and cement. The long-term field performance of cement-treated materials has been well documented in the literature, but no field data regarding the durability of materials treated with Class C fly ash or lime-fly ash could be identified in the literature review performed in this research.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 OVERVIEW

In this research, a full-factorial laboratory experiment including two granular base materials and three concentrations of each of three different stabilizers, with three replicates of each possible combination, was performed. Untreated specimens were also prepared as control samples, and all of the treatments were subjected to three separate tests, requiring preparation and testing of 180 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 granular base materials were used for this research project. The first was sampled from a full-depth reclamation project performed along I-84 in Weber Canyon near Morgan, Utah. This material was sampled during the summer of 2005 and contains about 60 percent reclaimed asphalt pavement (RAP). The second material was a crushed limestone collected during the summer of 2005 during a pavement reconstruction project along US-91 near Richmond, Utah. This material had been delivered to the job site from a local quarry. These particular aggregate base materials were selected for use in this research because of their extensive use in related projects and because of the close proximity of the corresponding field sites to the BYU Highway and Materials Laboratory. In the field, both materials were treated with 2 percent Portland cement.

Samples of the I-84 and US-91 base materials were transported to the BYU Highway and Materials Laboratory in bulk and were dried at 140°F and 212°F, respectively; a lower temperature was utilized for drying the I-84 aggregate to minimize volatilization of the asphalt cement in the RAP fraction of that material. Following drying, the materials were separated over the 3/4-in., 1/2-in., 3/8-in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200 sieves. After the bulk samples were sieved, a particle-size distribution was established for each material that facilitated reconstruction of replicate samples with identical gradations. Washed sieve analyses and liquid and plastic limit tests were performed to classify the material according to the American Association of State Highway and Transportation Officials (AASHTO) and Unified soil classification systems.

3.3 SPECIMEN PREPARATION

Once gradations were established, three to five samples with varying moisture contents were prepared for moisture-density testing of the untreated I-84 and US-91 materials. The coarse fraction, 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 added to the coarse fraction. The combined material was then mixed until it was uniform in color and texture. Each sample was then compacted into a 4-in.-diameter mold using modified Proctor compaction effort in accordance with ASTM D 1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort) Method B. The modified Proctor procedure requires compaction of the specimen in five lifts, with each lift consisting of 25 blows of a 10-lb hammer dropped from a height of 18 in. Following compaction, an additional five blows were applied with a finishing tool to level the specimen surface. Figure 3.1 shows the finishing tool being used by a researcher, with the compaction apparatus in the background. The specimen was then extruded from the mold as depicted in Figure 3.2, and its height and weight were measured. The specimen was subsequently dried to constant weight in an oven to facilitate calculation of gravimetric moisture content and dry density. Similar to drying of the bulk materials, specimens prepared using the I-84 material were dried at 140°F, while specimens prepared using the US-91 material were dried at 212°F. These values were plotted to determine the OMC and MDD for each untreated material.

Figure 3.1 Compaction apparatus and finishing tool.

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 modified Proctor procedure as described previously. The specimens were then capped with a high-strength gypsum compound as shown in Figure 3.3 to provide a flat surface on each end necessary to ensure equal 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 floating base as shown in Figure 3.4. The maximum load was divided by the cross-sectional area to obtain the compressive strength.

An initial mid-range concentration was selected for each stabilizer based on information in the literature and past research experience with the I-84 and US-91 materials. Moisture-density curves were then created for each material treated with the specified concentrations of Class C fly ash, lime-fly ash, 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

Figure 3.2 Hydraulic extruder.

Figure 3.3 Specimens capped for UCS testing.

Figure 3.4 UCS testing.

previously. Before the dry fine fraction was added to the coarse fraction, however, the stabilizer was added to the fine fraction, and the combination was mixed until it was uniform in color and texture. The fine fraction was then mixed with the coarse fraction prior to compaction. Following compaction, specimens were extruded, and their heights and weights were measured before the specimens were placed in an oven at the aforementioned temperatures for drying 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 OMCs, cured for a 7-day period, and tested for UCS under various conditions as prescribed by the practices identified in the literature review. A minimum of two replicate specimens were tested at each concentration. For this research project, a 7-day cure was selected as the basis for equivalency.

For UCS testing, specimens stabilized with Class C fly ash were sealed in air-tight plastic bags following extrusion to prevent moisture loss during the curing period. As depicted in Figure 3.5, curing occurred in an oven at 100°F for 7 days. After the

Figure 3.5 Curing conditions for specimens treated with Class C fly ash and lime-fly ash.

curing period, samples were immediately capped with gypsum and subjected to UCS testing as described previously.

As with Class C fly ash, lime-fly ash specimens were also sealed in air-tight plastic bags following extrusion and were cured at 100°F for 7 days. However, following curing, lime-fly ash specimens were soaked underwater for 4 hours as prescribed by ASTM C 593. Figure 3.6 shows several samples soaking in preparation for UCS testing. After the 4-hour soaking period, the specimens were capped with gypsum and tested.

Curing of specimens treated with Portland cement occurred at room temperature in a fog room, where they were subjected to 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 (*29*). Specimens were then capped with gypsum and subjected to UCS testing.

Results of the initial UCS testing performed with each stabilizer were evaluated to select additional stabilizer concentrations within a target 7-day UCS range of 200 to 600 psi specified by PCA personnel for this research. In the past, PCA has recommended 7-day UCSs as high as 600 psi for stabilized layers (*38*), which often led

Figure 3.6 Specimens soaking prior to UCS testing.

to unacceptable reflection cracking in asphalt pavements as discussed in Chapter 2. In recent years, however, PCA has reduced the target 7-day UCS to 400 psi (*39*), although some research suggests that even lower strengths may still provide adequate durability (*37*). Thus, low, medium, and high concentrations corresponding to 200, 400, and 600 psi, respectively, were investigated in this research.

Once additional stabilizer concentrations were selected, values for OMC, MDD, and 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 strength of 600 psi 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 concentrations corresponding to 200 and 400 psi to the concentration corresponding to 400 psi. 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.

For freeze-thaw testing, three replicates of each material treated with each stabilizer concentration were prepared, compacted, extruded, and cured as described in the previous section. 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. Figures 3.7 through 3.9 depict the freezing, thawing, and soaking configurations, respectively, for freeze-thaw testing. As prescribed in ASTM D 560, specimens were subjected to 12 freeze thaw-cycles in total. During each soaking period, care was taken to place samples 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, and all of the specimens were then 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, specimens were oven-dried at 140°F and 212°F for I-84 and US-91 materials, respectively, so that 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 the previous section. Following the curing period, specimens were weighed and placed upright inside a vacuum chamber as shown in Figure 3.10. 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

Figure 3.7 Freezing configuration for freeze-thaw testing.

Figure 3.8 Thawing configuration for freeze-thaw testing.

Figure 3.9 Soaking configuration for freeze-thaw testing.

Figure 3.10 Vacuum chamber used for vacuum saturation test.

depicted in Figure 3.11. 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 chamber, weighed, and capped with gypsum. Following capping, specimens were subjected to UCS testing before being dried in an oven at 140°F or 212°F to facilitate computation of moisture contents.

Figure 3.11 Vacuum saturation test configuration.

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. were also drilled in a line around the mold about 1/4 in. from the bottom as shown in Figure 3.12. The mold was also trimmed to about 5 in. in height.

Figure 3.12 Plastic mold used for tube suction test.

Specimens were prepared, compacted, and cured as described in the previous section, except that the specimens were compacted into the plastic molds. A metal sleeve was placed around the mold during compaction to prevent buckling of the sides of the mold. After curing, specimens were dried for 3 days at 104°F, following which initial dielectric readings were measured using a surface dielectric probe as displayed in Figure 3.13. According to the protocol given in Chapter 2, 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 specimens were placed in the water bath. Following testing, specimens were oven-dried, again at 140°F or 212°F, so that dry densities and moisture contents could be determined.

Figure 3.13 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 standard 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, retained UCS after the freeze-thaw test, UCS after the vacuum saturation test, retained UCS after the vacuum saturation test, and final dielectric value after the tube suction test. Factors included aggregate type, stabilizer type, stabilizer concentration level, and all of their interactions. Initially, a full model was created using all factors and their interactions. 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 ANOVA indicated that a main effect was significant, as indicated by a *p*-value less than 0.05, Tukey's mean separation procedure was used to identify the differences. Linear regression was also utilized to assess relationships between specific sets of test results, and coefficients of variation (CVs) were computed to facilitate evaluation of the repeatability of each test.

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. I-84 and US-91 aggregates were stabilized with Class C fly ash, lime-fly ash, and Portland cement in three concentrations each. Specimens were compacted using modified 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 ANOVA and Tukey's mean separation procedures.

CHAPTER 4

RESULTS

4.1 OVERVIEW

The following sections present the selected stabilizer concentrations and the results of freeze-thaw, vacuum saturation, and tube suction testing, as well as the results of statistical analyses performed on the data.

4.2 MATERIAL CHARACTERIZATION

Both the I-84 and US-91 materials were characterized using washed sieve analyses and liquid and plastic limit tests. Particle-size distributions from washed sieve analyses are presented in Table 4.1 and Figure 4.1. Since liquid and plastic limit tests indicated that both materials were non-plastic, the Atterberg limits could not be determined. According to the AASHTO and Unified soil classification procedures, the I-84 material was classified as A-1-a and SP (poorly graded sand with gravel),

Table 4.1 Particle-Size Distributions

Sieve Size	Percent Passing (%)	
	I-84	US-91
3/4 in.	100.0	100.0
1/2 in.	85.1	84.4
3/8 in.	75.2	71.8
No. 4	54.5	50.5
No. 8	42.7	39.1
No. 16	34.4	29.4
No. 30	25.8	22.0
No. 50	12.2	15.2
No. 100	2.6	9.6
No. 200	1.3	8.4

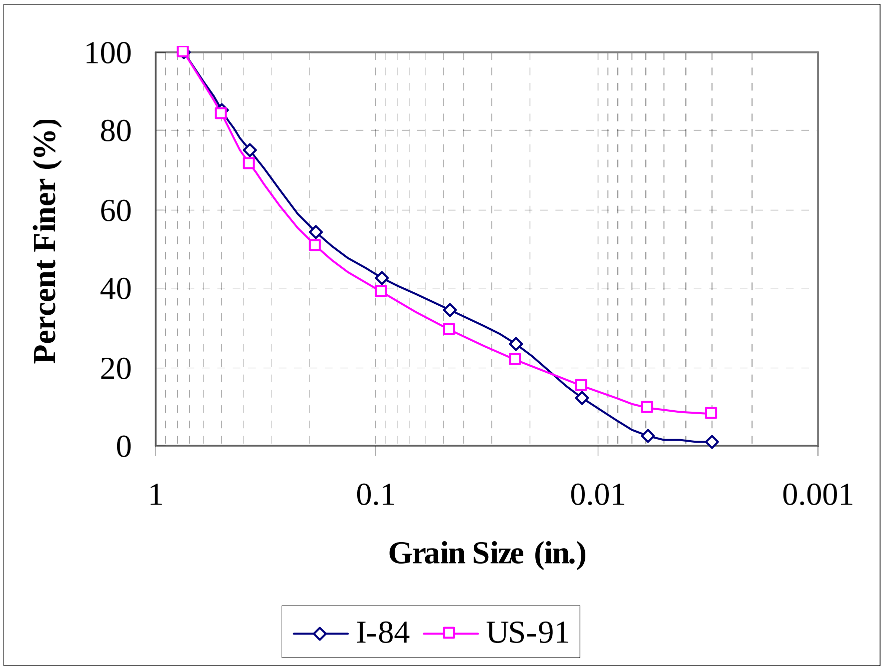

Figure 4.1 Particle-size distributions.

respectively, while the US-91 material was classified as A-1-a and SW-SM (well-graded sand with silt and gravel), respectively.

4.3 STABILIZER CONCENTRATIONS

Plots of stabilizer concentration versus 7-day UCS are shown in Figures 4.2 through 4.4 for Class C fly ash, lime-fly ash, and Portland cement, respectively. Appendix A provides the OMC, MDD, and UCS data associated with the trial stabilizer concentrations represented in these figures. Table 4.2 summarizes the stabilizer concentrations and values of OMC and MDD selected for aggregate testing. In the table, concentration levels of low, medium, and high correspond to target 7-day UCS values of 200, 400, and 600 psi, respectively. Stabilizer concentrations are reported as percentages of the weight of dry aggregate, while OMC is reported in each case as the percentage of the total weight of the dry aggregate and stabilizer. For the I-84 material, Figure 4.4 shows that the addition of more than 1.0 percent cement does not increase the specimen strength. While investigating the reasons for this behavior is beyond the scope of this research, previous researchers have suggested that the asphalt cement coating

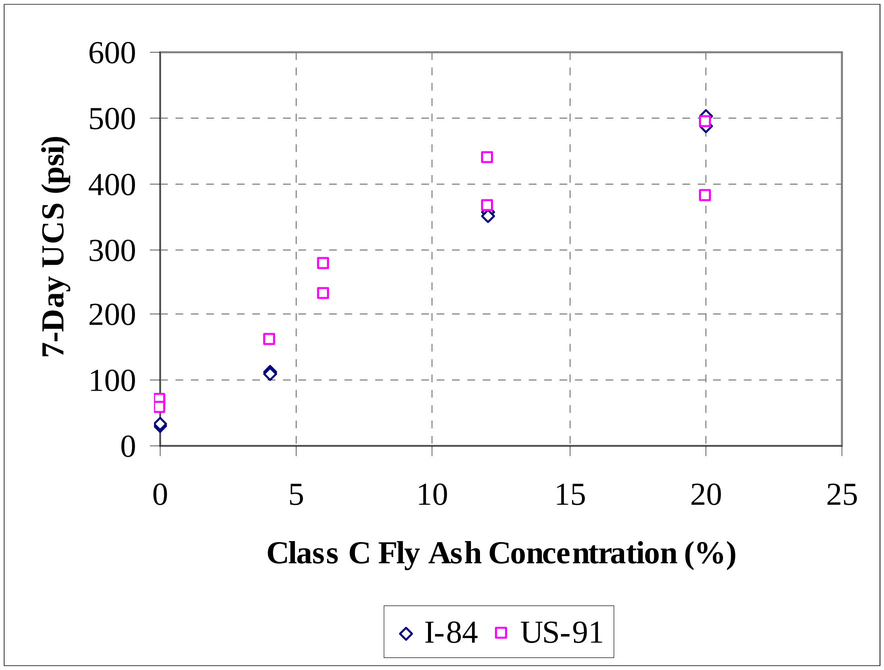

Figure 4.2 UCS data for materials treated with Class C fly ash.

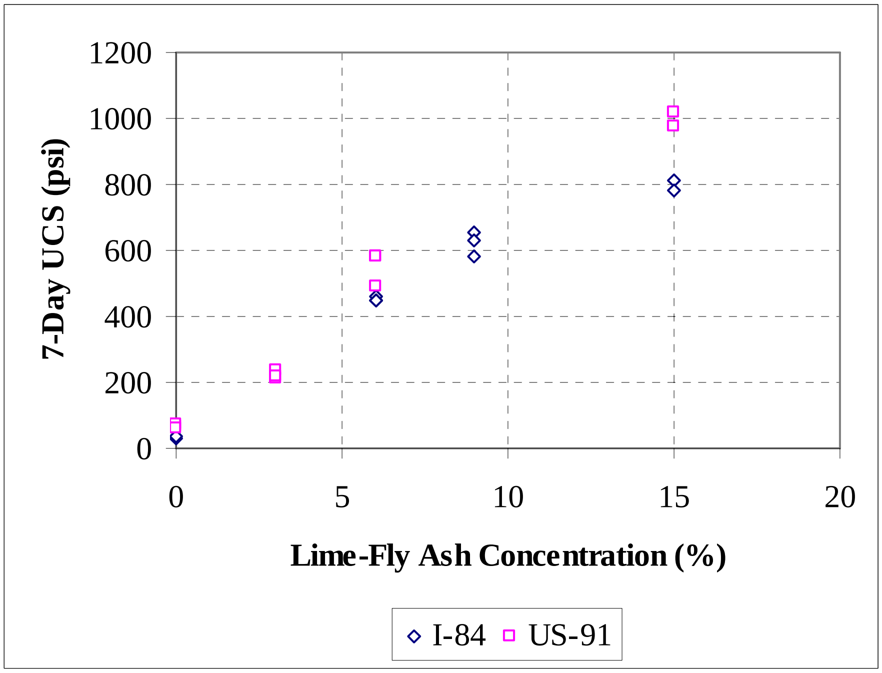

Figure 4.3 UCS data for materials treated with lime-fly ash.

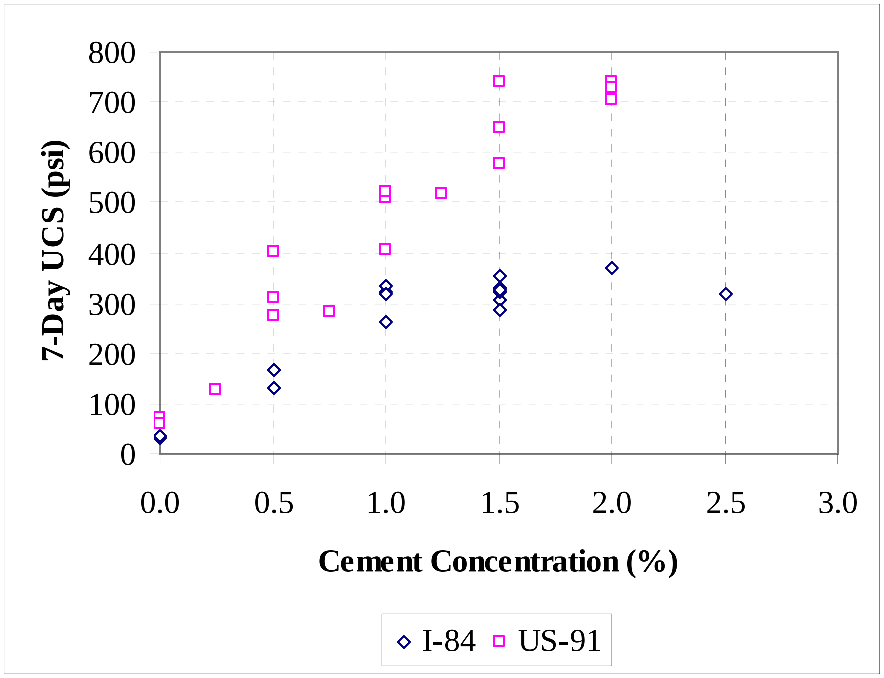

Figure 4.4 UCS data for materials treated with cement.

the RAP fraction of the I-84 material may inhibit the formation of cementitious bonds between aggregates (*40*). However, this unusual performance was not characteristic of specimens treated with Class C fly ash or lime-fly ash within the ranges of concentrations investigated in this research. The MDD values shown in Table 4.2 for cement-treated materials are the same as those listed for untreated materials for both the I-84 and US-91 aggregates because the effect of cement on the compaction characteristics was assumed to be negligible due to the low cement concentrations. The OMC values for the cement-treated specimens were estimated from the OMC values associated with the untreated specimens by adding 1 percentage point of water for every 4.0 percent cement added to the aggregate (*40*). That is, for a specimen stabilized with 2.0 percent cement, for example, the OMC of the untreated material would be increased by 0.5 percent as an estimation of the OMC of the cement-treated material.

Table 4.2 Stabilizer Concentrations Used for Testing

Aggregate Type	Stabilizer Type	Concentration Level	Stabilizer Concentration (%)	OMC (%)	MDD (pcf)
I-84	Untreated	-	-	5.9	129.6
	Class C Fly Ash	Low	7	5.4	130.2
		Medium	15	5.3	130.8
		High	23	5.8	129.0
	Lime-Fly Ash	Low	3	5.3	125.0
		Medium	6	5.4	121.1
		High	9	4.8	125.6
	Cement	Low	0.5	6.0	129.6
		Medium	1.0	6.2	129.6
		High	1.5	6.3	129.6
US-91	Untreated	-	-	5.9	139.2
	Class C Fly Ash	Low	4	4.0	137.1
		Medium	12	6.4	136.2
		High	20	6.0	134.4
	Lime-Fly Ash	Low	3	5.8	126.0
		Medium	5	5.6	127.4
		High	7	5.4	141.6
	Cement	Low	0.5	6.0	139.2
		Medium	1.0	6.2	139.2
		High	1.5	6.3	139.2

4.4 FREEZE-THAW TEST

Data collected during freeze-thaw testing are presented in Tables 4.3 and 4.4. Hyphens in the tables represent data that were not measured. Since both the untreated I-84 and US-91 specimens failed during the initial soaking period required before the commencement of the first freeze-thaw cycle, the strength and final moisture content of each of those specimens could not be measured. Although this was also the case for the US-91 specimens treated with the low concentration of Class C fly ash, the results generally indicate that treated specimens were stronger than untreated specimens. The final moisture contents of cement-treated specimens at the low concentration level are much higher than other moisture contents. These high moisture contents correspond with the relatively low densities associated with these specimens. Appendix A provides

Table 4.3 I-84 Freeze-Thaw Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	UCS (psi)	Final Moisture (%)
Untreated	-	1	128.0	-	-
		2	128.1	-	-
		3	128.7	-	-
Class C Fly Ash	Low	1	130.6	219	4.4
		2	129.7	223	4.4
		3	130.5	200	4.4
	Medium	1	130.3	460	4.5
		2	129.2	433	4.6
		3	129.9	524	4.4
	High	1	129.3	583	4.2
		2	129.9	808	4.2
		3	129.4	902	4.1
Lime-Fly Ash	Low	1	126.5	94	5.6
		2	126.1	117	5.5
		3	126.6	120	5.2
	Medium	1	128.4	310	5.0
		2	126.9	295	5.2
		3	129.7	403	4.5
	High	1	129.0	508	4.1
		2	128.0	459	4.4
		3	128.7	466	4.2
Cement	Low	1	117.3	150	8.6
		2	113.3	150	9.1
		3	118.4	156	8.8
	Medium	1	129.6	209	5.2
		2	129.0	208	5.0
		3	129.0	260	5.0
	High	1	129.5	330	5.0
		2	129.0	281	4.9
		3	129.9	316	4.7

additional weight data collected during each freeze-thaw cycle, as well as the final circumference of each specimen. Appendix B displays photographs of each group of specimens taken after curing but before testing and after 6 and 12 cycles of freezing and thawing.

Table 4.4 US-91 Freeze-Thaw Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	UCS (psi)	Final Moisture (%)
Untreated	-	1	137.1	-	-
		2	133.8	-	-
		3	136.7	-	-
Class C Fly Ash	Low	1	137.1	-	-
		2	136.1	-	-
		3	136.2	-	-
	Medium	1	136.1	387	5.7
		2	135.7	452	5.8
		3	135.0	480	5.8
	High	1	134.9	579	6.4
		2	134.3	715	6.4
		3	134.9	653	6.1
Lime-Fly Ash	Low	1	135.9	113	5.1
		2	136.2	240	5.2
		3	135.8	176	5.1
	Medium	1	137.8	345	5.5
		2	139.6	352	5.3
		3	137.7	357	5.4
	High	1	136.3	428	5.5
		2	136.1	368	5.5
		3	137.3	294	5.5
Cement	Low	1	137.5	169	5.7
		2	136.9	154	5.6
		3	135.8	132	5.5
	Medium	1	136.8	300	5.5
		2	137.6	315	5.4
		3	138.5	220	5.3
	High	1	137.7	645	5.5
		2	137.3	704	5.5
		3	137.4	619	5.3

Figure 4.5 is a graphical representation of the I-84 freeze-thaw test results. The solid bars represent UCS values of specimens before the freeze-thaw test, while the hatched bars represent UCS values of specimens after freeze-thaw cycling. This figure shows that, in general, most specimens lost strength during testing. The only exceptions to this trend were the medium and high concentrations of Class C fly ash. During the

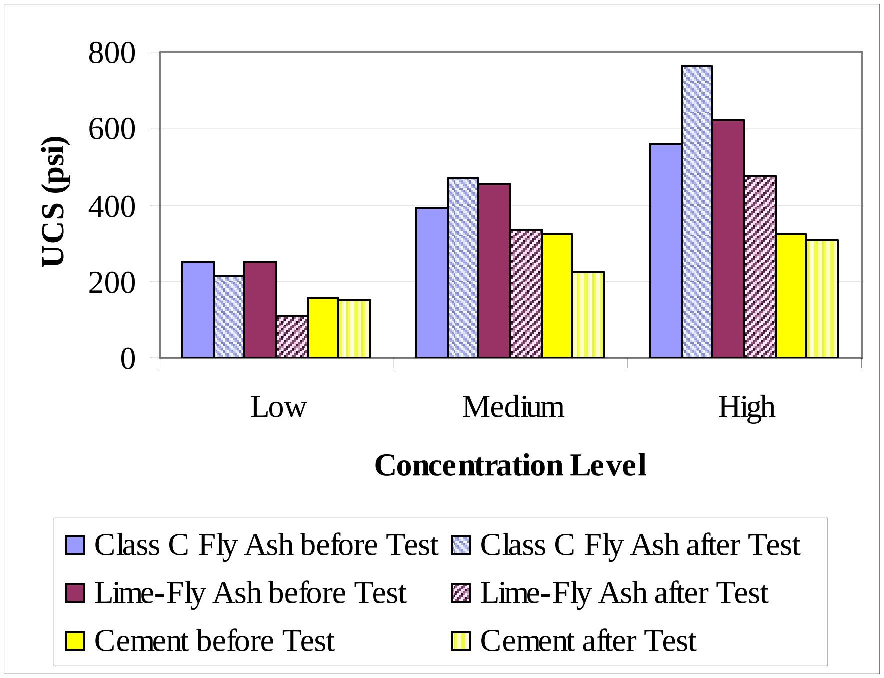

Figure 4.5 I-84 freeze-thaw test results.

course of testing, those specimens actually gained a substantial amount of strength. This strength gain can be attributed to the relatively long duration of the test. The freeze-thaw test required between 5 and 6 weeks to complete after initial curing. Class C fly ash-treated samples were still able to gain strength despite the adverse environment they experienced. The lime-fly ash samples lost considerable strength at all concentration levels, while the cement-treated samples performed well at low and high concentration levels. As discussed in the previous section, the I-84 material did not gain appreciable strength with additions of high concentrations of cement; specimens treated with high concentrations of cement did, however, retain more strength during testing than medium concentrations.

Figure 4.6 is a plot of the US-91 freeze-thaw test results. Noticeably absent from this figure is the UCS of Class C fly ash-treated specimens at the low concentration level. At the conclusion of freeze-thaw cycling, all that remained of each of those specimens was an approximately 3-in.-diameter sphere that was unsuitable for UCS testing. While specimens treated at the low concentration of Class C fly ash performed poorly, specimens treated at the medium and high concentrations performed

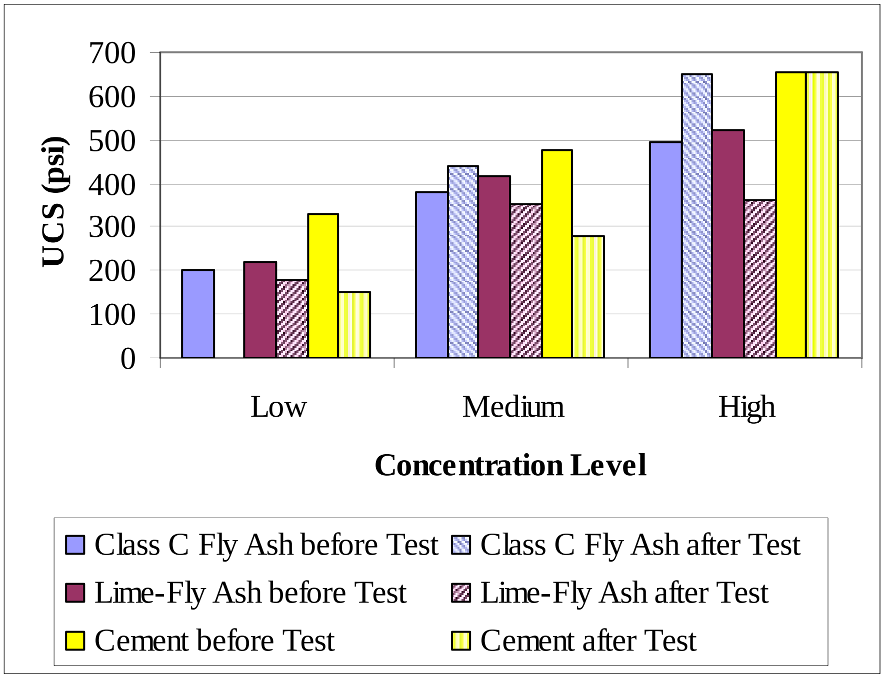

Figure 4.6 US-91 freeze-thaw test results.

exceptionally well. As was the case with the I-84 material, the Class C fly ash-treated specimens gained strength during testing. The lime-fly ash- treated specimens lost some strength at low and medium concentrations and substantial strength at high concentrations. Cement-treated specimens performed well at the high concentration level but lost considerable strength at the low and medium concentration levels.

4.5 VACUUM SATURATION TEST

Data collected during vacuum saturation testing are shown in Tables 4.5 and 4.6. The tables indicate that the addition of stabilizers at all concentration levels significantly improved specimen strengths compared to the untreated materials. Given that the final moisture contents were all higher than the corresponding OMCs, the vacuum saturation procedure was effective at causing moisture absorption during testing. On average, specimens absorbed 1.4 percent moisture over OMC during the vacuum saturation test. The results of vacuum saturation testing for the I-84 material are plotted in Figure 4.7. Since the vacuum saturation test requires only 2 hours to perform, the test results were not influenced by the pozzolanic reactivity that allowed specimens to gain strength

Table 4.5 I-84 Vacuum Saturation Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	UCS (psi)	Final Moisture (%)
Untreated	-	1	123.7	4	10.2
		2	123.3	10	9.8
		3	123.4	6	10.1
Class C Fly Ash	Low	1	130.7	160	7.0
		2	132.1	189	6.7
		3	130.6	193	6.9
	Medium	1	131.0	365	6.6
		2	131.6	399	6.4
		3	130.0	451	6.8
	High	1	129.3	404	6.9
		2	129.1	427	6.9
		3	129.4	734	6.5
Lime-Fly Ash	Low	1	130.0	162	7.1
		2	129.0	156	7.1
		3	130.1	166	7.1
	Medium	1	131.3	353	6.6
		2	131.1	415	6.7
		3	131.3	349	6.4
	High	1	131.6	454	6.3
		2	131.7	555	6.2
		3	131.2	512	6.0
Cement	Low	1	128.5	130	7.2
		2	128.3	139	7.8
		3	128.6	150	7.6
	Medium	1	127.9	263	7.1
		2	128.5	301	6.8
		3	128.2	239	7.1
	High	1	127.6	283	7.1
		2	128.9	329	6.8
		3	128.9	326	6.9

during the freeze-thaw test. However, the strengths of the Class C fly ash-treated specimens at a medium concentration level before and after testing indicate that the strength was slightly higher after the test. This small discrepancy can probably be attributed to the variability inherent in specimen preparation and UCS testing; Figure 4.2 illustrates the variability in UCS between replicate specimens stabilized with Class C fly

Table 4.6 US-91 Vacuum Saturation Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	UCS (psi)	Final Moisture (%)
Untreated	-	1	140.0	10	6.8
		2	139.6	28	6.4
		3	137.9	8	7.2
Class C Fly Ash	Low	1	142.0	102	6.4
		2	140.5	120	6.4
		3	140.5	75	6.6
	Medium	1	136.4	343	6.9
		2	136.3	361	6.9
		3	135.8	313	7.1
	High	1	132.3	338	7.6
		2	132.0	377	7.8
		3	131.7	363	7.9
Lime-Fly Ash	Low	1	138.7	192	6.6
		2	137.4	151	6.7
		3	138.1	210	6.3
	Medium	1	138.3	321	6.6
		2	135.9	404	6.8
		3	137.4	339	6.8
	High	1	136.2	392	6.8
		2	136.6	376	6.6
		3	136.6	321	6.4
Cement	Low	1	137.8	170	6.8
		2	138.1	174	6.7
		3	137.8	218	7.0
	Medium	1	139.3	380	6.4
		2	138.8	400	6.7
		3	138.4	354	6.9
	High	1	135.8	355	5.8
		2	138.2	456	6.5
		3	138.3	519	7.8

ash. The strength loss of specimens treated at all concentration levels of cement and the high concentration level of Class C fly ash was relatively small, while the strength loss of specimens treated at all concentration levels of lime-fly ash and the low concentration level of Class C fly ash was considerable.

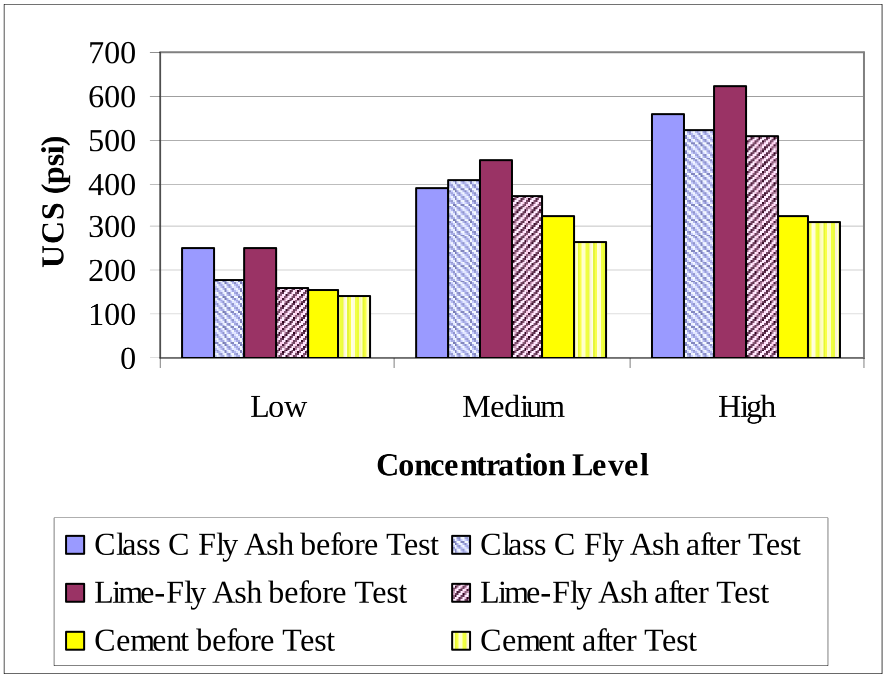

Figure 4.7 I-84 vacuum saturation test results.

Figure 4.8 is a plot of the results from the US-91 vacuum saturation test. These results indicate that all specimens lost considerable strength at high concentrations. All of the specimens treated with stabilizers at medium concentration levels lost about the same amount of strength, while lime-fly ash-treated specimens lost less strength than cement or Class C fly ash-treated specimens at low concentration levels.

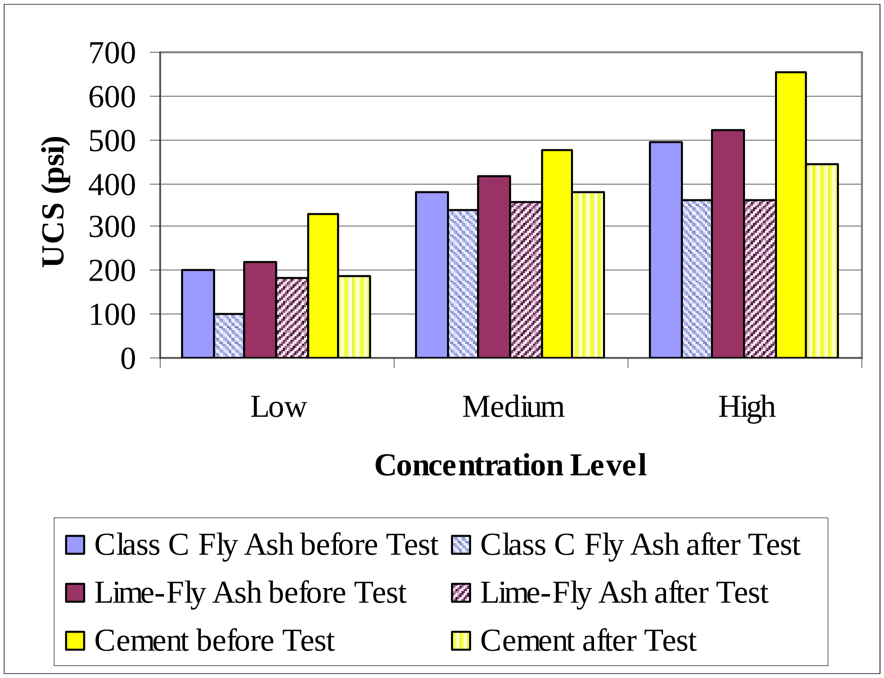

Figure 4.8 US-91 vacuum saturation test results.

4.6 TUBE SUCTION TEST

Tables 4.7 and 4.8 present results from tube suction testing. Appendix A provides additional dielectric values recorded daily during the testing. Without the addition of a stabilizer, both the I-84 and US-91 materials were marginally moisture susceptible, with average final dielectric values of 10.8 and 10.1, respectively.

The I-84 tube suction test results are displayed graphically in Figure 4.9. The lime-fly ash-treated specimens were the only specimens that exhibited final dielectric values higher than those associated with the untreated specimens. Thus, all other stabilizers at the various concentrations were effective in reducing the moisture/frost susceptibility of the aggregates to a satisfactory level.

The results of the US-91 tube suction tests are shown in Figure 4.10, which indicates that cement was the only stabilizer able to reduce the moisture/frost susceptibility of the US-91 material to a satisfactory level at all three concentration levels. Although the high concentration of lime-fly ash treatment was also able to satisfactorily reduce the moisture susceptibility, all other concentrations of lime-fly ash and Class C fly ash were ineffective in treating the US-91 material with respect to the tube suction test criteria.

Table 4.7 I-84 Tube Suction Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	Final Dielectric Value	Final Moisture (%)
Untreated	-	1	131.5	10.3	6.5
		2	131.2	11.5	6.5
		3	132.3	10.7	6.4
Class C Fly Ash	Low	1	136.0	4.4	2.2
		2	136.1	5.1	2.3
		3	135.8	5.2	2.2
	Medium	1	137.6	5.0	2.3
		2	136.6	4.9	2.3
		3	136.7	5.2	2.2
	High	1	137.7	4.8	2.1
		2	134.9	5.2	2.2
		3	136.5	5.7	2.3
Lime-Fly Ash	Low	1	134.0	12.6	4.4
		2	135.4	14.0	4.4
		3	135.0	12.8	4.6
	Medium	1	137.6	5.2	2.0
		2	137.3	5.1	2.0
		3	137.7	5.7	2.1
	High	1	137.3	5.0	1.7
		2	137.9	6.3	1.7
		3	138.3	5.7	1.6
Cement	Low	1	131.2	9.9	5.8
		2	130.9	7.2	6.1
		3	130.6	6.7	5.6
	Medium	1	130.8	3.7	3.8
		2	131.6	3.7	3.7
		3	130.1	3.6	3.8
	High	1	130.1	3.5	3.5
		2	132.3	4.0	3.4
		3	133.1	4.0	3.3

Table 4.8 US-91 Tube Suction Test Results

Stabilizer Type	Concentration Level	Specimen	Dry Density (pcf)	Final Dielectric Value	Final Moisture (%)
Untreated	-	1	139.1	10.1	6.4
		2	138.6	10.8	6.5
		3	138.0	9.4	6.4
Class C Fly Ash	Low	1	142.8	11.4	6.5
		2	143.0	10.5	6.7
		3	143.1	8.5	6.6
	Medium	1	140.2	9.0	7.4
		2	140.0	12.7	7.7
		3	141.0	12.0	7.5
	High	1	135.4	9.9	9.1
		2	131.6	13.6	8.6
		3	136.9	14.6	8.6
Lime-Fly Ash	Low	1	140.2	11.6	6.6
		2	139.4	8.5	6.7
		3	140.1	10.7	6.7
	Medium	1	140.7	9.2	6.0
		2	139.1	10.8	6.8
		3	140.5	11.7	6.7
	High	1	138.6	10.2	6.8
		2	139.4	7.4	6.0
		3	138.6	9.3	6.8
Cement	Low	1	139.9	7.1	6.4
		2	139.6	6.2	6.5
		3	140.3	7.7	6.5
	Medium	1	139.7	4.8	5.1
		2	138.6	8.2	6.6
		3	140.3	5.1	5.8
	High	1	138.6	4.9	5.7
		2	139.0	8.1	6.6
		3	139.0	4.6	5.5

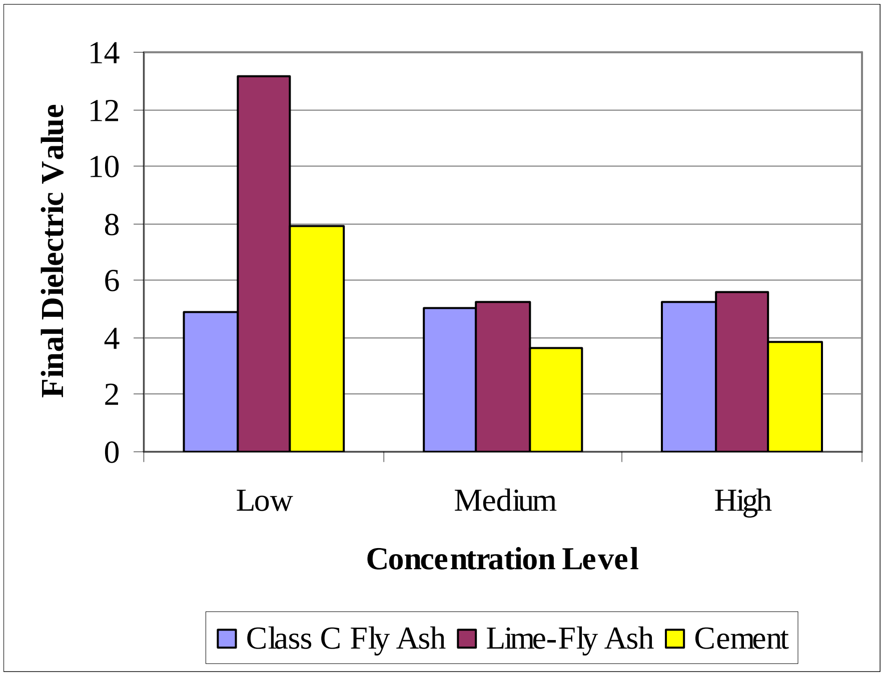

Figure 4.9 I-84 tube suction test results.

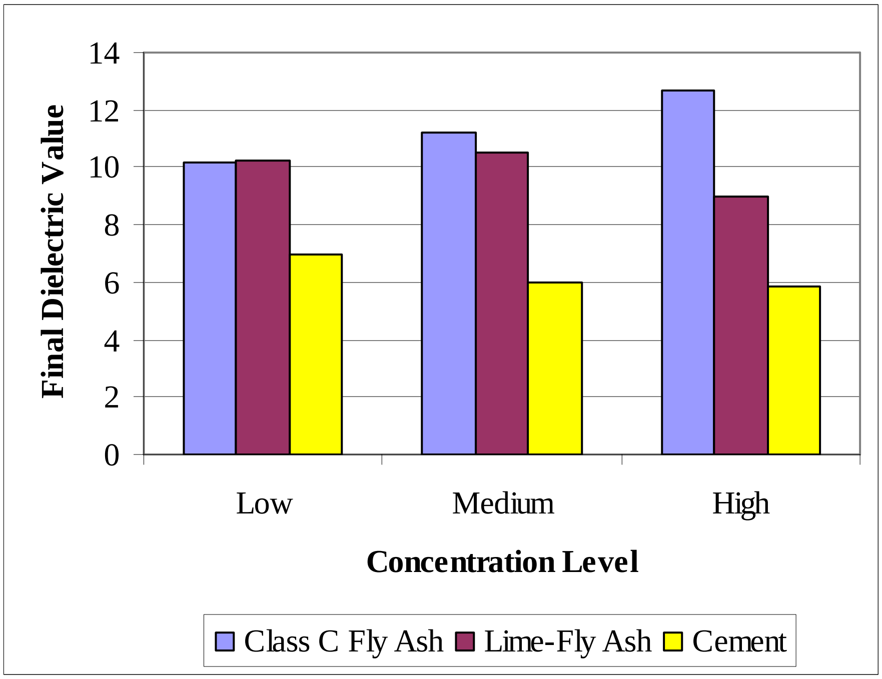

Figure 4.10 US-91 tube suction test results.

4.7 STATISTICAL ANALYSES

Table 4.9 shows the *p*-values computed in the ANOVA for each factor, including main effects and interactions. The table shows the significance levels associated with the reduced model in each case. As described in Chapter 3, only factors having *p*-values less than or equal to 0.15 were included; the hyphens in the table indicate that the *p*-values in those cases exceeded 0.15. For UCS and retained UCS after freeze-thaw testing, as well as for dielectric value in the tube suction test, all factors and interactions were included. For UCS and retained UCS after vacuum saturation testing, only the main effects and one or two, respectively, of the two-way interactions were included. Even though the *p*-values associated with aggregate type for UCS after freeze-thaw testing and UCS after vacuum saturation testing were greater than 0.15, this factor was included in the analysis because at least one interaction involving aggregate type was significant in each case, as indicated by a *p*-value of less than 0.05. A discussion of the statistical analyses relating to the main effects and interactions is given in the following sections.

Table 4.9 Significance Levels for Main Effects and Interactions

Factor	*p*-values				
	Freeze-Thaw Test		Vacuum Saturation Test		Tube Suction Test
	UCS	Retained UCS	UCS	Retained UCS	Dielectric Value
Aggregate Type	0.9761	0.0260	0.2725	0.0060	<0.0001
Stabilizer Type	<0.0001	0.0002	0.1677	0.8354	<0.0001
Concentration Level	<0.0001	<0.0001	<0.0001	0.0040	<0.0001
Aggregate Type * Stabilizer Type	<0.0001	0.0045	<0.0001	0.0343	<0.0001
Aggregate Type * Concentration Level	0.0618	0.0154	-	-	<0.0001
Stabilizer Type * Concentration Level	<0.0001	<0.0001	-	0.1404	<0.0001
Aggregate Type * Stabilizer Type * Concentration Level	<0.0001	0.0020	-	-	0.0308

4.7.1 Main Effects

Tables 4.10 through 4.12 contain the least square mean values associated with the main effects of aggregate type, stabilizer type, and concentration level, respectively. The least square mean is the best estimate of the subpopulation mean for a given level of a given factor (*41*). Table 4.10 shows that, while UCS values measured after freeze-thaw and vacuum saturation testing were similar for both aggregates, the I-84 material retained more strength during freeze-thaw cycling and vacuum saturation and exhibited lower final dielectric values during tube suction testing than the US-91 material. As indicated in Table 4.9, these differences between aggregates are significant. Although the I-84 material performed better than the US-91 material, the I-84 material required

Table 4.10 Least Square Means for Main Effects of Aggregate Type

Test	Response Variable	I-84	US-91
Freeze-Thaw	UCS (psi) Retained UCS (%)	340 89	341 78
Vacuum Saturation	UCS (psi) Retained UCS (%)	319 85	301 74
Tube Suction	Dielectric Value	6.1	9.2

Table 4.11 Least Square Means for Main Effects of Stabilizer Type

Test	Response Variable	Class C Fly Ash	Lime-Fly Ash	Cement
Freeze-Thaw	UCS (psi) Retained UCS (%)	423 100	303 72	295 79
Vacuum Saturation	UCS (psi) Retained UCS (%)	318 81	324 78	288 79
Tube Suction	Dielectric Value	8.2	9.0	5.7

Table 4.12 Least Square Means for Main Effects of Concentration Level

Test	Response Variable	Low	Medium	High
Freeze-Thaw	UCS (psi) Retained UCS (%)	134 59	351 88	537 103
Vacuum Saturation	UCS (psi) Retained UCS (%)	159 70	353 87	418 81
Tube Suction	Dielectric Value	8.9	7.0	7.0

higher stabilizer concentrations to reach the target 7-day UCS values specified in this research. Table 4.10 also shows that, on average, the UCS and retained UCS were higher for specimens tested in freeze-thaw cycling than the corresponding values associated with vacuum saturation testing. This observation suggests that the vacuum saturation test is more severe than the freeze-thaw test, especially for materials characterized by continuing pozzolanic reactivity. As suggested previously, the apparent differences in test severity may be substantially attributable to differences in test durations.

With respect to comparing the different stabilizers investigated in this research, the results of Tukey's mean separation procedure indicated that, for both UCS and retained UCS after freeze-thaw cycling, Class C fly-treated specimens were significantly stronger than both lime-fly ash- and cement-treated specimens, which were not significantly different from each other. Although Table 4.11 displays some differences in values obtained from the vacuum saturation test, Tukey's mean separation procedure showed that none of the three stabilizer types were significantly different from each other with respect to either UCS or retained UCS. Dielectric values measured during tube suction testing were lowest for cement-treated specimens as shown in Table 4.11, indicating that cement performed better than other stabilizers in reducing the moisture/frost susceptibility of the treated materials. Although all three of the dielectric values shown in the table would be associated with a satisfactory ranking, as they are all less than 10, Tukey's mean separation procedure indicated that the differences in dielectric values between cement-treated specimens and both Class C fly ash- and lime-fly ash-treated specimens were significant; the dielectric values of Class C fly ash- and lime-fly ash-treated specimens were not significantly different, however.

The least square means for main effects of concentration level presented in Table 4.12 indicate that as the stabilizer concentration level increased from low to high, specimens performed better in nearly all cases. The only exceptions were the retained UCS after vacuum saturation and the dielectric value obtained in the tube suction test. In these two cases, specimens treated with high stabilizer concentrations did not perform better than those treated with medium stabilizer concentrations. In both cases, Tukey's mean separation procedure indicated that the differences between medium and high concentrations were not significant. Differences in all other stabilizer concentrations were significant.

4.7.2 Interactions

ANOVA results indicate that all three of the possible two-way interactions were significant in one or more of the tests, and the three-way interaction was significant for UCS after freeze-thaw testing. Since the purpose of the statistical analysis was to identify significant factors, implications of the three-way interaction are not discussed in this report. Table 4.13 lists the least square mean values for interactions between aggregate type and stabilizer type for each of the response variables, while Figures 4.11 through 4.15 show the extent to which the effects of aggregate type depend on stabilizer type for each response variable included in the research. Similarly, Table 4.14 contains the least square mean values for interactions between aggregate type and concentration level for each of the response variables, while Figures 4.16 through 4.18 show the extent to which the effects of aggregate type depend on concentration level for each response variable. Data relating to the vacuum saturation test are missing from Table 4.14 because the interaction between aggregate type and concentration level was not significant for either UCS or retained UCS. Table 4.15 contains the least square mean values for interactions between stabilizer type and concentration level for each of the response variables, while Figures 4.19 through 4.22 show the extent to which the effects of stabilizer type depend on concentration level for each response variable. Data relating to UCS after vacuum saturation are missing from Table 4.15 and the subsequent figures because the interaction between stabilizer type and concentration level was not significant in that case.

Table 4.13 Least Square Means for Interactions between Aggregate Type and Stabilizer Type

Aggregate Type	Stabilizer Type	Freeze-Thaw Test		Vacuum Saturation		Tube Suction Test
		UCS (psi)	Retained UCS (%)	UCS (psi)	Retained UCS (%)	Dielectric Value
I-84	Class C Fly Ash	483	115	369	90	5.0
	Lime-Fly Ash	308	65	347	76	8.0
	Cement	229	88	240	90	5.1
US-91	Class C Fly Ash	363	85	266	72	11.3
	Lime-Fly Ash	297	78	301	80	9.9
	Cement	362	69	336	69	6.3

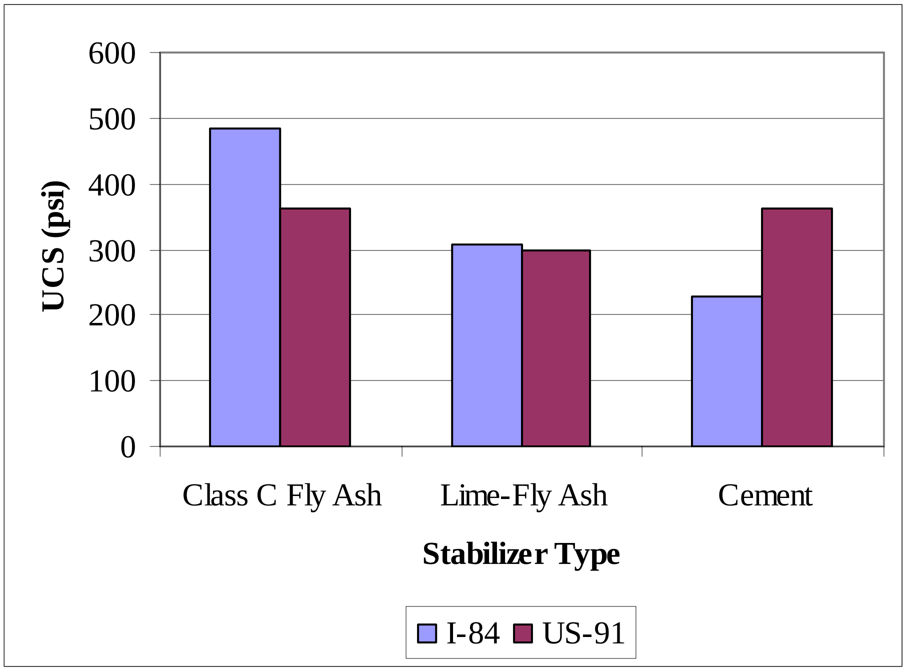

Figure 4.11 Interaction between aggregate type and stabilizer type for UCS after the freeze-thaw test.

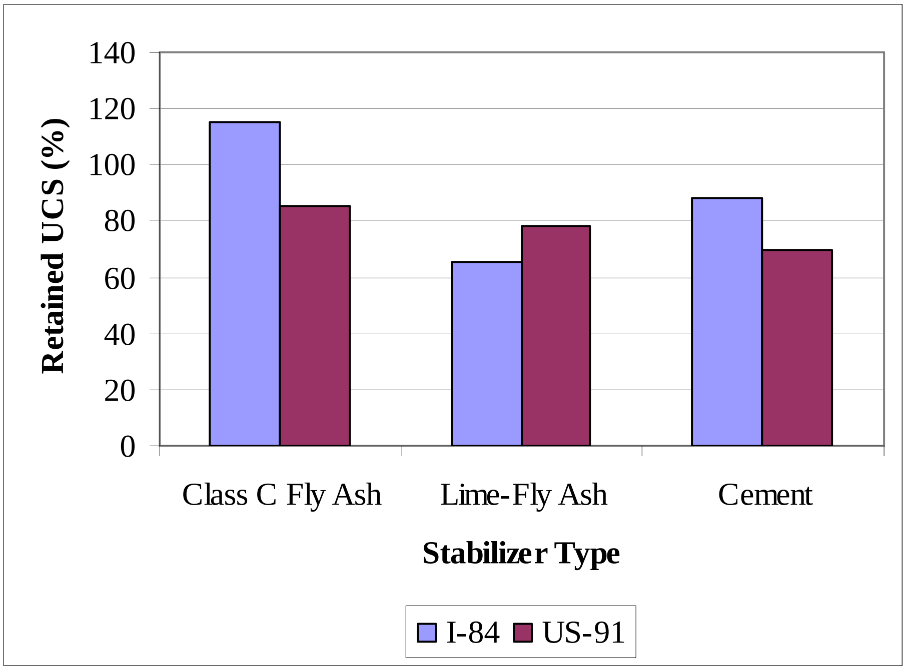

Figure 4.12 Interaction between aggregate type and stabilizer type for retained UCS after the freeze-thaw test.

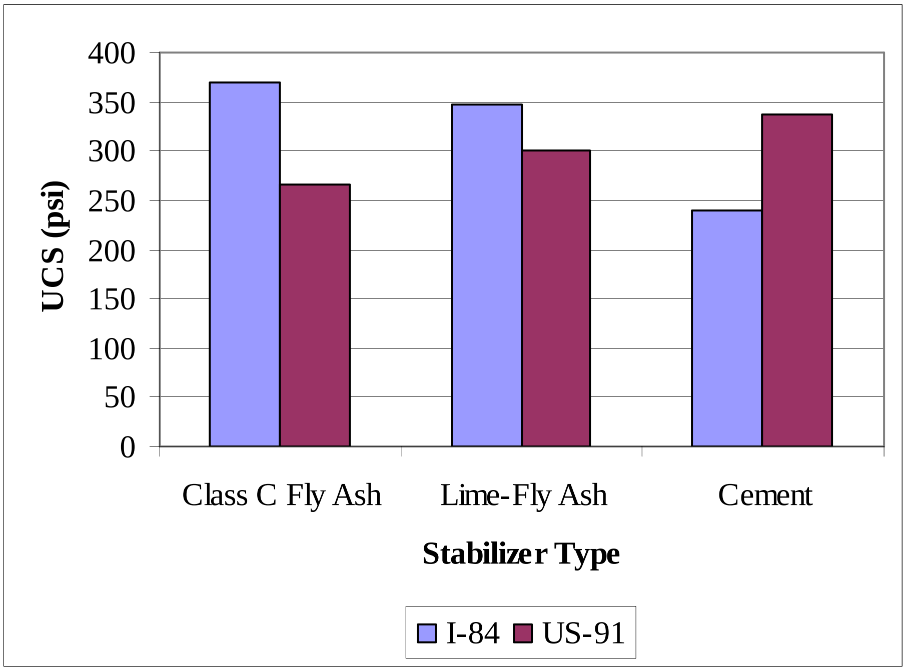

Figure 4.13 Interaction between aggregate type and stabilizer type for UCS after the vacuum saturation test.

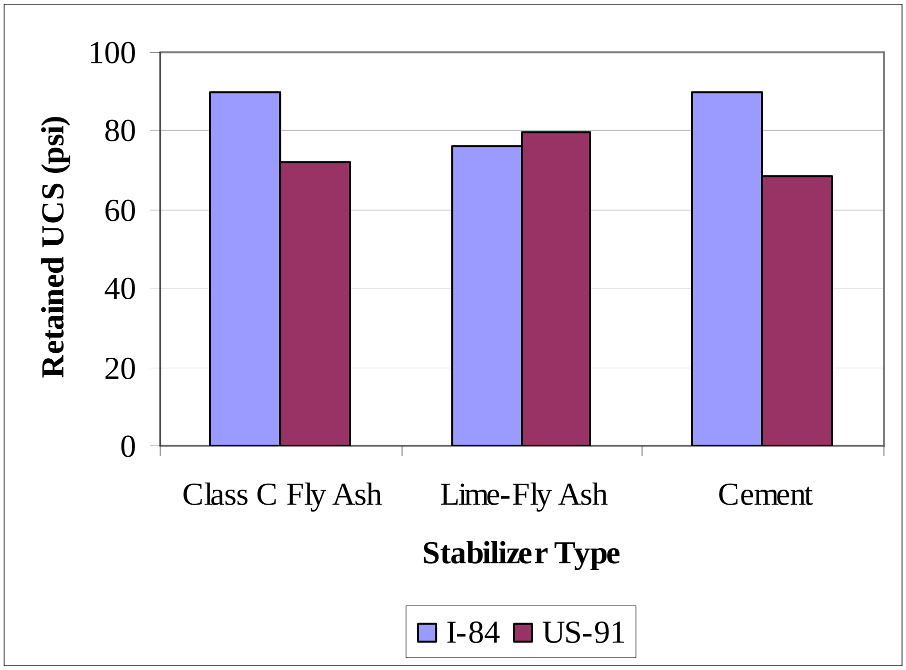

Figure 4.14 Interaction between aggregate type and stabilizer type for retained UCS after the vacuum saturation test.

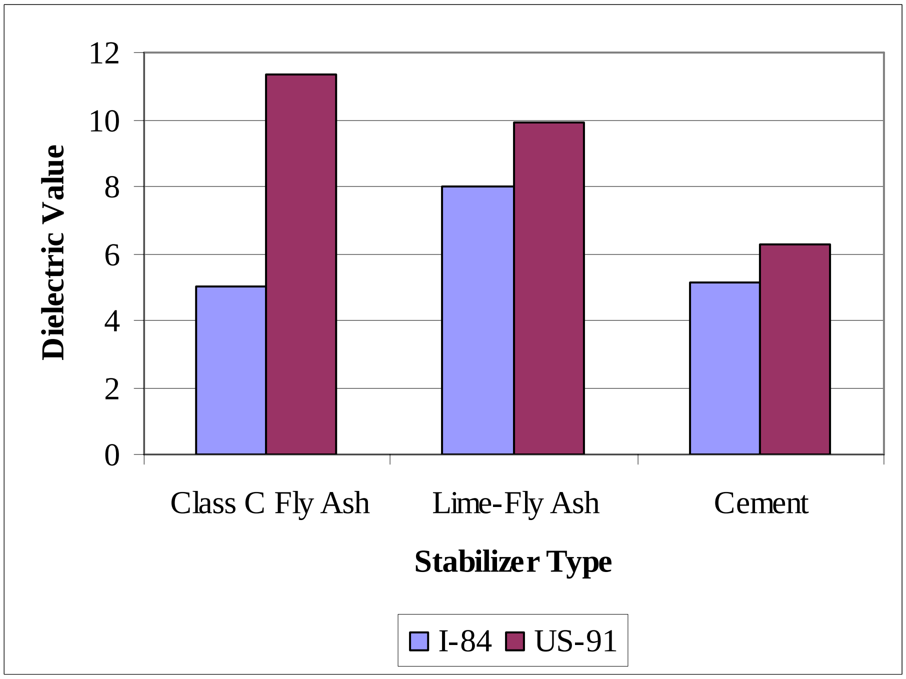

Figure 4.15 Interaction between aggregate type and stabilizer type for dielectric value after the tube suction test.

Table 4.14 Least Square Means for Interactions between Aggregate Type and Concentration Level

Aggregate Type	Concentration Level	Freeze-Thaw Test		Tube Suction Test
		UCS (psi)	Retained UCS (%)	Dielectric Value
I-84	Low	159	76	8.6
	Medium	345	88	4.6
	High	517	104	4.9
US-91	Low	109	42	9.1
	Medium	356	87	9.3
	High	556	103	9.2

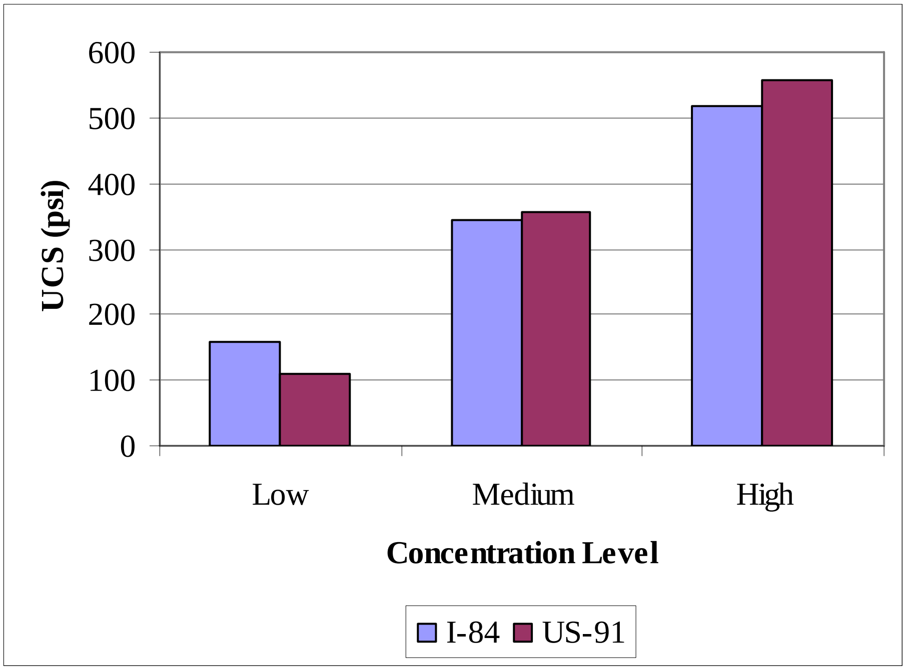

Figure 4.16 Interaction between aggregate type and concentration level for UCS after the freeze-thaw test.

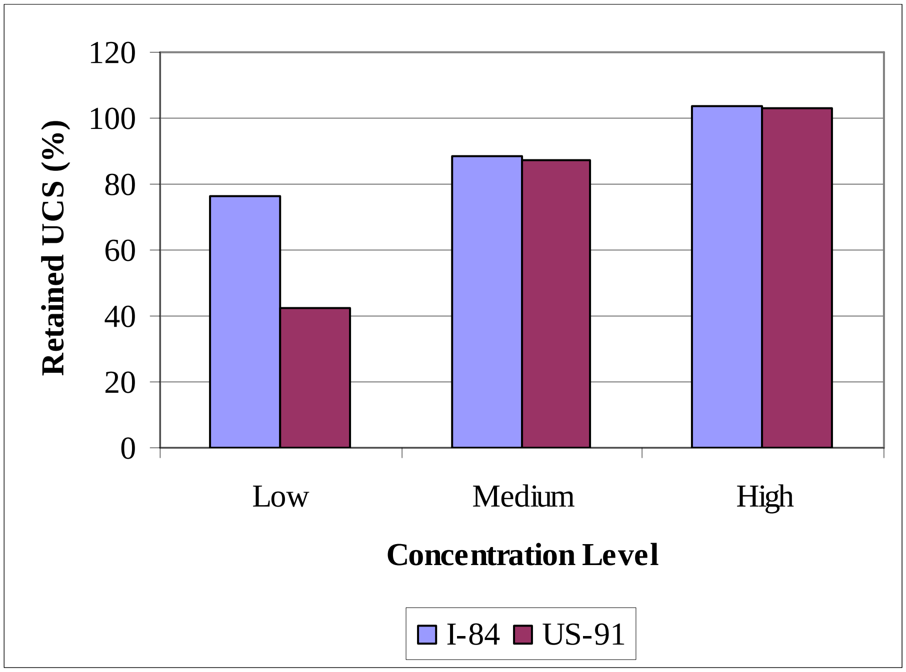

Figure 4.17 Interaction between aggregate type and concentration level for retained UCS after the freeze-thaw test.

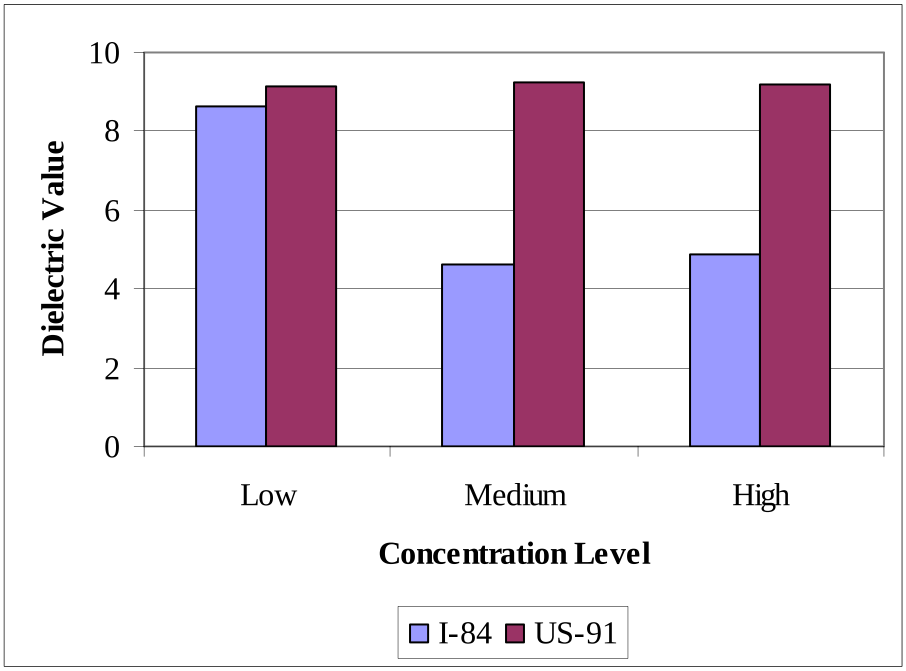

Figure 4.18 Interaction between aggregate type and concentration level for dielectric value after the tube suction test.

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

Stabilizer Type	Concentration Level	Freeze-Thaw Test		Vacuum Saturation Test	Tube Suction Test
		UCS (psi)	Retained UCS (%)	Retained UCS (%)	Dielectric Value
Class C Fly Ash	Low	107	43	62	7.5
	Medium	456	119	97	8.1
	High	707	138	85	9.0
Lime-Fly Ash	Low	143	61	74	11.7
	Medium	344	79	84	7.9
	High	421	74	77	7.3
Cement	Low	152	73	74	7.4
	Medium	252	65	81	4.8
	High	483	98	82	4.8

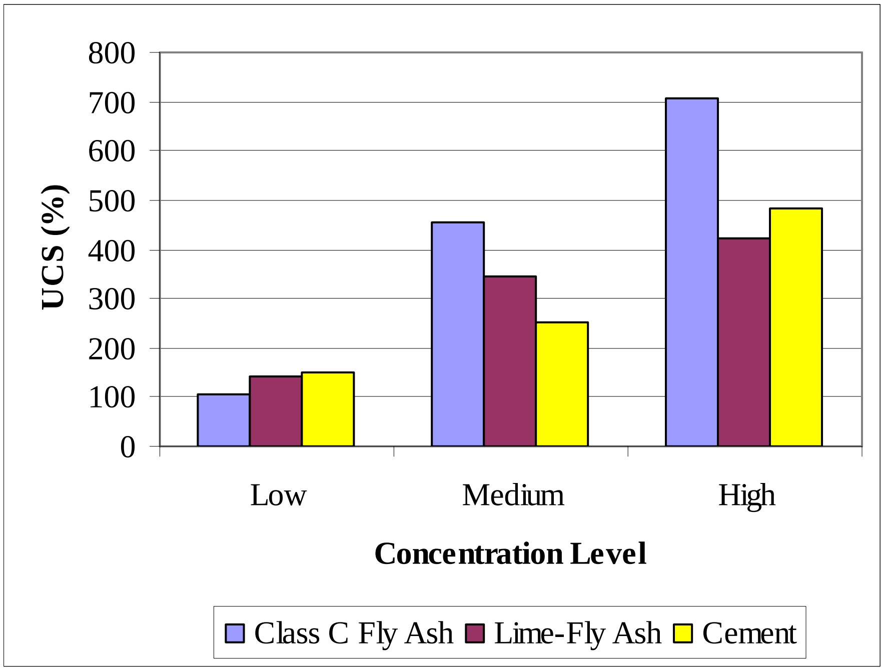

Figure 4.19 Interaction between stabilizer type and concentration level for UCS after the freeze-thaw test.

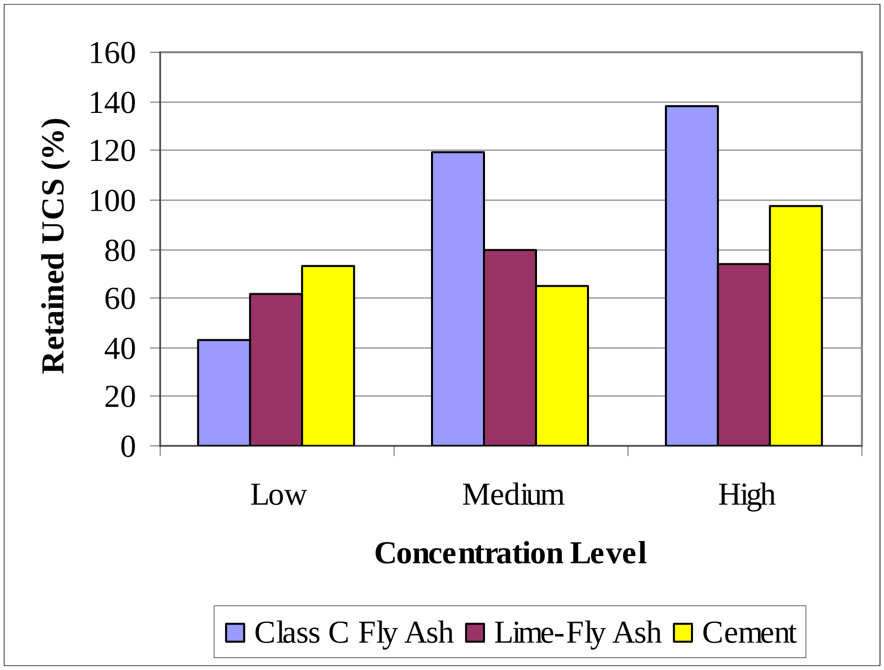

Figure 4.20 Interaction between stabilizer type and concentration level for retained UCS after the freeze-thaw test.

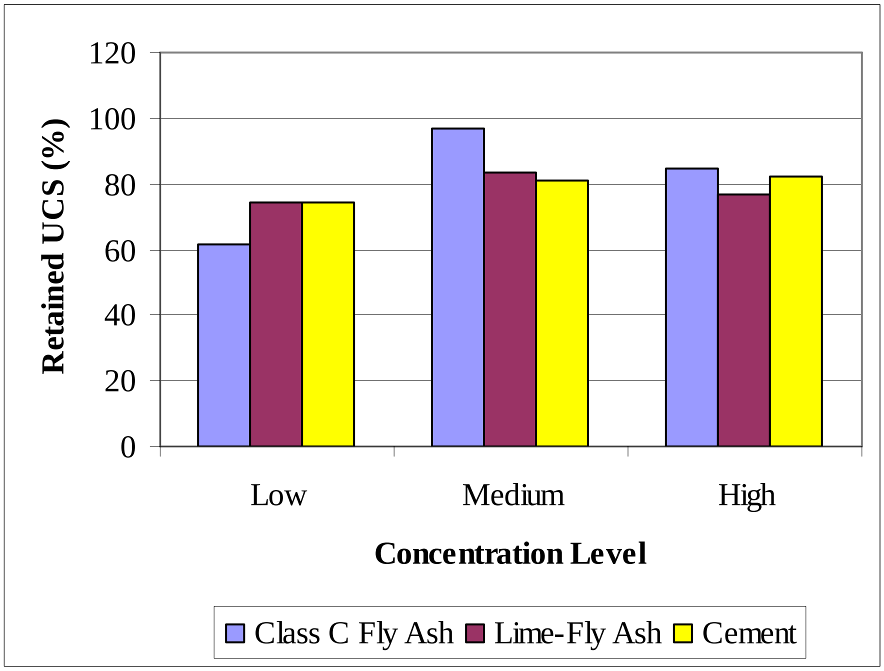

Figure 4.21 Interaction between stabilizer type and concentration level for retained UCS after the vacuum saturation test.

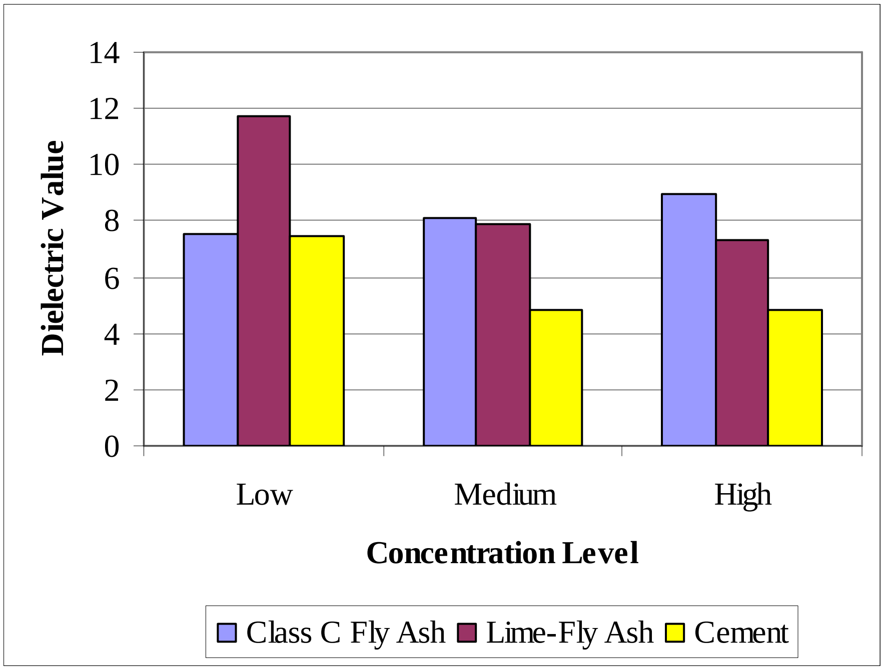

Figure 4.22 Interaction between stabilizer type and concentration level for dielectric value after the tube suction test.

4.7.3 Correlations

One of the objectives of this research project was to determine if correlations exist between the freeze-thaw, vacuum saturation, and tube suction tests. Figure 4.23 shows a plot of the UCS after freeze-thaw cycling versus the UCS after vacuum saturation. The coefficient of determination (R^2 value) associated with this correlation is comparatively high at 0.699. Figures 4.24 and 4.25 are plots of UCS after freeze-thaw cycling versus final dielectric value and UCS after vacuum saturation versus final dielectric value, respectively. In both plots, the data points appear to be randomly distributed; the corresponding R^2 values associated with these correlations are 0.015 and 0.137, respectively. Retained UCS after freeze-thaw cycling is compared with final dielectric value in the tube suction test in Figure 4.26, while retained UCS after vacuum saturation is compared with final dielectric value in the tube suction test in Figure 4.27. The corresponding R^2 values for these relationships are 0.053 and 0.103, suggesting very weak correlations.

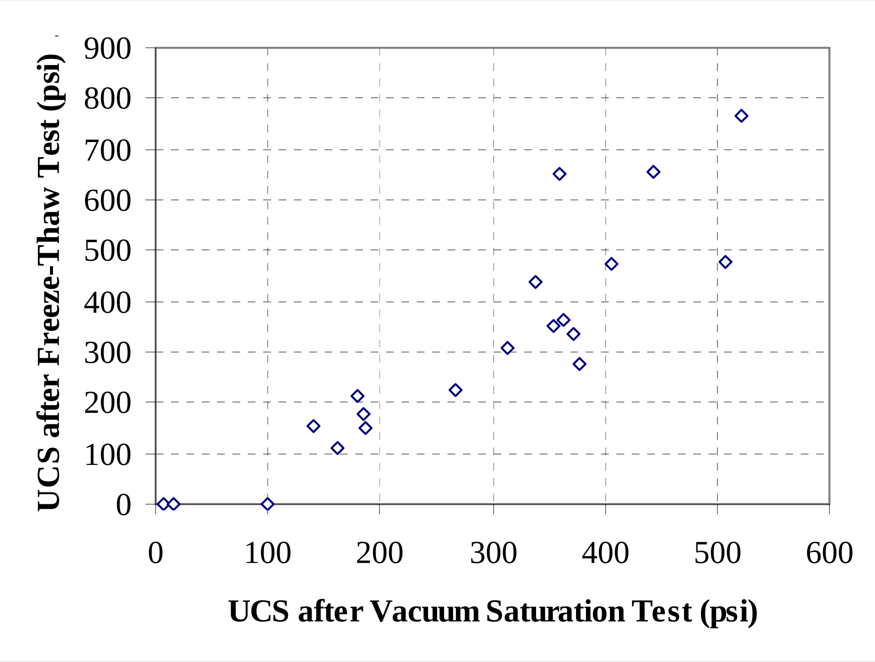

Figure 4.23 Correlation between UCS after the freeze-thaw test and UCS after the vacuum saturation test.

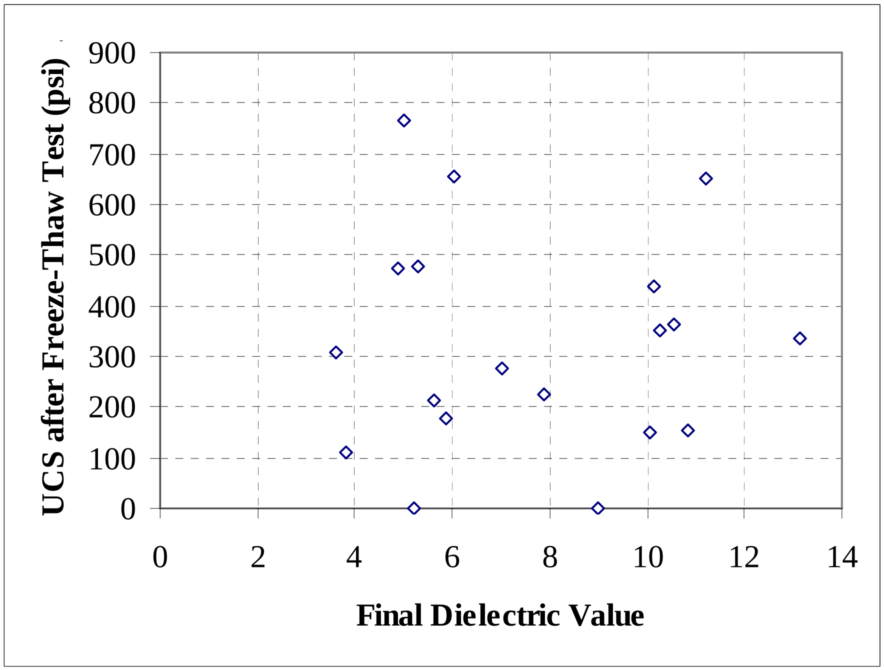

Figure 4.24 Correlation between UCS after the freeze-thaw test and final dielectric value in the tube suction test.

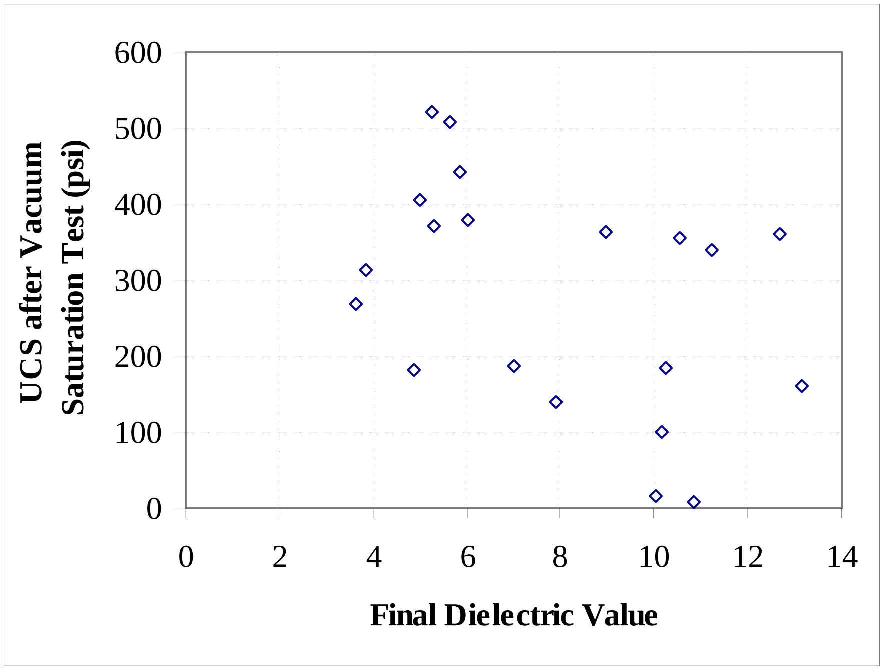

Figure 4.25 Correlation between UCS after the vacuum saturation test and final dielectric value in the tube suction test.

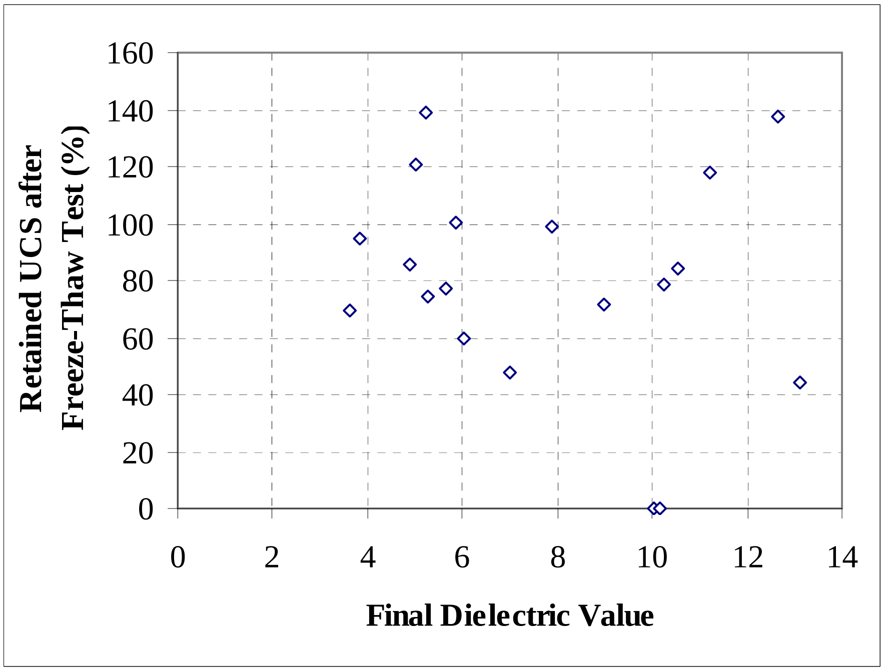

Figure 4.26 Correlation between retained UCS after the freeze-thaw test and final dielectric value in the tube suction test.

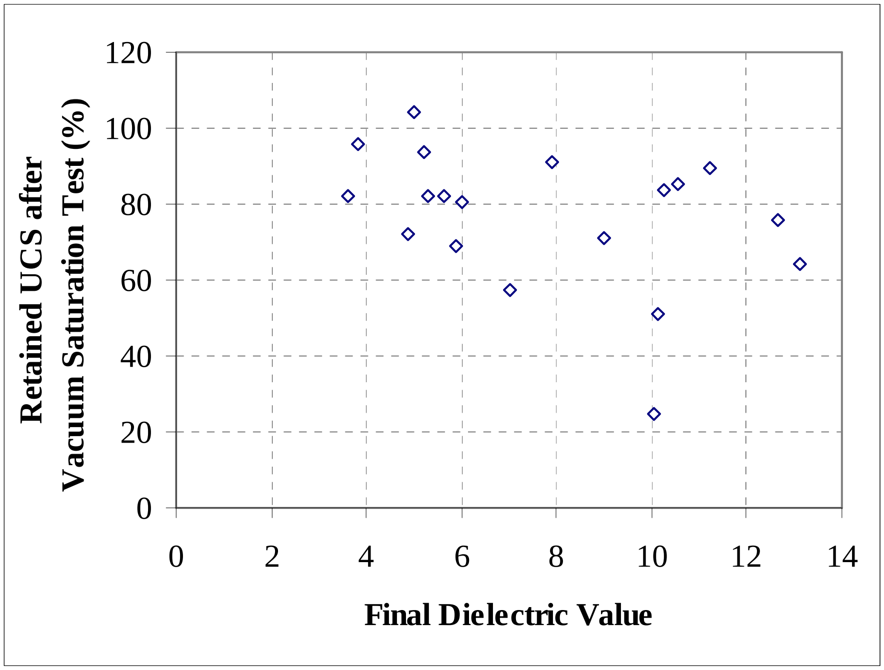

Figure 4.27 Correlation between retained UCS after the vacuum saturation test and final dielectric value in the tube suction test.

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 (*41*). 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 4.16. Hyphens in the table represent specimens that failed during testing. The average CVs for UCS after freeze-thaw cycling, UCS after vacuum saturation, and dielectric value after tube suction testing were 12.5, 16.8, and 12.9 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 0.462, insufficient evidence exists to claim that the differences in the computed CVs are statistically significant.

Table 4.16 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 (%)
I-84	Untreated	-	-	-	-	7	3.1	44.5	10.8	0.6	5.6
	Class C Fly Ash	Low	214	12.3	5.8	181	18.1	10.0	4.9	0.4	8.5
		Medium	472	46.6	9.9	405	43.3	10.7	5.0	0.1	2.9
		High	764	163.9	21.4	522	183.9	35.2	5.2	0.5	9.3
	Lime-Fly Ash	Low	110	14.3	13.0	161	4.9	3.0	13.1	0.8	5.7
		Medium	336	58.6	17.4	372	36.8	9.9	5.3	0.3	6.1
		High	478	26.2	5.5	507	50.3	9.9	5.6	0.6	11.1
	Cement	Low	152	3.5	2.3	140	10.4	7.4	7.9	1.7	21.7
		Medium	226	29.6	13.1	268	31.3	11.7	3.6	0.1	2.1
		High	309	25.4	8.2	313	25.8	8.2	3.8	0.3	6.8
US-91	Untreated	-	-	-	-	15	10.9	70.6	10.1	0.7	7.0
	Class C Fly Ash	Low	-	-	-	99	22.8	23.1	10.2	1.5	14.8
		Medium	440	47.8	10.9	339	24.5	7.2	11.2	2.0	17.6
		High	649	68.1	10.5	359	19.7	5.5	12.7	2.5	19.6
	Lime-Fly Ash	Low	176	63.7	36.2	184	30.1	16.3	10.3	1.6	15.6
		Medium	351	6.0	1.7	355	43.9	12.4	10.6	1.2	11.8
		High	364	67.0	18.4	363	37.5	10.3	9.0	1.4	16.1
	Cement	Low	151	18.9	12.5	187	26.8	14.3	7.0	0.7	10.6
		Medium	278	51.3	18.4	378	23.2	6.1	6.0	1.9	31.2
		High	656	43.7	6.7	443	82.7	18.7	5.9	2.0	33.4

4.8 SUMMARY

Results from freeze-thaw cycling and vacuum saturation testing indicate that nearly all specimens lost strength during testing. Medium and high concentrations of Class C fly ash tested in freeze-thaw cycling were exceptions to this trend; in these cases, the specimens gained appreciable strength during testing due to continuing pozzolanic reactivity. The magnitude of strength loss for all other specimens depended on aggregate type, stabilizer type, concentration level, and test type. Lime-fly ash at the low concentration level was the only stabilizer unable to satisfactorily reduce the moisture/frost susceptibility of the I-84 material in the tube suction test, while all concentrations of cement and high concentrations of lime-fly ash were the only stabilizers able to satisfactorily reduce the moisture/frost susceptibility of the US-91 material in the tube suction test.

The ANOVA showed that many main effects and interactions were significant in the results of freeze-thaw, vacuum saturation, and tube suction testing. 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

The Portland Cement Association commissioned a research project at BYU to compare selected laboratory durability tests available for assessing stabilized aggregate base 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 granular base materials, three stabilizers at three concentration levels each, and three durability tests in a full-factorial experimental design. The granular base materials consisted of an aggregate-RAP blend and a crushed limestone, while the three stabilizer types included Class C fly ash, lime-fly ash, and Type I/II Portland cement. Specimens were tested for durability using the freeze-thaw test, the vacuum saturation test, and the tube suction test.

5.2 FINDINGS

Analyses of the test results indicated that the UCS and retained UCS were higher for specimens tested in freeze-thaw cycling than the corresponding values associated with vacuum saturation testing. This observation suggests that the vacuum saturation test is more severe than the freeze-thaw test, especially for materials characterized by continuing pozzolanic reactivity. The analyses also indicated that the I-84 material retained more strength during freeze-thaw cycling and vacuum saturation and exhibited lower final dielectric values during tube suction testing than the US-91 material. Although the I-84 material performed better than the US-91 material, the I-84 material required higher stabilizer concentrations to reach the target 7-day UCS values specified in this research.

After freeze-thaw testing, the Class C fly-treated specimens were significantly stronger than both lime-fly ash- and cement-treated specimens, which were not significantly different from each other. In the vacuum saturation test, none of the three stabilizer types were significantly different from each other with respect to either UCS or retained UCS. Dielectric values measured during tube suction testing were lowest for cement-treated specimens, indicating that cement performed better than other stabilizers in reducing the moisture/frost susceptibility of the treated materials. Although the mean dielectric values associated with all three of the stabilizers corresponded to a satisfactory ranking, Tukey's mean separation procedure indicated that the differences in dielectric values between cement-treated specimens and both Class C fly ash- and lime-fly ash-treated specimens were significant; the dielectric values of Class C fly ash- and lime-fly ash-treated specimens were not significantly different, however. The results also show that, as the stabilizer concentration level increased from low to high, specimens performed better in nearly all cases.

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

Engineers interested in specifying a comparatively severe laboratory durability test should consider vacuum saturation testing for specimens treated with stabilizers similar to those evaluated in this research. The vacuum saturation test is superior to both the freeze-thaw and tube suction tests because of the shorter duration and lack of a need for daily specimen monitoring. Although the Class C fly ash used in this research performed well, further investigation of various sources of Class C fly ash is recommended because of the variability inherent in that material. Similar research should be performed on subgrade soils, which are also routinely stabilized in pavement construction. 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 I-84 OMC and MDD Values

Stabilizer Type	Stabilizer Concentration (%)	Moisture Content (%)	Dry Density (pcf)	OMC (%)	MDD (pcf)
Untreated	-	3.9	128.3	5.9	129.6
		4.7	129.2		
		5.7	129.6		
		6.4	129.5		
		7.3	128.5		
Class C Fly Ash	4	4.6	128.9	4.6	128.7
		5.6	129.6		
		6.4	128.0		
	12	4.8	130.2	5.2	131.2
		4.3	130.0		
		5.2	131.2		
		6.1	129.2		
	20	4.2	128.5	5.6	129.6
		4.8	128.5		
		6.2	126.6		
Lime-Fly Ash	6	3.9	118.1	5.4	121.1
		4.8	120.3		
		5.7	120.6		
		6.7	114.1		
	9	4.0	121.6	4.8	125.6
		4.8	125.6		
		5.7	121.8		
	15	7.2	123.4	4.6	141.5
		5.7	137.7		
		4.3	141.2		
		2.9	129.5		

Table A.2 US-91 OMC and MDD Values

Stabilizer Type	Stabilizer Concentration (%)	Moisture Content (%)	Dry Density (pcf)	OMC (%)	MDD (pcf)
Untreated	-	3.8	131.7	5.9	139.2
		4.4	134.9		
		5.1	137.0		
		5.6	138.5		
		6.5	139.2		
		7.1	136.8		
Class C Fly Ash	4	5.8	137.1	4.0	137.1
		6.7	136.1		
		7.5	134.3		
	6	4.8	133.4	5.9	136.8
		5.6	136.6		
		6.5	136.4		
		7.4	134.7		
	12	4.4	131.2	6.4	136.2
		6.3	136.1		
		7.0	132.9		
		7.3	133.0		
	20	5.1	134.0	6.0	134.4
		6.1	134.3		
		6.9	132.5		
Lime-Fly Ash	3	5.0	124.4	5.8	126.0
		6.0	125.7		
		6.8	118.0		
	6	5.0	125.0	5.5	128.0
		5.5	127.9		
		5.9	124.5		
	7	5.0	138.8	5.4	141.6
		5.4	141.6		
		6.0	138.5		
	15	4.5	133.3	5.5	135.5
		5.9	134.7		
		7.3	119.8		

Table A.3 I-84 7-Day UCS Values

Stabilizer Type	Stabilizer Concentration (%)	Specimen	UCS (psi)
Untreated	-	1	32
		2	35
Class C Fly Ash	4	1	111
		2	108
	12	1	356
		2	350
	20	1	502
		2	487
Lime-Fly Ash	6	1	462
		2	449
		3	447
	9	1	656
		2	581
		3	629
	15	1	810
		2	785
Cement	0.5	1	166
		2	169
		3	133
	1.0	1	321
		2	333
		3	320
		4	262
	1.5	1	306
		2	321
		3	286
		4	329
		5	327
		6	353
	2.0	1	372
	2.5	1	320

Table A.4 US-91 7-Day UCS Values

Stabilizer Type	Stabilizer Concentration (%)	Specimen	UCS (psi)
Untreated	-	1	67
		2	71
		3	58
Class C Fly Ash	4	1	162
	6	1	276
		2	231
	12	1	440
		2	364
	20	1	494
		2	380
Lime-Fly Ash	3	1	212
		2	236
		3	218
	6	1	493
		2	583
		3	579
	15	1	976
		2	1015
Cement	0.3	1	129
	0.5	1	276
		2	310
		3	403
	0.8	1	284
	1.0	1	404
		2	509
		3	520
	1.3	1	517
	1.5	1	650
		2	738
		3	577
	2.0	1	741
		2	704
		3	730

Table A.5 Additional I-84 Freeze-Thaw Test Results

Stabilizer Type	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	7	1	4.533	4.526	4.513	4.512	4.510	4.540	4.507	4.511	-	4.500	4.477	4.458	12.57
		2	4.512	4.510	4.492	4.498	4.493	4.501	4.481	4.476	-	4.445	4.418	4.392	12.57
		3	4.513	4.513	4.490	4.505	4.503	4.506	4.485	4.488	-	4.460	4.432	4.398	12.57
	15	1	4.508	4.518	4.514	4.520	4.522	4.519	4.531	4.533	-	4.548	4.525	4.519	12.57
		2	4.523	4.522	4.518	4.525	4.533	4.536	4.527	4.540	-	4.552	4.545	4.520	12.57
		3	4.515	4.518	4.513	4.523	4.517	4.533	4.520	4.527	-	4.538	4.510	4.517	12.57
	23	1	4.463	4.464	4.454	4.465	4.471	4.478	4.470	4.471	-	4.494	4.481	4.474	12.57
		2	4.465	4.469	4.462	4.474	4.475	4.488	4.475	4.475	-	4.498	4.483	4.473	12.57
		3	4.420	4.428	4.421	4.435	4.432	4.444	4.433	4.432	-	4.449	4.424	4.423	12.57
Lime-Fly Ash	3	1	4.544	4.548	4.548	4.542	4.505	4.503	4.477	4.426	4.380	4.354	4.345	4.304	12.57
		2	4.551	4.550	4.542	4.536	4.489	4.495	4.468	4.424	4.390	4.358	4.355	4.281	12.57
		3	4.553	4.548	4.540	4.534	4.487	4.503	4.468	4.428	4.396	4.364	4.338	4.278	12.57
	6	1	4.665	4.680	4.685	4.688	4.654	4.683	4.679	4.658	4.657	4.659	4.670	4.653	12.57
		2	4.653	4.680	4.683	4.689	4.671	4.687	4.688	4.673	4.666	4.664	4.690	4.671	12.57
		3	4.647	4.655	4.654	4.657	4.637	4.664	4.659	4.636	4.634	4.630	4.657	4.642	12.57
	9	1	4.592	4.605	4.607	4.610	4.601	4.611	4.615	4.604	4.610	4.613	4.633	4.623	12.57
		2	4.602	4.610	4.614	4.622	4.610	4.623	4.620	4.610	4.616	4.622	4.636	4.627	12.57
		3	4.608	4.613	4.623	4.629	4.617	4.628	4.627	4.615	4.630	4.631	4.644	4.629	12.57
Cement	0.5	1	4.413	4.370	4.387	4.386	4.400	4.398	4.396	4.378	4.388	4.374	4.371	4.370	12.57
		2	4.671	4.598	4.611	4.606	4.626	4.626	4.622	4.605	4.614	4.601	4.594	4.592	12.57
		3	4.637	4.613	4.620	4.615	4.638	4.637	4.644	4.628	4.632	4.629	4.628	4.628	12.57
	1.0	1	-	4.493	4.451	4.442	4.403	4.376	4.366	3.525	4.345	4.301	4.289	4.263	12.57
		2	-	4.505	4.448	4.460	4.430	4.413	4.394	3.905	4.376	4.351	4.331	4.301	12.57
		3	-	4.493	4.441	4.422	4.395	4.386	4.361	4.359	4.356	4.340	4.326	4.306	12.57
	1.5	1	-	4.524	4.491	4.497	4.490	4.477	4.466	4.475	4.468	4.459	4.447	4.443	12.57
		2	-	4.538	4.509	4.509	4.485	4.475	4.469	4.461	4.451	4.444	4.430	4.412	12.57
		3	-	4.544	4.495	4.520	4.502	4.467	4.469	4.467	4.463	4.449	4.442	4.425	12.57

Table A.6 Additional US-91 Freeze-Thaw Test Results

Stabilizer Type	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	4	1	4.718	4.684	4.559	4.394	4.124	3.657	2.996	2.165	1.679	1.217	0.796	0.505	-
		2	4.714	4.630	4.532	4.409	4.240	3.995	3.741	3.501	3.178	3.024	2.783	2.612	-
		3	4.695	4.625	4.489	4.322	4.109	3.840	3.502	3.186	2.966	2.721	2.375	2.200	-
	12	1	4.756	4.754	4.752	4.752	4.744	4.759	4.749	4.739	4.732	4.738	4.752	4.741	12.57
		2	4.740	4.734	4.734	4.732	4.718	4.738	4.730	4.725	4.715	4.721	4.729	4.721	12.57
		3	4.774	4.766	4.765	4.764	4.753	4.765	4.758	4.754	4.745	4.751	4.761	4.754	12.57
	20	1	4.803	4.801	4.802	4.804	4.796	4.806	4.800	4.791	4.290	4.794	4.806	4.803	12.57
		2	4.800	4.802	4.801	4.801	4.793	4.803	4.804	4.788	4.796	4.802	4.811	4.803	12.57
		3	4.816	4.815	4.814	4.813	4.807	4.810	4.813	4.789	4.798	4.807	4.811	4.806	12.57
Lime-Fly Ash	3	1	5.047	5.036	5.001	4.964	4.897	4.801	4.668	4.586	4.518	4.414	4.315	4.191	12.44
		2	5.045	5.035	5.028	5.011	4.857	4.792	4.652	4.560	4.468	4.412	4.300	4.193	12.57
		3	5.058	5.039	5.002	4.959	4.954	4.919	4.853	4.764	4.679	4.619	4.525	4.449	12.55
	5	1	-	4.432	4.416	4.381	4.374	4.358	4.334	4.302	4.295	4.265	4.234	4.208	12.57
		2	-	4.468	4.439	4.419	4.414	4.416	4.397	4.400	4.396	4.377	4.346	4.325	12.57
		3	-	4.482	4.447	4.436	4.414	4.391	4.363	4.356	4.321	4.284	4.235	4.206	12.57
	7	1	-	4.726	4.682	4.679	4.665	4.656	4.648	4.617	4.610	4.590	4.566	4.549	12.57
		2	-	4.721	4.686	4.686	4.667	4.640	4.621	4.603	4.586	4.576	4.561	4.551	12.57
		3	-	4.689	4.652	4.551	4.519	4.498	4.488	4.477	4.448	4.417	4.391	4.368	12.57
Cement	0.5	1	-	4.761	4.685	4.560	4.485	4.386	4.222	4.116	3.923	3.681	3.485	3.312	12.52
		2	-	4.699	4.540	4.407	4.314	4.227	4.106	4.002	3.755	3.511	3.348	3.152	11.30
		3	-	4.551	4.358	4.182	4.045	3.876	3.668	3.503	3.272	3.050	2.843	2.632	12.20
	1.0	1	-	4.805	4.779	4.745	4.719	4.697	4.675	4.662	4.653	4.625	4.596	4.572	12.57
		2	-	4.716	4.635	4.590	4.579	4.542	4.515	4.915	4.496	4.448	4.413	4.370	12.57
		3	-	4.803	4.752	4.733	4.706	4.677	4.651	4.662	4.651	4.606	4.585	4.554	12.57
	1.5	1	-	4.896	4.845	4.849	4.836	4.832	4.819	4.830	4.835	4.826	4.821	4.800	12.57
		2	-	4.879	4.839	4.849	4.817	4.829	4.808	4.813	4.820	4.812	4.809	4.792	12.57
		3	-	4.864	4.834	4.840	4.813	4.800	4.790	4.809	4.811	4.797	4.792	4.771	12.57

Table A.7 Additional I-84 Tube Suction Test Results

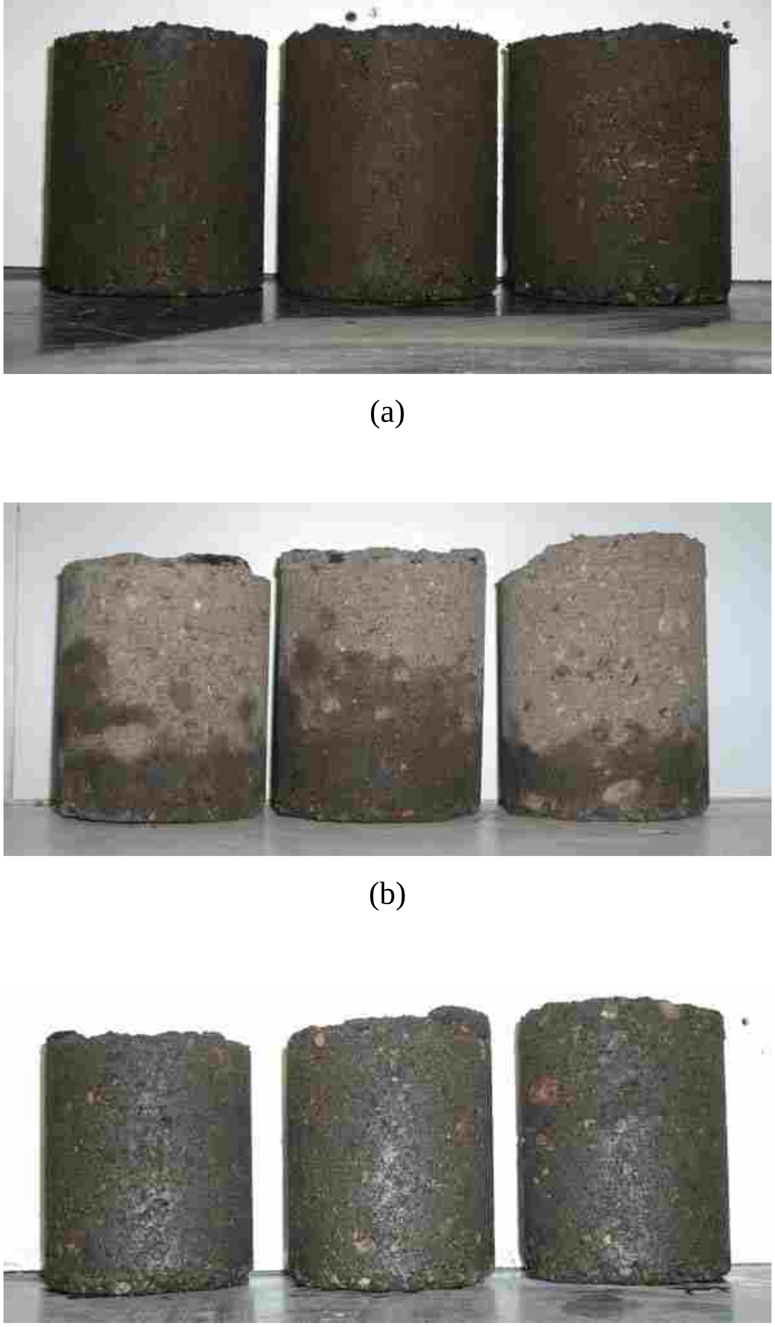
Stabilizer Type	Stabilizer Concentration (%)	Specimen	Dielectric Value per Day										
			0	1	2	3	4	5	6	7	8	9	10
Untreated	-	1	2.8	6.1	5.0	5.7	8.1	6.2	5.9	9.7	4.2	7.9	10.3
		2	2.8	6.0	5.0	6.8	9.7	7.3	7.1	11.7	4.9	8.8	11.5
		3	2.9	6.2	6.5	8.2	10.2	7.8	8.4	10.7	5.7	9.5	10.7
Class C Fly Ash	7	1	3.0	4.0	4.2	4.9	3.7	4.3	4.4	4.1	-	4.3	4.4
		2	3.5	4.6	4.7	4.9	3.7	4.7	4.8	4.6	-	4.9	5.1
		3	3.5	4.6	5.0	5.9	5.0	4.8	4.9	4.8	-	5.2	5.2
	15	1	3.7	4.7	5.0	4.0	4.2	4.9	4.9	4.9	-	4.8	5.0
		2	3.6	4.5	4.6	3.4	3.8	4.7	5.1	4.6	-	4.8	4.9
		3	3.9	4.9	5.0	3.9	3.7	5.1	5.1	4.9	-	5.2	5.2
	23	1	4.0	4.7	5.0	5.4	5.5	4.9	4.8	4.7	-	5.0	4.8
		2	4.1	4.8	5.0	5.4	5.5	5.0	5.1	5.0	-	5.2	5.2
		3	4.6	5.2	5.5	6.1	6.0	5.6	5.7	5.6	-	5.7	5.7
Lime-Fly Ash	3	1	1.3	4.4	5.0	5.5	7.8	11.6	12.3	12.1	12.4	11.9	12.6
		2	1.1	4.5	4.8	5.7	9.7	13.7	14.5	13.5	14.3	13.8	14.0
		3	1.0	4.7	5.1	7.8	11.4	12.1	12.3	12.3	12.5	12.2	12.8
	6	1	1.2	4.1	4.5	4.8	4.9	5.0	5.0	5.2	5.7	5.1	5.2
		2	1.0	4.2	4.5	4.7	4.8	4.8	5.0	5.7	5.7	4.9	5.1
		3	1.0	4.9	5.0	5.2	5.3	5.5	5.6	5.9	5.9	5.8	5.7
	9	1	1.0	4.1	4.3	4.5	4.6	4.7	4.9	4.9	5.0	5.1	5.0
		2	1.0	4.8	5.0	5.2	5.4	5.6	5.9	6.9	6.6	6.1	6.3
		3	1.0	4.6	4.9	5.0	5.1	5.3	5.5	5.7	5.5	5.3	5.7
Cement	0.5	1	2.7	5.9	3.3	3.9	5.8	3.0	5.6	8.5	6.6	9.3	9.9
		2	2.4	5.5	3.1	4.2	6.4	2.6	4.7	8.2	5.0	7.3	7.2
		3	2.4	5.4	2.7	3.0	5.3	2.2	4.4	6.6	4.7	6.1	6.7
	1.0	1	2.6	5.8	3.5	3.5	2.0	2.0	2.9	5.8	-	3.8	3.7
		2	2.4	5.7	3.5	2.8	2.1	2.0	3.4	6.6	-	3.8	3.7
		3	2.4	5.8	3.4	3.7	2.1	2.2	2.8	6.4	-	3.6	3.6
	1.5	1	2.4	6.3	2.9	3.5	1.3	2.2	3.2	6.5	3.1	3.4	3.5
		2	2.9	6.6	3.1	3.7	1.6	2.4	3.2	6.6	3.6	3.9	4.0
		3	2.9	6.5	3.5	3.9	2.3	2.6	3.1	7.1	3.9	4.1	4.0

Table A.8 Additional US-91 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	3.3	8.6	6.9	7.4	8.7	6.4	7.1	9.0	4.9	8.5	10.1
		2	3.7	9.0	7.5	7.4	10.0	5.8	7.1	9.9	4.8	8.7	10.8
		3	3.0	8.1	6.6	6.2	8.8	5.6	6.6	9.5	3.5	6.7	9.4
Class C Fly Ash	7	1	1.9	10.7	11.5	11.6	8.5	11.8	11.9	12.1	12.1	11.4	11.4
		2	1.2	9.6	10.5	10.1	9.6	10.7	10.4	10.3	10.4	9.9	10.5
		3	1.0	8.1	8.1	9.1	10.0	8.7	8.6	8.8	9.5	8.1	8.5
	15	1	1.5	6.9	7.8	8.4	11.3	8.1	8.6	9.2	9.2	8.7	9.0
		2	1.0	7.3	8.2	9.7	9.8	10.6	11.9	11.8	11.8	12.0	12.7
		3	1.5	8.0	9.1	9.9	8.2	11.2	11.5	11.9	11.9	12.2	12.0
	23	1	1.5	10.8	10.7	9.3	10.0	10.2	10.1	10.1	10.0	9.9	9.9
		2	1.9	10.2	13.8	13.6	13.2	13.0	13.8	13.2	13.3	13.2	13.6
		3	1.8	14.4	14.4	14.4	14.4	14.7	14.5	14.6	14.5	14.3	14.6
Lime-Fly Ash	3	1	4.2	7.9	11.2	10.6	11.0	11.0	10.8	11.4	11.0	10.8	11.6
		2	4.0	6.1	8.2	8.2	7.9	7.8	8.6	8.5	7.6	8.7	8.5
		3	4.3	6.2	9.4	9.6	10.1	9.3	9.7	10.1	10.1	10.1	10.7
	6	1	3.9	5.0	5.8	7.3	8.2	8.0	8.8	9.2	8.6	9.1	9.2
		2	4.0	5.0	7.8	8.0	9.1	8.8	10.2	11.0	10.2	10.8	10.8
		3	4.0	7.1	11.4	11.6	11.6	11.4	11.3	11.5	11.1	11.9	11.7
	9	1	3.2	5.2	7.1	7.8	8.3	8.6	9.6	10.2	9.5	10.5	10.2
		2	3.3	4.1	4.7	5.0	5.6	6.0	6.6	8.0	6.8	7.2	7.4
		3	3.5	5.2	8.1	9.0	9.4	9.1	9.6	9.8	8.9	9.1	9.3
Cement	0.5	1	2.9	6.0	3.9	5.3	7.4	3.9	5.4	5.7	5.9	7.8	7.1
		2	2.7	5.7	3.9	4.6	5.9	3.5	4.8	3.1	4.9	6.6	6.2
		3	2.5	6.0	4.3	5.3	7.3	3.4	5.1	7.7	5.2	7.7	7.7
	1.0	1	3.1	6.3	3.8	4.0	2.5	2.6	4.3	6.6	3.9	5.0	4.8
		2	3.2	6.3	4.2	5.1	3.8	3.8	5.6	9.4	6.0	8.5	8.2
		3	2.8	5.8	3.8	3.7	2.5	2.4	3.8	7.6	4.3	5.1	5.1
	1.5	1	3.3	6.2	3.9	4.2	3.1	3.2	4.5	7.3	4.4	5.5	4.9
		2	3.2	6.7	4.8	5.2	4.9	5.0	6.1	10.4	6.7	9.6	8.1
		3	3.2	6.8	3.7	3.9	2.3	2.4	3.8	6.8	4.3	4.6	4.6

APPENDIX B:

PICTORAL RESULTS OF FREEZE-THAW CYCLING

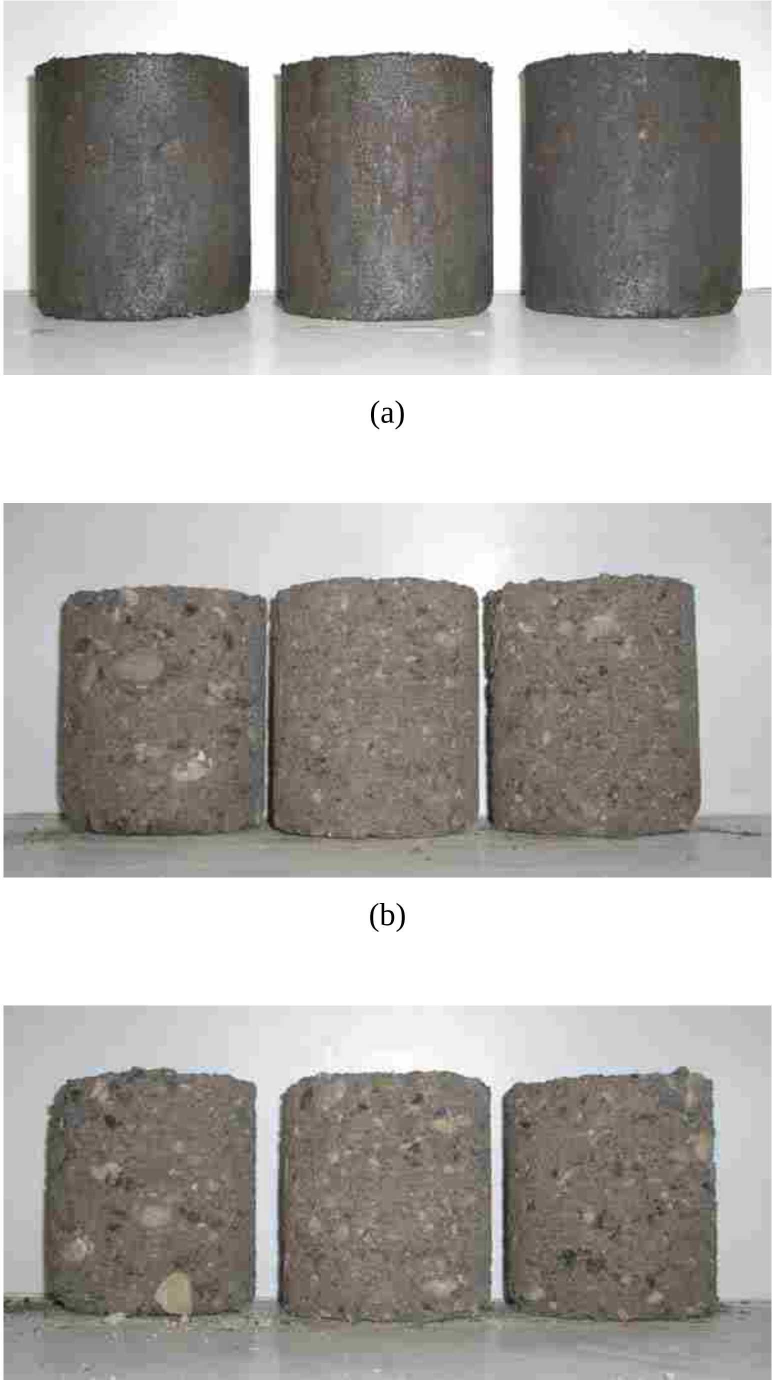


(a)

(b)

(c)

Figure B.1 I-84 specimens treated with 0.5 percent cement after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

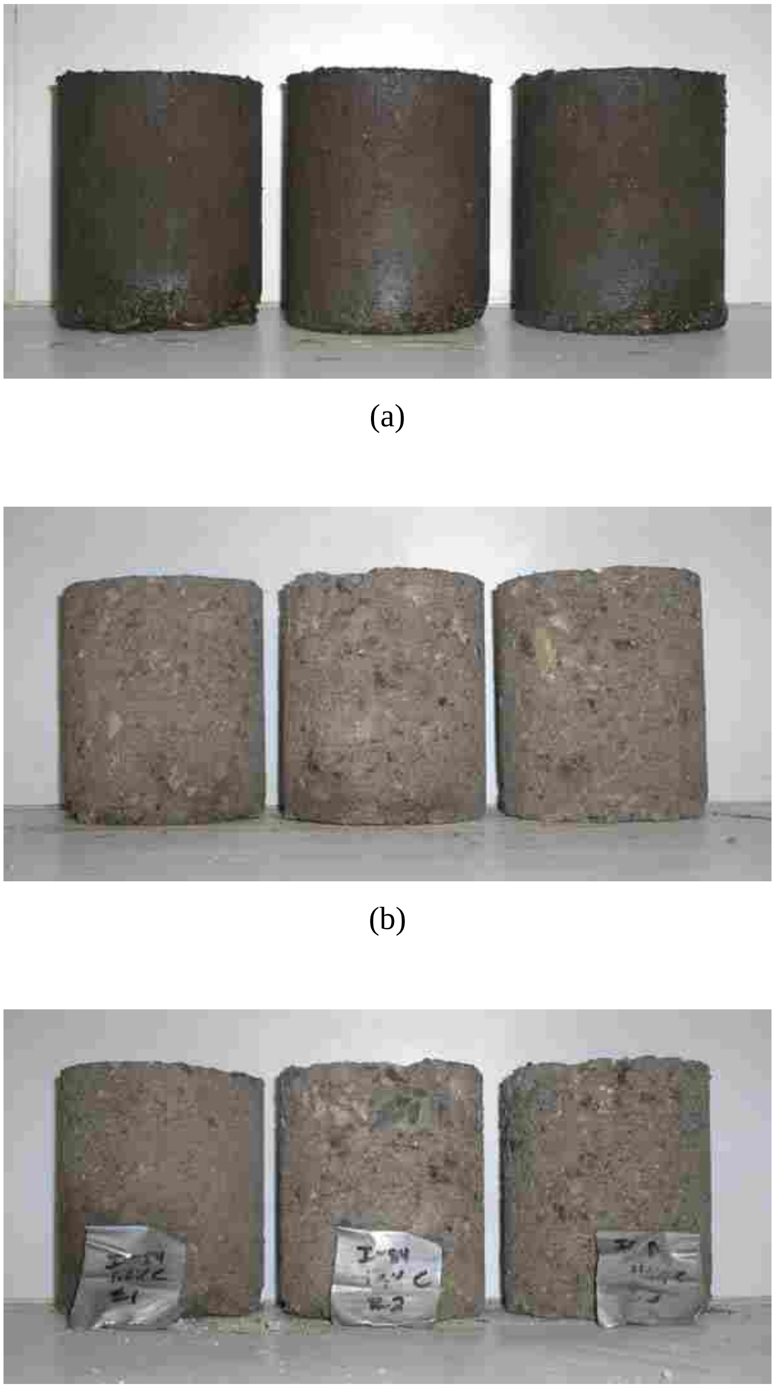


(a)

(b)

(c)

Figure B.2 I-84 specimens treated with 1.0 percent cement after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

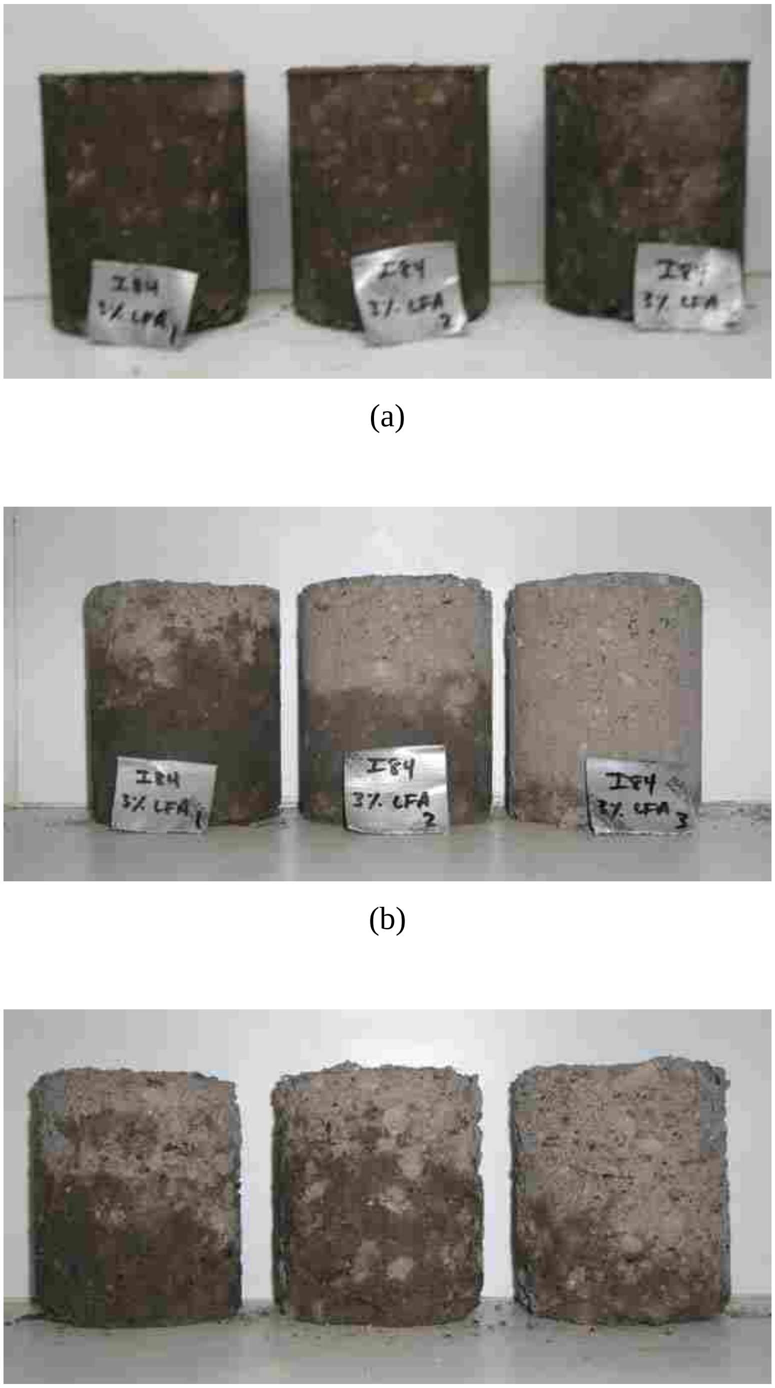


(a)

(b)

(c)

Figure B.3 I-84 specimens treated with 1.5 percent cement after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

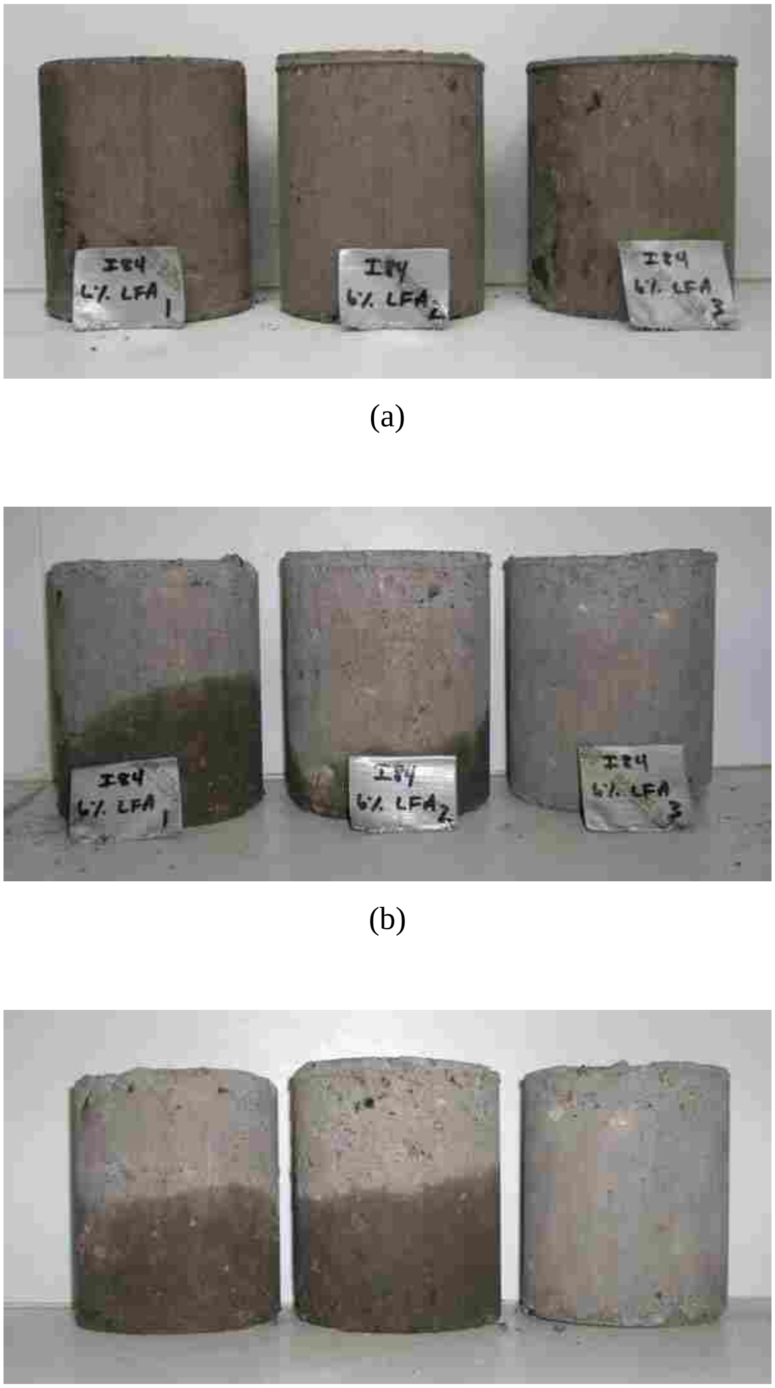


(a)

(b)

(c)

Figure B.4 I-84 specimens treated with 3 percent lime-fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

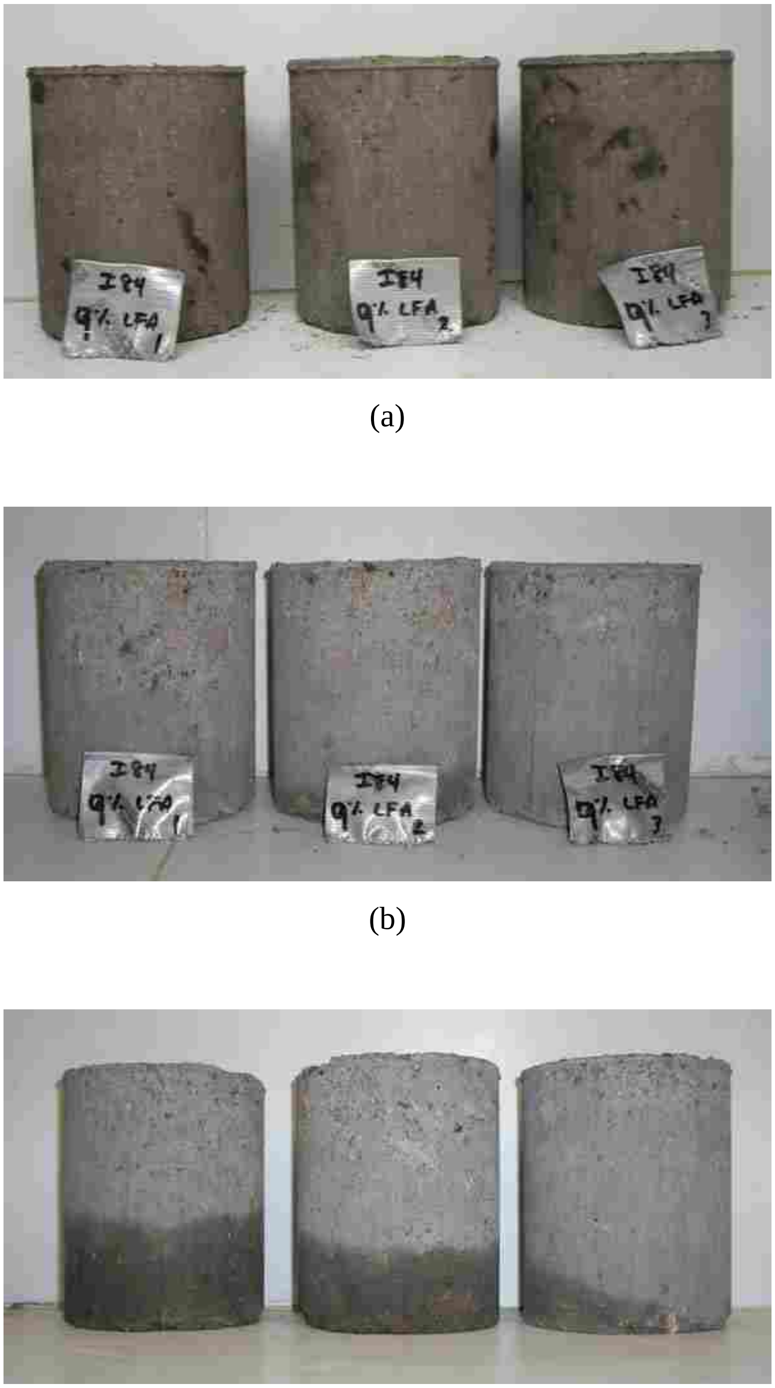


(a)

(b)

(c)

Figure B.5 I-84 specimens treated with 6 percent lime-fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

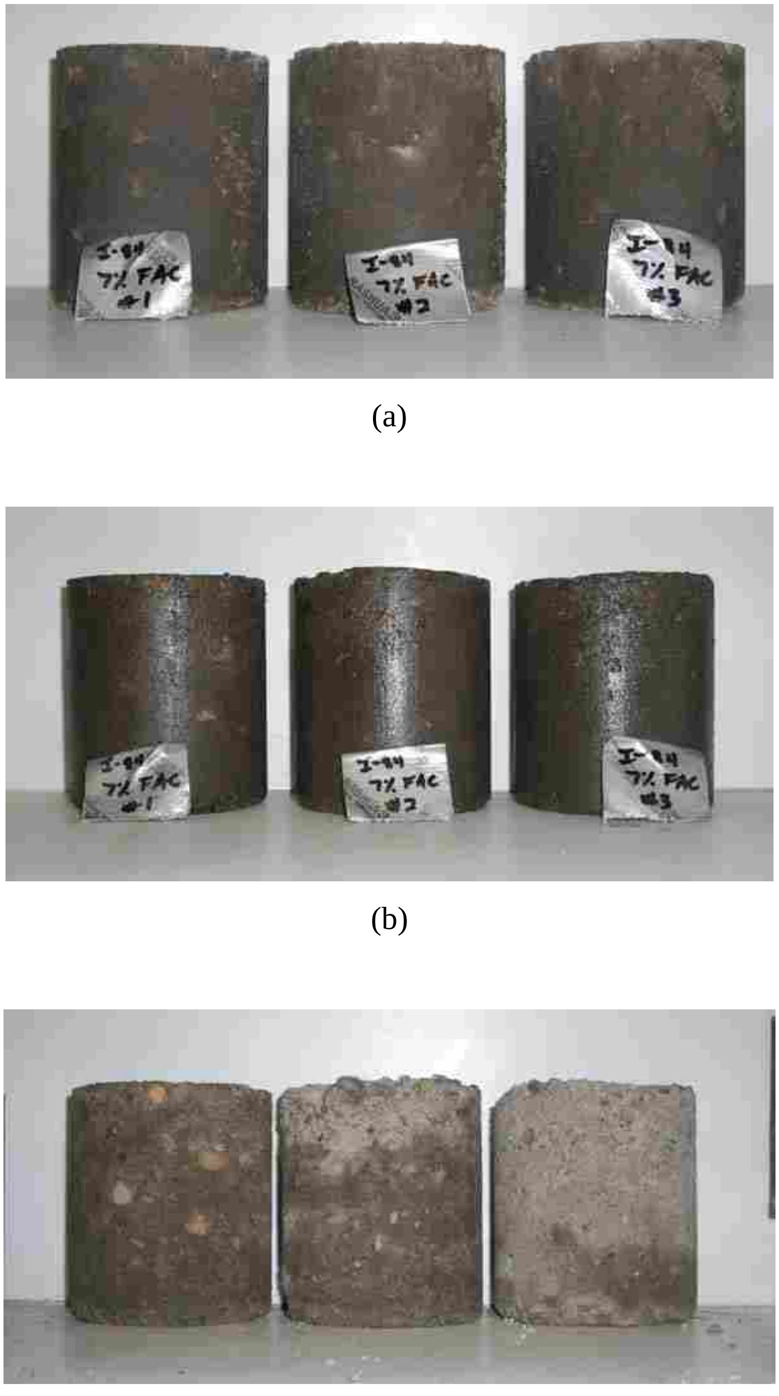


(a)

(b)

(c)

Figure B.6 I-84 specimens treated with 9 percent lime-fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

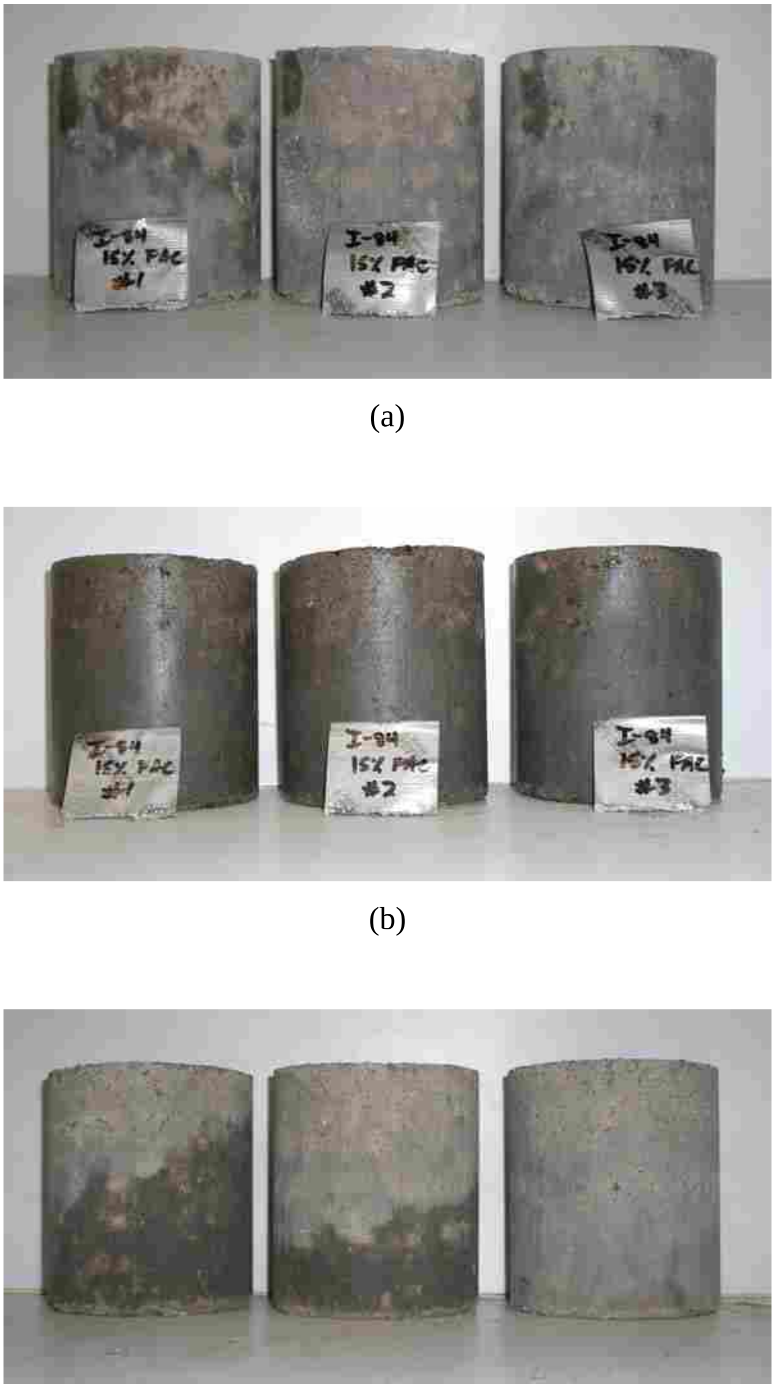


(a)

(b)

(c)

Figure B.7 I-84 specimens treated with 7 percent class C fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

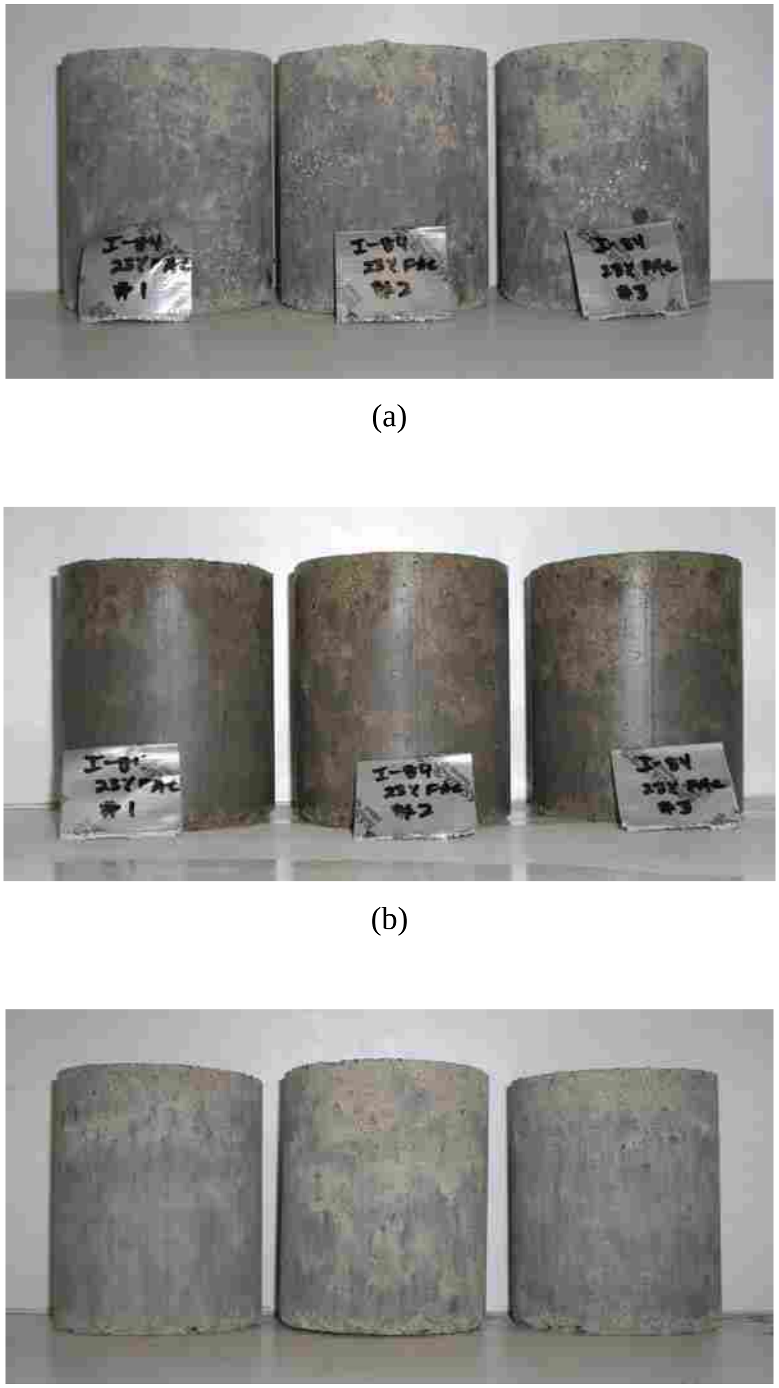


(a)

(b)

(c)

Figure B.8 I-84 specimens treated with 15 percent class C fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

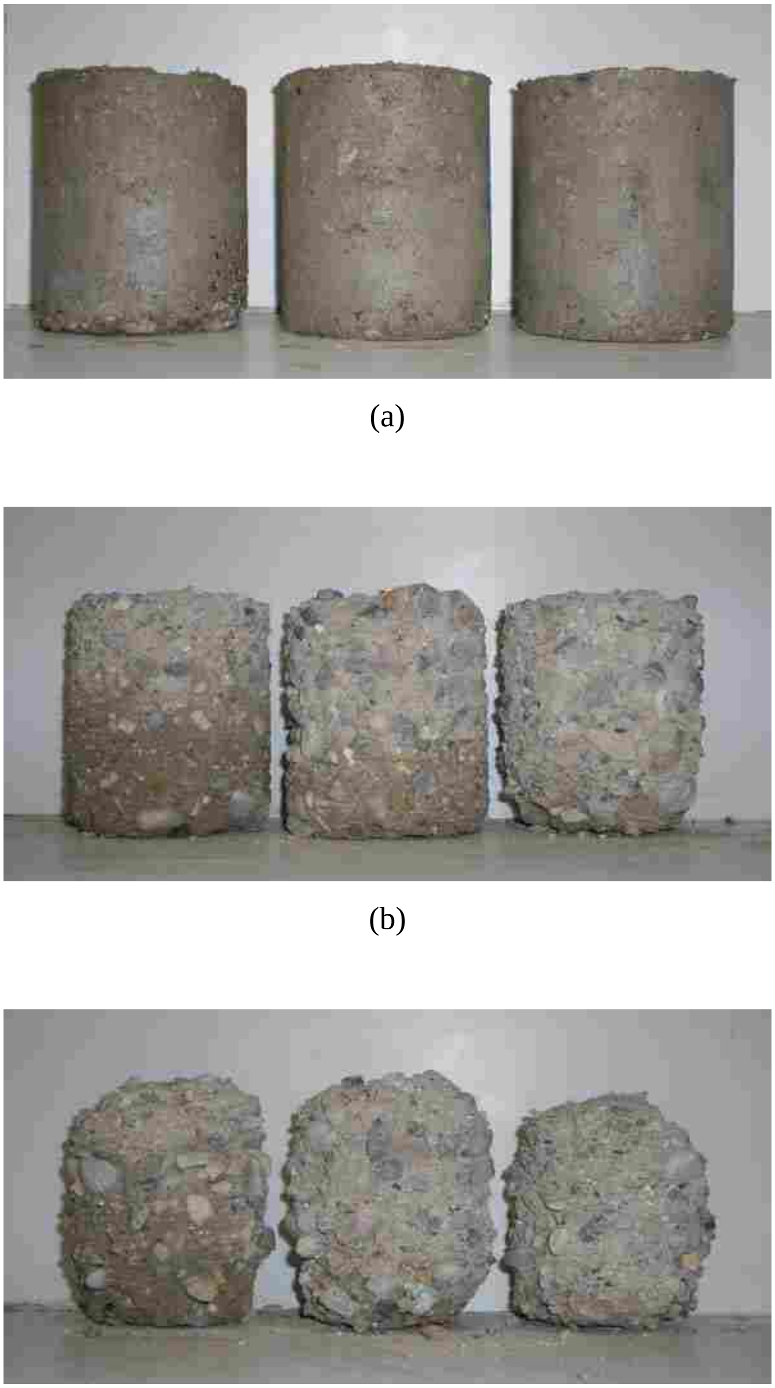


(a)

(b)

(c)

Figure B.9 I-84 specimens treated with 23 percent class C fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

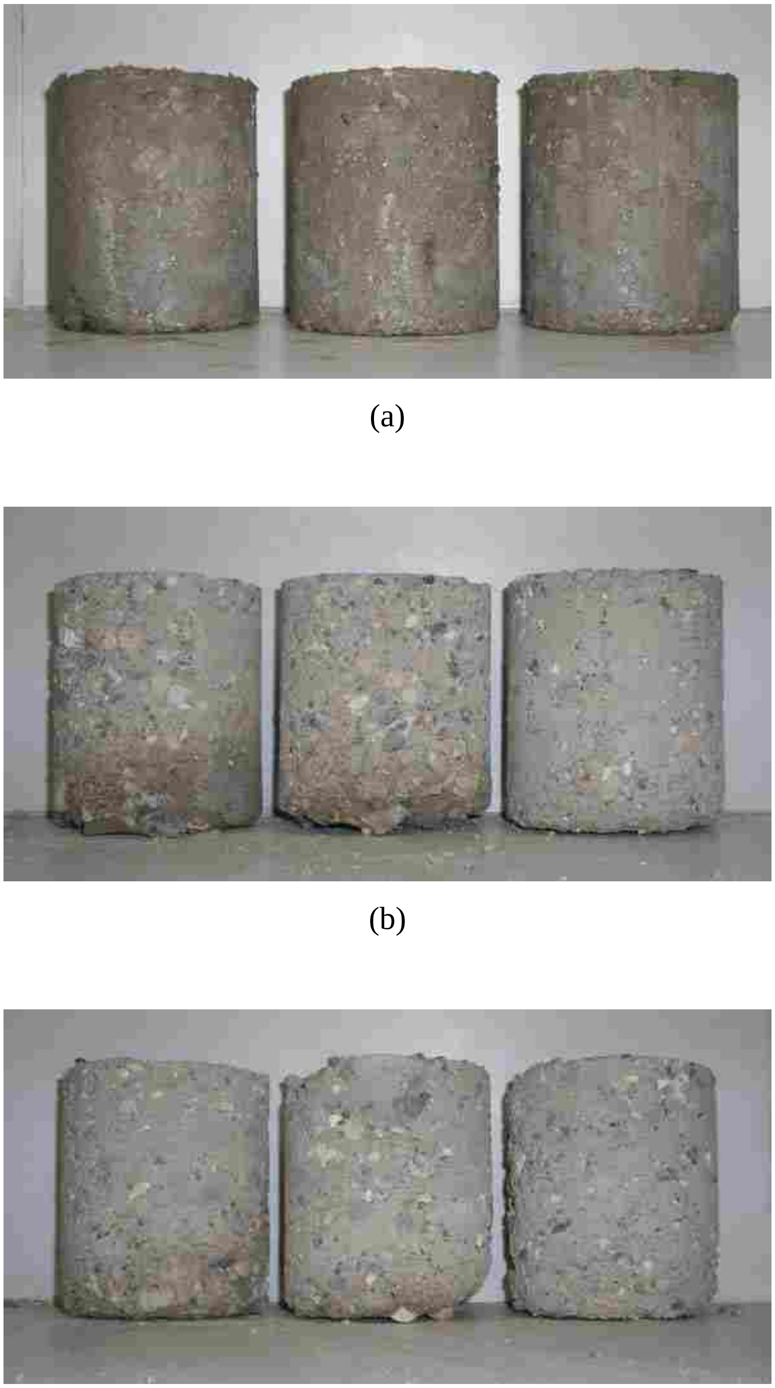


(a)

(b)

(c)

Figure B.10 US-91 specimens treated with 0.5 percent cement after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

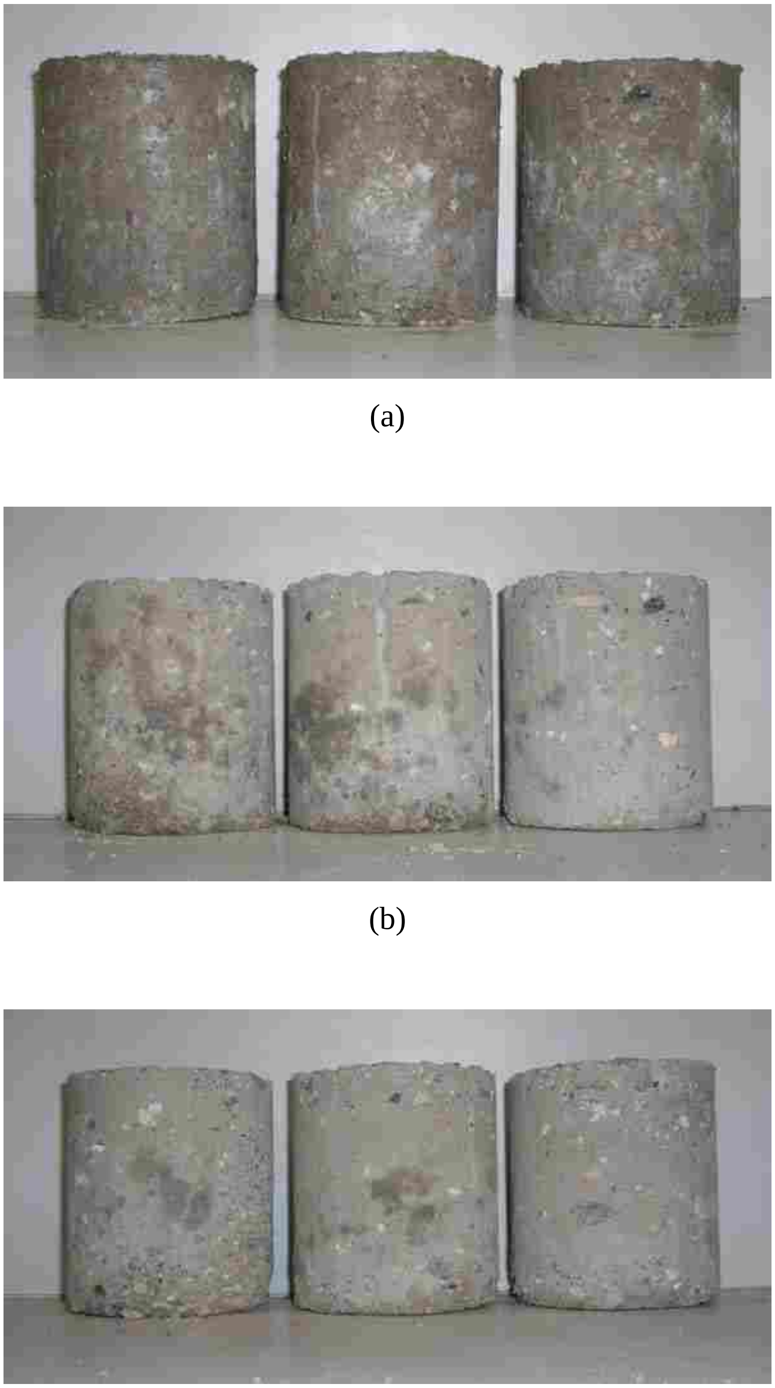


(a)

(b)

(c)

Figure B.11 US-91 specimens treated with 1.0 percent cement after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

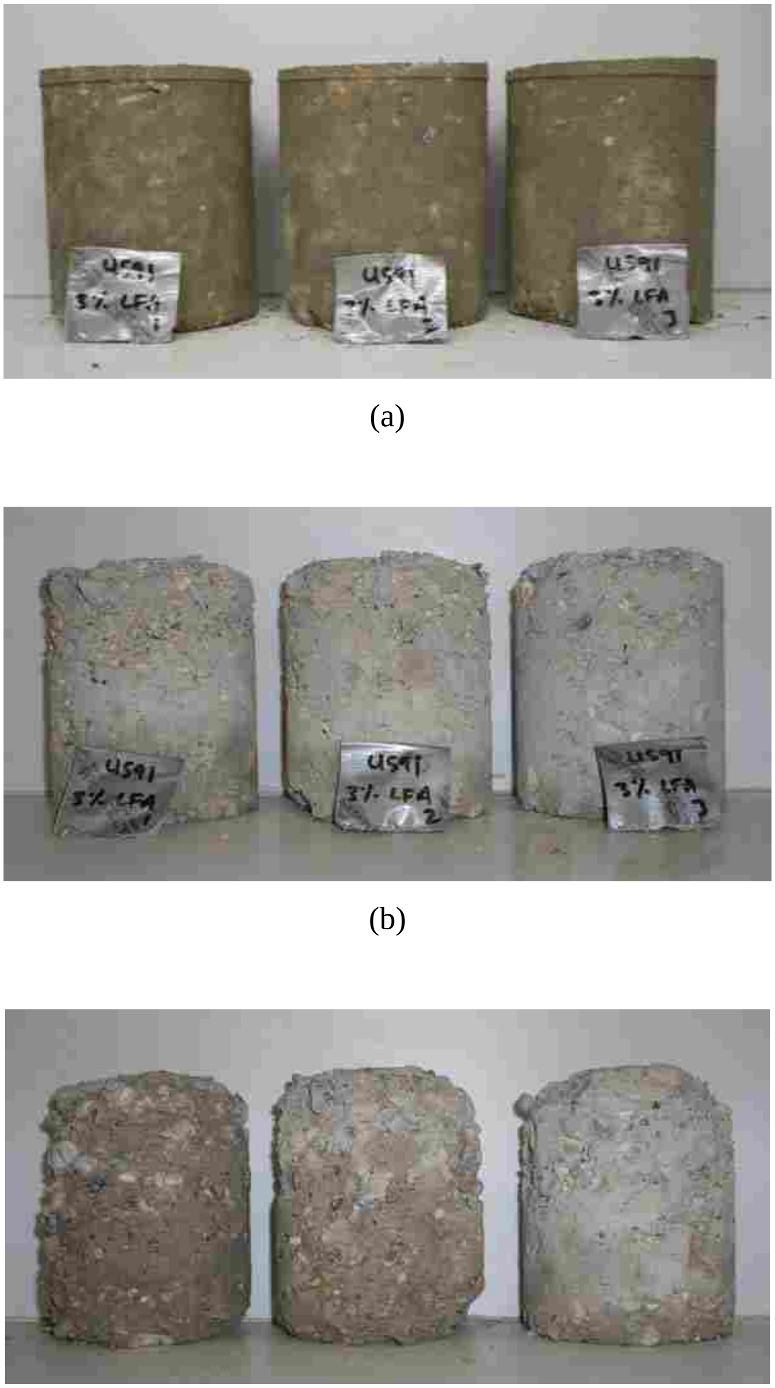


(a)

(b)

(c)

Figure B.12 US-91 specimens treated with 1.5 percent cement after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

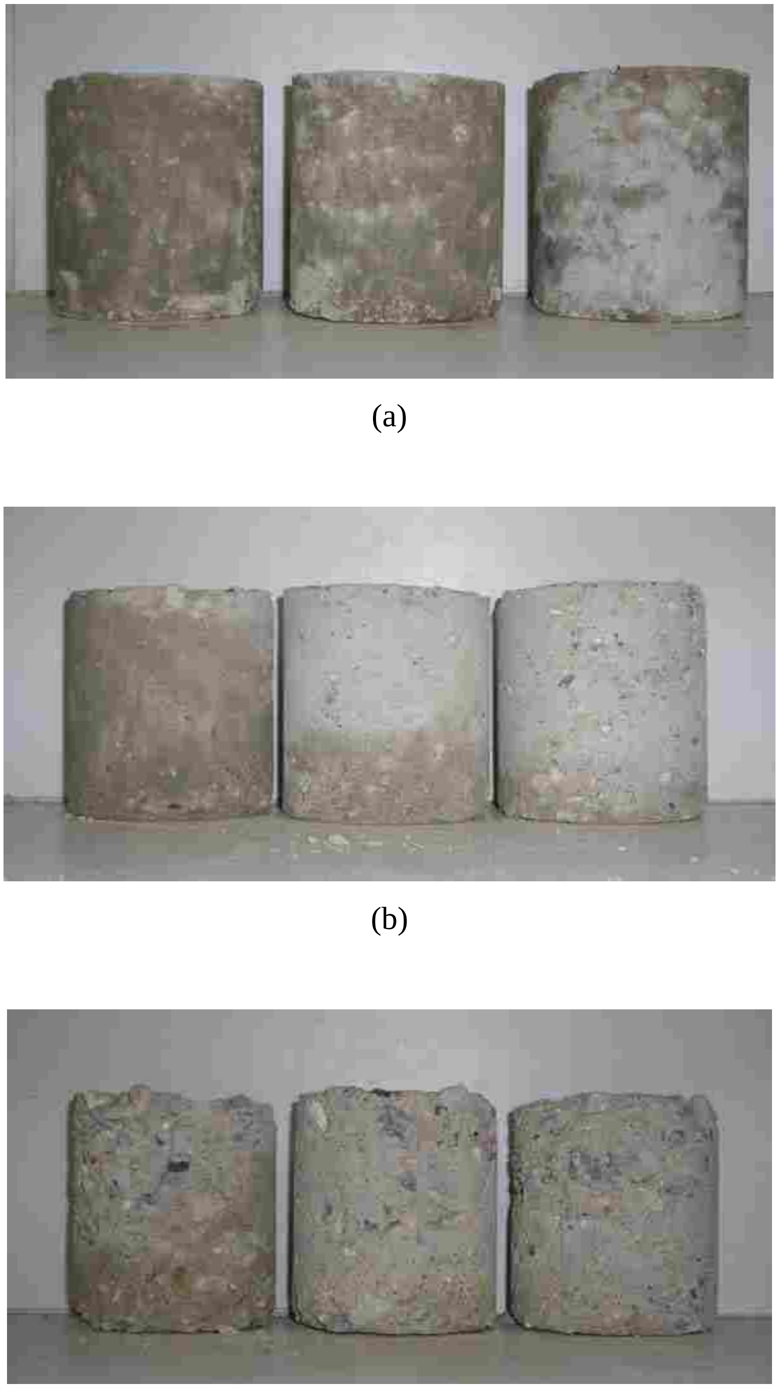


(a)

(b)

(c)

Figure B.13 US-91 specimens treated with 3 percent lime-fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

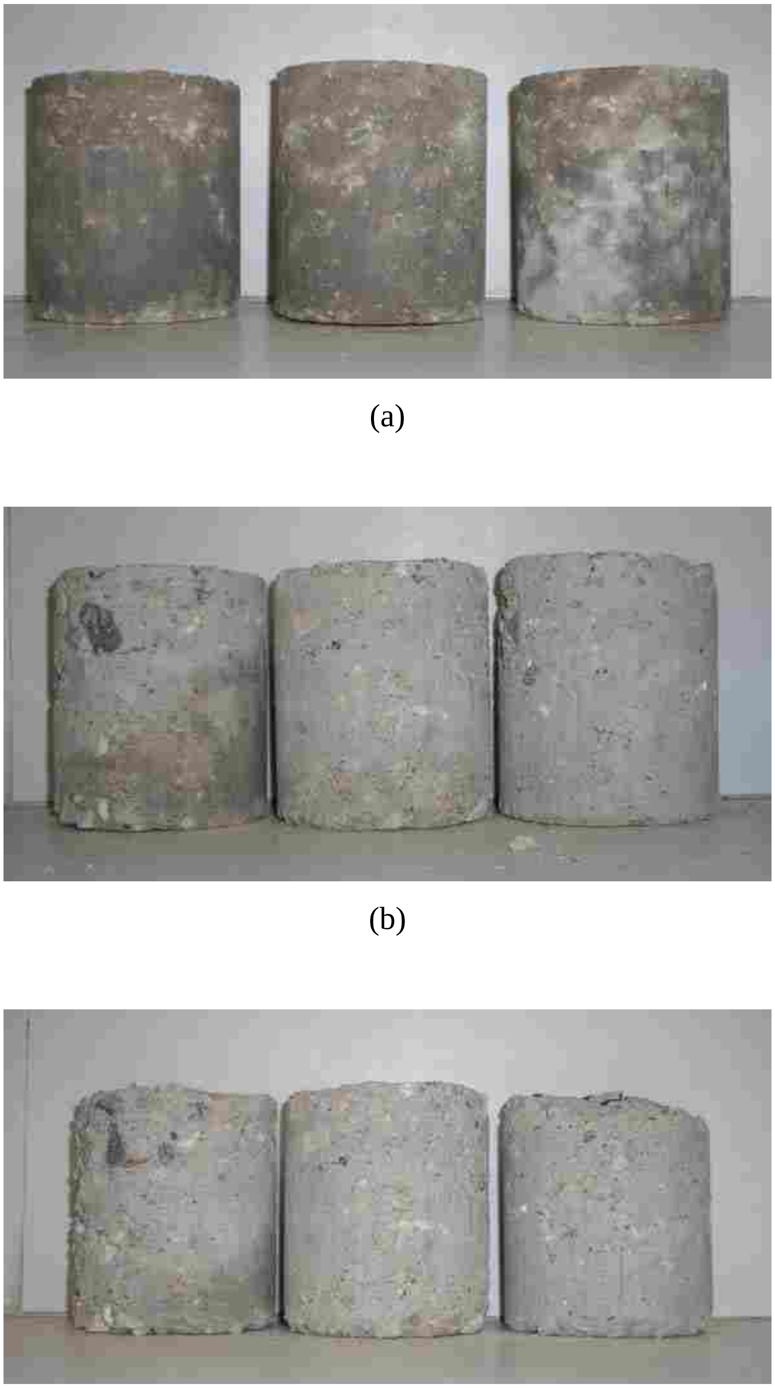


(a)

(b)

(c)

Figure B.14 US-91 specimens treated with 5 percent lime-fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

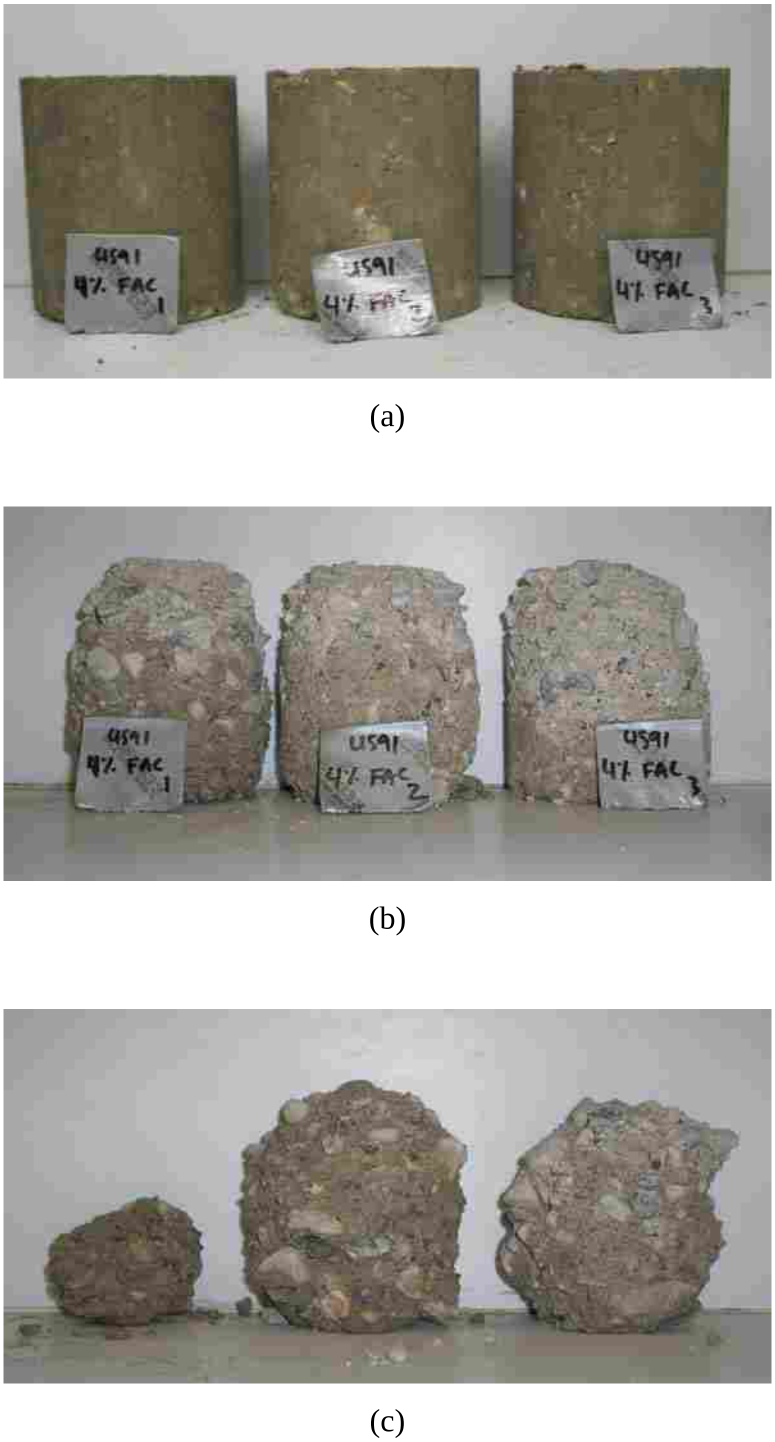


(a)

(b)

(c)

Figure B.15 US-91 specimens treated with 7 percent lime-fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

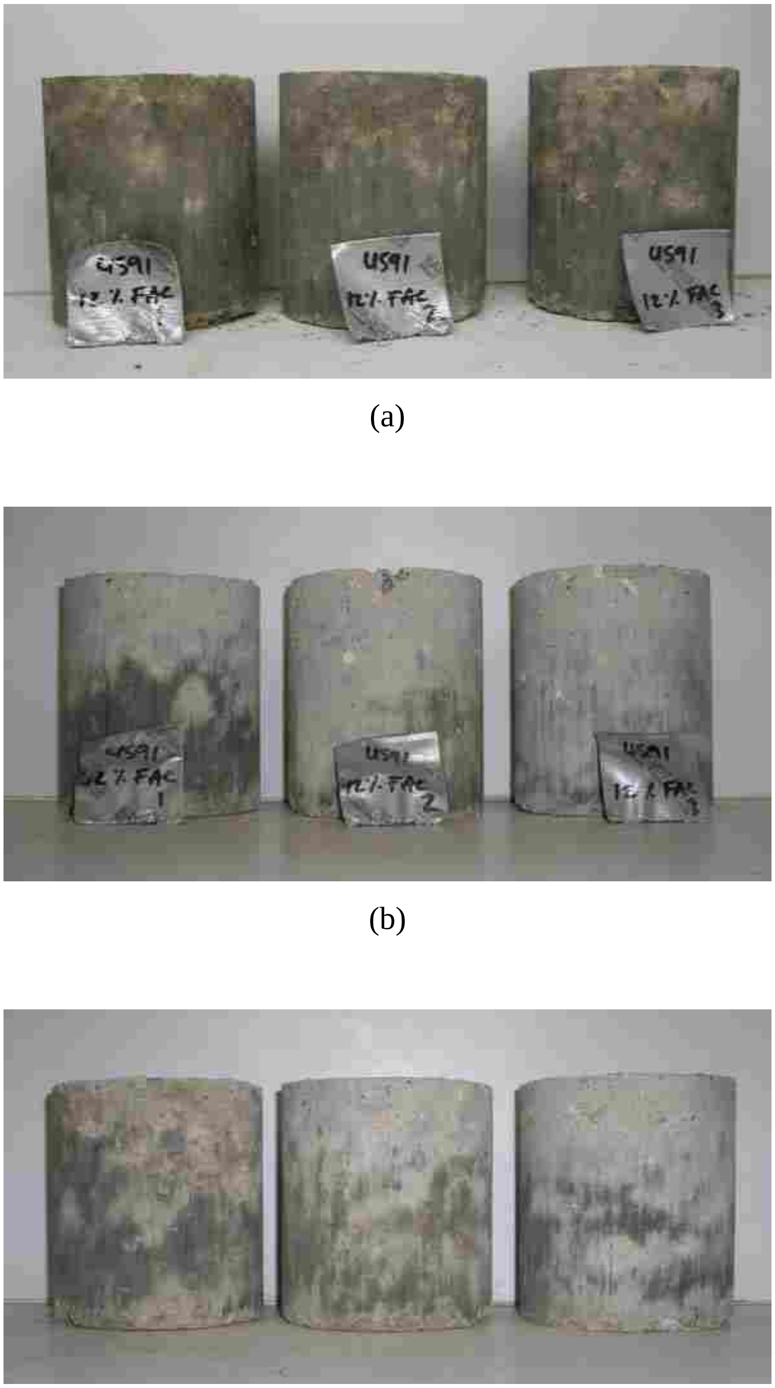


(a)

(b)

(c)

Figure B.16 US-91 specimens treated with 4 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.17 US-91 specimens treated with 12 percent class C fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.

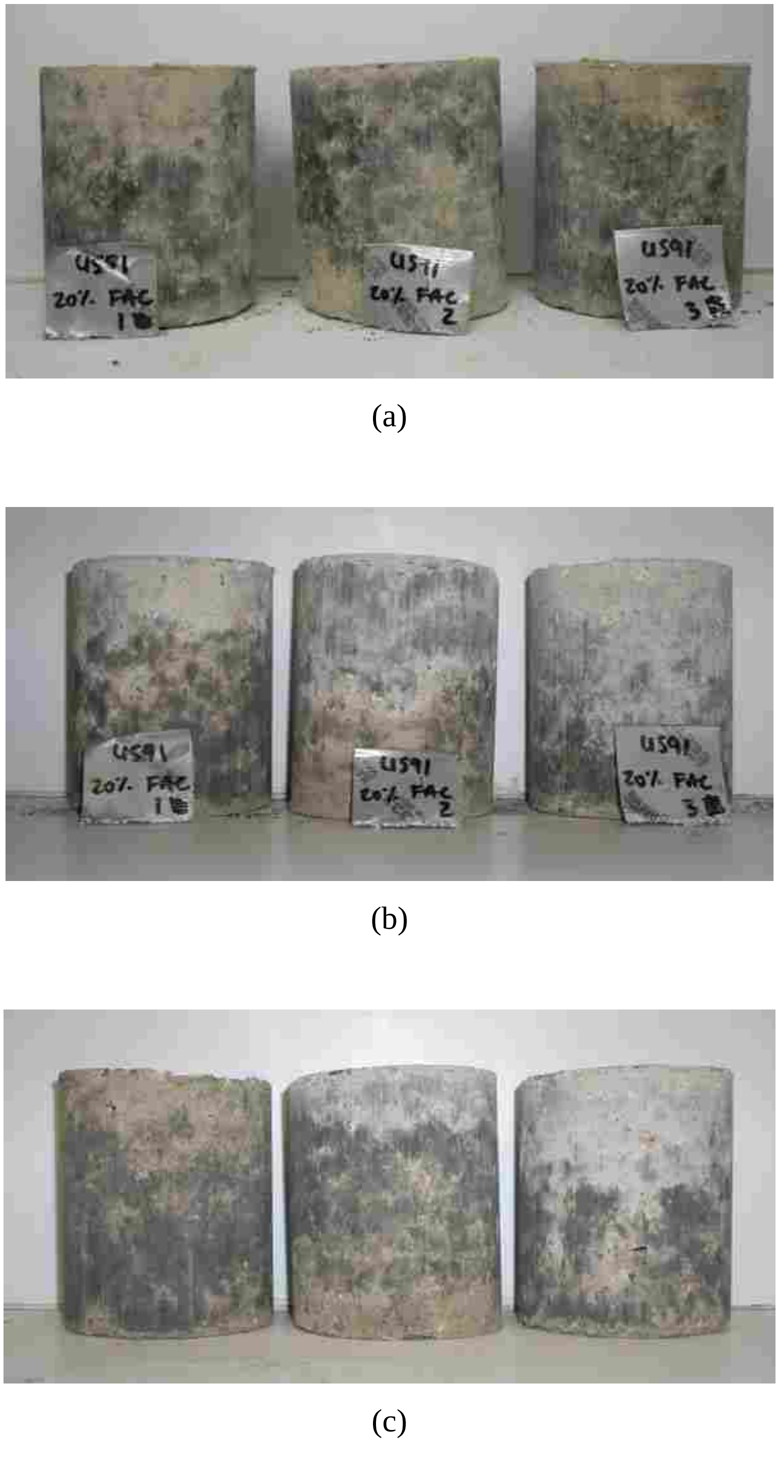


Figure B.18 US-91 specimens treated with 20 percent class C fly ash after (a) 0 cycles, (b) 6 cycles, and (c) 12 cycles of freeze-thaw testing.