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Assessment of the Tube Suction Test for Identifying Non-Frost-Susceptible Soils Stabilized with Cement

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ASSESSMENT OF THE TUBE SUCTION TEST FOR IDENTIFYING NON-FROST-SUSCEPTIBLE SOILS STABILIZED WITH CEMENT

by

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GRADUATE COMMITTEE APPROVAL

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ABSTRACT

ASSESSMENT OF THE TUBE SUCTION TEST FOR

IDENTIFYING NON-FROST-SUSCEPTIBLE

SOILS STABILIZED WITH CEMENT

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Master of Science

Frost heave is a primary mechanism of pavement distress in cold regions. The distress exhibited is dependent on the frost susceptibility of the soil within the depth of frost penetration, the availability of subsurface water, and the duration of freezing surface temperatures. Cement stabilization is one technique used to mitigate the effects of frost heave.

The tube suction test (TST) is one possible method for determining the frost susceptibility of soils in the laboratory. The purpose of this research was to assess the utility of the TST for identifying non-frost-susceptible (NFS) materials stabilized with cement. This research investigated two aggregate base materials from Alaska that have exhibited negligible frost susceptibility in the field. The unconfined compressive strength (UCS), final dielectric value in the TST, and frost heave at three levels of cement treatment and in the untreated condition were evaluated for both materials.

The data collected in this research indicate that, for the two known NFS materials included in this study, the TST is a good indicator of frost heave behavior. The total

heave of the untreated materials was approximately 0.15 in. at the conclusion of the 10-day freezing period, which classifies these materials as NFS according to the U.S Army Corp of Engineers. Both materials had final dielectric values of less than 10 in the TST, indicating a superior moisture susceptibility rating.

The results of this research suggest that the TST should be considered for identifying NFS materials, including those stabilized with cement. Additional testing should be performed on known NFS materials stabilized with cement and other additives to further assess the validity of using the TST to differentiate between frost-susceptible and NFS materials.

Consistent with previous studies, this research indicates that, once a sufficient amount of cement has been added to significantly reduce frost heave, additional cement has only a marginal effect on further reduction. Therefore, to avoid unnecessary expense in construction, the minimum cement content required for preventing frost heave should be identified through laboratory testing and specified by the engineer. In this work, UCS values ranging between 200 psi and 400 psi after a 7-day cure were typically associated with this minimum cement content. Because the scope of this research is limited to two aggregate base materials, further testing is also necessary to validate this finding.

AKNOWLEDGMENTS

I would like to thank the Portland Cement Association and the Alaska Department of Transportation and Public Facilities for supplying funding and materials to make this research possible. My appreciation goes out to Dr. Spencer Guthrie for his guidance and enthusiasm throughout this project and to David Anderson for his technical support. I would also like to thank the following students for their help and encouragement throughout this process: Aimee Birdsall, Matt Roper, Rebecca Crane, Adam Birdsall, Thad Pinkerton, Ash Brown, and Josh Rupp. Last of all, I would like to let my family and friends know I am grateful for their love and support with my educational pursuits.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

A primary mechanism of pavement distress in cold regions is frost heave. Frost heave occurs as ice lenses form within the pavement structure and can lead to differential vertical movement, causing pavement cracking and pavement roughness during winter time (*1*, *2*, *3*). In the spring when the ice lenses melt, layers underlying the pavement surface can become super-saturated, resulting in a reduction of bearing capacity that leads to permanent damage of the affected pavement structure (*4*, *5*). Pavement damage resulting from these mechanisms is dependent on the frost susceptibility of the soil within the depth of frost penetration, the availability of subsurface water, and the duration of the freezing air temperatures at the pavement surface (*1*, *3*). Therefore, in a cold environment with frost-susceptible soils, moisture is the most important factor controlling frost heave. Cement stabilization is one method used to mitigate problems associated with frost-susceptible soils (*4*). Strength and durability are two key properties of soil-cement mixtures (*6*). Adequate strength and durability are needed to withstand traffic loading and destructive forces from weathering.

Laboratory testing to determine the frost susceptibility of soils is expensive and time-consuming (*7*). Therefore, a reliable, inexpensive, and relatively rapid method is needed for characterizing both untreated and cement-treated materials to differentiate between those that are frost-susceptible and those that are not. Engineers in cold regions, where significant amounts of frost penetration occur from long periods of freezing temperatures, would benefit from this kind of characterization method.

A recently developed laboratory test method that may prove reliable in the assessment of frost susceptibility is the tube suction test (TST). The TST was developed in a cooperative effort between the Finnish National Road Administration and the Texas

Transportation Institute (*8*). This method is used to assess the moisture susceptibility of aggregate base materials. The final mean surface dielectric value obtained from the TST over a 10-day capillary soak is empirically related to the expected performance of an aggregate base material (*8*). Texas and Finnish aggregates were tested to develop the rating system currently used to relate dielectric value to aggregate performance (*9*). With the development of the TST, the Portland Cement Association (PCA) has shown interest in implementing this new procedure for the assessment of soil-cement durability.

Previous research has consisted of materials testing for correlation of moisture susceptibility and dielectric value measured using the TST (*8, 10*, *11*). Research at Brigham Young University (BYU) has been performed on cement-treated, frost-susceptible Montana silt to develop a relationship between frost heave test results and final dielectric value. That research indicated that the addition of small amounts of cement, corresponding to a 7-day UCS of 200 psi, increased frost heave but that higher cement contents provided complete protection against frost heave. The collected data also showed that the addition of cement decreased the dielectric value of the treated materials in the TST (*12*). To complement the previous work on frost-susceptible silt, the present study focused on non-frost-susceptible (NFS) materials. Given that the literature is largely absent of data investigating the relationship between frost heave and TST results for NFS materials stabilized with cement, the purpose of this research was to assess the utility of the TST for identifying cement-treated NFS materials.

1.2 SCOPE

The Alaska Department of Transportation and Public Facilities provided two aggregate base materials exhibiting negligible frost susceptibility in the field. The materials were sampled from milepost 26 along the Dalton Highway and milepost 134 along the Elliott Highway in Alaska. Figure 1.1 shows the locations of the borrow pits from which the materials were obtained. These materials were evaluated for unconfined compressive strength (UCS), final dielectric value in the TST, and frost heave at three levels of cement treatment and in the untreated condition. The UCS was used to measure material strength at 7-day and 28-day cures for each level of cement treatment. Finally, an analysis of variance (ANOVA) was performed to determine the significance of the test results.

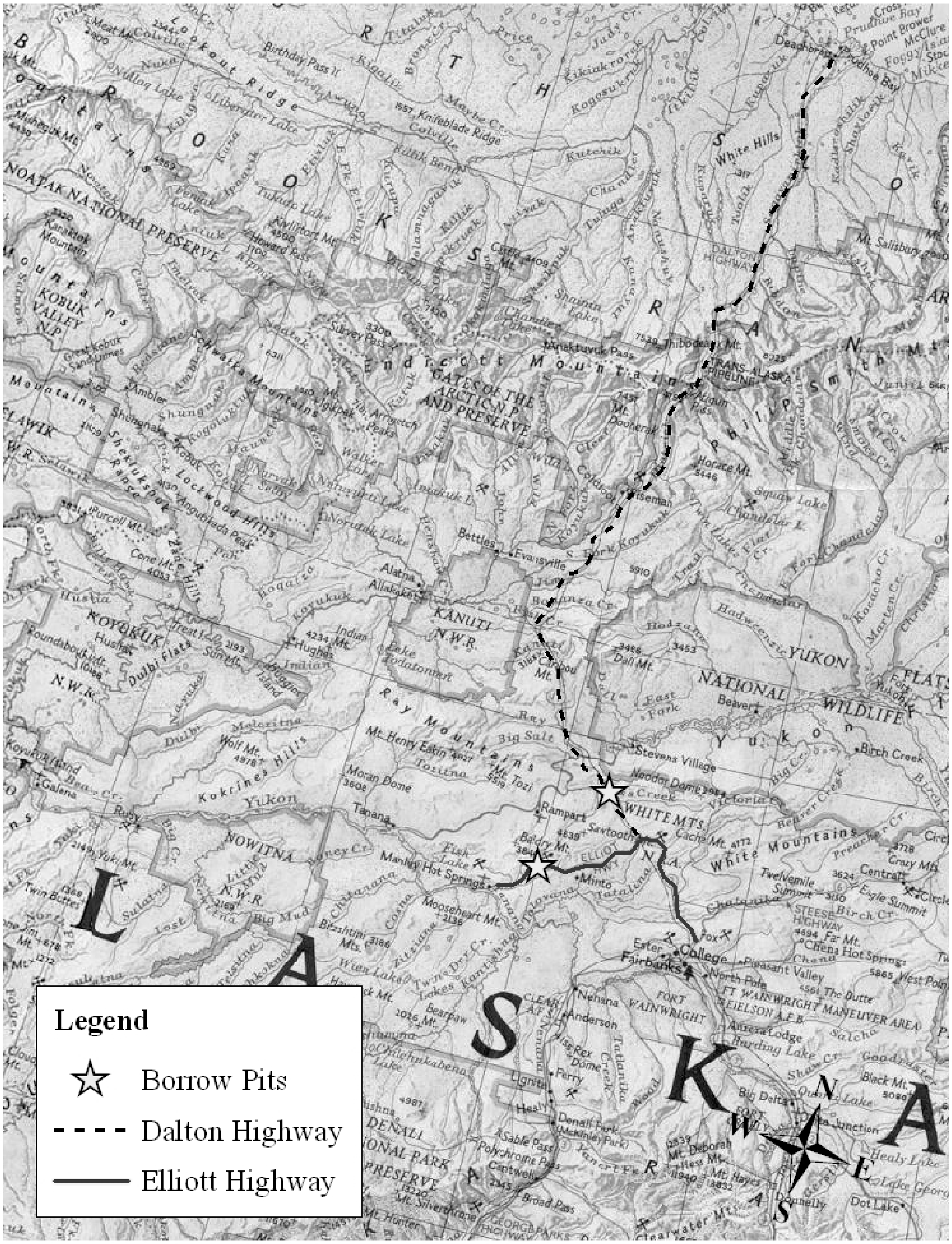

FIGURE 1.1 Borrow pit locations for materials.

1.3 OUTLINE

This report contains five chapters. Chapter 1 presents the objectives and scope of the research, and Chapter 2 describes the mechanisms of frost heave and cement stabilization. Chapter 3 discusses the test procedures used in the laboratory to characterize the material and assess UCS, moisture susceptibility, and frost heave. Chapter 4 presents results from the experimentation, and, finally, Chapter 5 presents a summary of the research findings and provides recommendations.

CHAPTER 2

FROST HEAVE MECHANISMS AND MITIGATION

2.1 OVERVIEW

This chapter discusses the processes contributing to frost heave, including freezing front penetration, soil suction, and hydraulic conductivity. Also presented in this chapter are several advantages of using cement stabilization for mitigating frost heave and a discussion of testing procedures available for designing cement-treated materials.

2.2 FROST HEAVE

Frost heave is the vertical displacement of a surface due to the formation of ice lenses within the underlying soil in response to freezing temperatures penetrating the ground. The process of frost heaving can cause significant damage to susceptible pavement structures in regions of seasonal freezing and thawing (*4, 7*).

In laboratory frost heave testing, the rate per day at which a specimen heaves is an indication of the frost susceptibility of the soil. The U. S. Army Corps of Engineers has developed a frost susceptibility classification based on the rate of heave per day exhibited by a soil as shown in Table 2.1 (*7*).

TABLE 2.1 Frost Susceptibility Classifications of Soil

Average Rate of Heave (in./day)	Frost Susceptibility Classification
0-0.02	Non-frost susceptible
0.02-0.04	Very low
0.04-0.08	Low
0.08-0.16	Medium
0.16-0.31	High
>0.31	Very high

Two processes can contribute to the total heave experienced within a soil. The first process is in-situ freezing. This process occurs as the freezing front penetrates downward and the existing pore water freezes in its original location. The increasing volume of the water as it changes from a liquid to a solid state can lead to volume expansions of up to 9 percent of the volume of the water. In NFS soils, the heave associated with in-situ freezing is usually responsible for any increases in volume that may occur (*13*, *14*, *15*). The second process contributing to total heave is segregation freezing. Segregation freezing is the formation of ice lenses as water is drawn to the freezing front from outside sources or underlying unfrozen soil by suction (*5*, *15*). The growth of ice lenses at the freezing front is the main contributor to heave in frost-susceptible soils (*14*).

The rate at which a freezing front penetrates the ground is a function of the difference between the heat supplied to and the heat removed from the freezing front. Penetration is initiated as temperatures at the pavement surface fall below freezing. Heat moves from warmer underlying pavement layers toward cooler layers at the surface; when sufficient heat is extracted, freezing occurs. A greater difference between these temperatures will lead to a faster frost penetration rate. The rate of frost penetration is a factor in the amount of heave experienced within a soil. When penetration of the freezing front proceeds rapidly, frost heave is limited to that resulting primarily from in-situ freezing even in frost-susceptible soils. However, if the penetration proceeds slowly in a semi-steady-state condition, segregation freezing and substantial frost heave are more likely to occur (*15*, *16*).

The growth of ice lenses occurs in frost-susceptible soils when available moisture and freezing temperatures are both present. Though saturation levels of the soil may vary throughout a soil column, zones in which ice lenses form are usually saturated. In unsaturated soil, the pore spaces of the soil matrix are filled with both air and water. The air must be replaced with water or ice for frost heave to occur within the freezing zone (*1*, *5*).

The frost susceptibility of a given soil is primarily dependent on its suction characteristics and hydraulic conductivity (*8*). Total suction of an unsaturated soil is comprised of both matric and osmotic suction. Matric suction can be described as the difference between the air and water pressure within the soil matrix. It varies as the moisture content of the soil changes (*17*, *18*). Capillary action experienced within a soil structure is due to matric suction and can be compared with rise in a capillary tube. The interfaces between air and water within the soil matrix form menisci. The radius of curvature of a given meniscus is comparable to the radius of curvature of the meniscus in a capillary tube. The height of capillary rise within the capillary tube is inversely proportional to the radius of curvature of the meniscus. Similarly, the radii of curvature of the menisci in a soil matrix are inversely proportional to matric suction. A decrease in radius causes an increase in suction, and therefore fine-grained materials with smaller pore sizes have greater suction than more coarse-grained soils (*8*, *19*).

Osmotic suction results from the solute concentration of the pore water. Water moves through the process of osmosis from regions of low salt concentration to zones of higher concentration. Increases in solute concentrations of near-surface pore water in cold regions can occur from the leaching of deicing salts into upper pavement layers, potentially causing water to move upward by osmotic suction. The movement of water will continue until equilibrium ion concentrations are established in the pore water (*8*).

Even though fine-grained soils generally exhibit greater capillarity, void spaces in the soil need to be large enough for water movement to occur sufficiently quickly in response to changes in suction in the soil matrix for ice lens formation to occur. The ability and rate of water to move through a soil are controlled by hydraulic conductivity, or coefficient of permeability. A few factors affecting hydraulic conductivity include mineralogy, fines content, density, void size, and water content of the soil (*8*). The interconnectivity of the void spaces between soil particles creates a path through which water can travel. The more interconnected these void spaces are, the higher the hydraulic conductivity will be, and the more easily water can flow through the soil (*8*).

Because a given soil layer often exhibits spatial variability in its properties, the rate of ice lens development typically varies with depth and with horizontal distance. The non-uniform development of ice lenses can result in differential displacement at the ground surface, causing pavement distress (*1*, *2*).

Thaw weakening is another damaging effect directly associated with the occurrence of frost heave. As warmer temperatures at the ground surface begin to cause thawing of the pavement structure, the segregated ice lenses begin to melt. Excess moisture can become trapped between the surface and underlying frozen layers if drainage of the soil is inadequate. The near-surface pavement layers can become super-saturated, which can lead to dramatically reduced bearing capacity of the soil (*2*, *4*, *5*).

Both frost heave and thaw weakening cause significant damage to pavements each year and require considerable expenditures by transportation agencies in constructing and maintaining affected roadways (*20*). The differential displacement due to frost heave causes unevenness and surface roughness usually associated with cracking and breaking of pavement surfaces (*1*, *2, 7*). Traffic loading can then cause permanent damage to a pavement structure during spring when the bearing capacity is reduced (*3, 13*).

2.3 CEMENT STABILIZATION

To achieve desirable bearing capacity and material durability, especially with respect to frost action, soil stabilization can be used to modify both natural soils and recycled materials. A stabilizing agent commonly used for this purpose is Portland cement, which was first used as a stabilizing agent in 1917 (*21*). Cement stabilization offers increased rates of strength gain compared to other stabilizing additives, occurs with the addition of only water, can be used with many different soil types and gradations, and exhibits low sensitivity to organic matter in soil (*21*). Furthermore, the addition of adequate amounts of cement to a soil will decrease its hydraulic conductivity, thus reducing the rate at which water can migrate through the treated material (*22*). The main disadvantage of using cement to stabilize a soil is that compaction must be completed within a relatively short time (*21*, *23*).

The main components of cement are tricalcium silicate (C_3S) and dicalcium silicate (C_2S). The principal product resulting from the reaction of water and calcium silicate is calcium silicate hydrate (C-S-H). The C-S-H grows to fill pore spaces in a soil and bonds the particles together to increase the strength of the soil-cement (*21*, *23*).

Strength and durability are important properties in the design of soil-cement mixtures used in pavement structures (*6*). If designed correctly, cement-treated material will exhibit adequate long-term improvements in strength and durability compared to untreated soil. However, too much cement, while providing increased strength, can cause problems with durability due primarily to shrinkage cracking, which occurs during cement hydration due to self-desiccation of the treated layer (*23*, *24*). Conversely, adding insufficient amounts of cement will lead to inadequate strength and durability.

Durability of soil-cement mixtures has been traditionally determined using American Society for Testing and Materials (ASTM) D 559 and D 560. ASTM D 559 requires brush tests in conjunction with wet-dry cycling of compacted soil-cement mixtures, while ASTM D 560 requires brush tests in conjunction with freeze-thaw cycling of compacted specimens.

Both the wet-dry and freeze-thaw test protocols consist of compacting two replicate specimens from the same mixture and allowing them to cure for 7 days in a moist room. After the 7-day cure for wet-dry testing, the specimens are soaked for 5 hours. Specimen 1, which is prepared to assess volume-moisture relationships, is weighed. Both specimens are then placed in an oven for 42 hours at 160°F to dry. After curing, the freeze-thaw specimens are placed in a freezer at -10°F for 24 hours. Specimen 1 is weighed again, and both are allowed to thaw for 23 hours. At this point in both testing procedures, the specimens are weighed, and specimen 2, which is prepared to assess soil-cement losses, is subjected to brushing. Brushing consists of two brush strokes on all surfaces of the specimen with a force of 3 lbf. This process is repeated 12 times.

Clearly, these tests are both subjective and time-consuming, and the test results depend to a great degree on the consistency of the individual performing the test (*25*). Another disadvantage of these testing methods for soil-cement durability is that they do not accurately represent mechanisms that cause deterioration in the field. Because of the tedious nature of durability testing using ASTM D 559 and ASTM D 560, the UCS has been increasingly used as the single design parameter for cement content determination by transportation agencies and materials engineers, even though it is a reflection of only strength. Some agencies have also begun to use alternative testing methods such as the TST (*8*).

2.4 SUMMARY

Frost heave is a primary mechanism of pavement distress in cold regions. Total heave results from a combination of in-situ freezing and segregation freezing. In a frost-susceptible soil, the majority of the heave is caused by the formation of ice lenses associated with segregation freezing, which depends upon the suction characteristics and hydraulic conductivity of the soil.

Cement stabilization of materials is one technique available for mitigating the effects of frost action. Advantages of using cement as a stabilizer are increased strength, only needing water to initiate cement hydration, its ability to be used with many different soil types and gradations, and its low sensitivity to organic matter in soil. As cement begins to hydrate, cementitious products are created that bond soil particles together, thereby increasing both material strength and durability. Current methods for testing soil-cement durability are subjective and time-consuming, leading some transportation agencies to use alternative methods for determining cement contents for stabilization. In particular, the use of the TST to assess the durability of soil-cement mixtures was of interest in this research.

CHAPTER 3

TESTING PROCEDURES

3.1 OVERVIEW

This chapter discusses the procedures used in this research for material characterization, specimen compaction, and assessment of compressive strength, moisture susceptibility, and frost heave.

3.2 MATERIAL CHARACTERIZATION

The Alaska Department of Transportation and Public Facilities provided two aggregate base materials exhibiting negligible frost susceptibility in the field. The materials arrived at BYU in bulk and were dried and separated over several sieves. The gradation determined from this separation was used to construct replicate samples with identical gradations for further testing.

The materials were characterized using both the American Association of State Highway and Transportation Officials (AASHTO) and the Unified Soil Classification System (USCS) methods. These methods require determinations of the particle-size distribution and Atterberg limits of the soil. An 11-pound sample constructed following the gradation developed from the bulk separation of materials was subjected to a washed sieve analysis, which was performed in accordance with ASTM D 2217 for determination of the particle-size distribution of materials coarser than 0.003 in. A hydrometer analysis was performed in accordance with ASTM D 422 for determination of the particle-size distribution of materials finer than 0.003 in. The Atterberg limits of the materials were determined using ASTM D 4318. The multipoint liquid limit method (Method A) was used to determine the liquid limit of the materials.

In addition to particle-size distribution and Atterberg limits determinations, specific gravity, absorption, and electrical conductivity tests were performed. Specific gravity testing was performed in accordance with ASTM D 854, and absorption was determined in accordance with ASTM C 127. Electrical conductivity was measured using a dual platinum-plate, contacting-type sensor as an assessment of soil salinity. For each material, two samples of 0.18 oz of material finer than the No. 40 sieve were equilibrated in 3.5 oz of de-ionized water in the electrical conductivity test (*2*).

3.3 COMPACTION

In this research, specimens of the base materials were prepared using ASTM D 1557 Method C with the exception of frost heave test specimens, which were tested using ASTM D 1557 Method D. Each specimen was prepared using the gradation determined from the bulk separation mentioned previously. The portions of the materials coarser than the No. 4 sieve were soaked in de-ionized water for a period of 24 hours to allow for water absorption by the aggregate. Type I/II Portland cement was mixed with the portion of the materials finer than the No. 4 sieve, where applicable. Just before compaction, the finer portion of the material was mixed thoroughly with the coarser material.

Compacted specimens were prepared for determination of the optimum moisture content (OMC) and the maximum dry density (MDD), UCS, moisture susceptibility, and frost heave behavior of each material at three levels of cement treatment and in the untreated condition.

3.3.1 Moisture-Density Relations for Untreated Materials

A moisture-density curve was developed by compacting 4-in.-diameter specimens at various moisture contents in a mold of known volume. The dry density and moisture content of each specimen were calculated and plotted to determine the OMC and MDD for both materials.

3.3.2 Trial Cement Contents

The UCS of cement-treated materials used for road base is commonly specified by individual state highway departments. Historically, recommendations for cement contents are based on achieving satisfactory performance in ASTM D 559 or ASTM D 560, which often requires 7-day UCS values greater than 600 psi. In response to performance problems associated with shrinkage cracking of heavily cement-stabilized base layers, PCA is currently promoting the use of reduced cement contents corresponding to 7-day UCS values of 300 to 400 psi. Therefore, as requested by PCA, the target 7-day UCS values used in this research were 200 psi as a lower limit, 400 psi to correspond with current cement recommendations, and 600 psi as an upper limit.

To quantify the relationship between cement content and strength for each material, one specimen of each material was compacted at each of four trial cement contents expected to encompass the target UCS values. Additional water, equivalent to 25 percent of the weight of cement added to a given specimen, was added for cement hydration at the time of compaction.

The compacted specimens were allowed to cure for a 7-day period at 100 percent relative humidity. After curing, each specimen was soaked for a 4-hour period, capped with high-strength gypsum, and subjected to UCS testing, which was performed at a constant strain rate of 0.05 in./minute. The UCS was plotted against cement content to facilitate identification of cement contents corresponding to UCS values of 200, 400, and 600 psi.

3.3.3 Specimen Preparation

The cement contents selected to achieve 7-day UCS values of 200, 400, and 600 psi were used to prepare specimens for 7-day and 28-day UCS testing, moisture susceptibility testing, and frost heave testing. Each compacted specimen was prepared using the gradation determined from the bulk separation of material conducted in this research and compacted at OMC.

3.3.3.1 Unconfined Compressive Strength

For each cement content corresponding to the target values of 200, 400, and 600 psi, both 7-day and 28-day UCS values were determined. Three replicate specimens for each of the cement contents were prepared for evaluation after each of the curing periods using the method of compaction described previously.

3.3.3.2 Moisture Susceptibility

Moisture susceptibility was measured using the TST. TST specimens were compacted into 4-in.-diameter plastic cylinders to a height of 4.58 in. and allowed to cure for 7 days at 100 percent relative humidity. Filter paper was placed in the bottom of each cylinder to prevent fines from washing out of the specimen during testing. The plastic molds were pre-drilled with 0.0625-in.-diameter holes at 0.5-in. spacing around the base of the specimen approximately 0.25 in. from the bottom of the mold to allow for water ingress into each specimen during testing.

3.3.3.3 Frost Heave

Frost heave specimens were compacted into 6-in.-diameter plastic cylinders. The specimens for frost heave testing were compacted in general accordance with ASTM D 1557 Method D with a modification of the height. In order to allow for a larger temperature difference between the heat source and heat sink during testing, each specimen was compacted to a height of approximately 9 in. in 10 lifts at 56 blows per lift. As with the TST specimens, filter paper was placed in the bottom of each cylinder to prevent the fines from washing out during testing. Each specimen was cured for 28 days at 100 percent relative humidity.

The plastic cylinders were pre-drilled with seven 0.125-in.-diameter holes in the bottom, which were placed to allow water uptake by the specimens during testing. Three specimens for each test group were randomly selected for frost penetration monitoring using thermocouples. To allow for insertion of the thermocouples in a given specimen, slots were cut into the plastic cylinder at 1-in. intervals starting at 3 in. from the bottom of the specimen. Consecutive slits were placed on opposite sides of the cylinder; the locations of the holes in the bottom and the slots in the side of a typical plastic cylinder are shown in Figure 3.1.

FIGURE 3.1 Plastic molds for frost heave.

3.4 TESTING

The compacted specimens were tested for UCS, moisture susceptibility, and frost heave. The following sections discuss the methods used for these tests.

3.4.1 Unconfined Compressive Strength

The UCS of each specimen was determined in accordance with ASTM D 1633. Following curing, both 7-day and 28-day test specimens were soaked under water for a 4-hour period, capped with gypsum, and subjected to UCS testing, which was performed at a constant strain rate of 0.05 in./minute. A capped specimen in the compression machine is shown in Figure 3.2.

FIGURE 3.2 Test specimen subjected to UCS testing.

3.4.2 Moisture Susceptibility

The TST was performed to assess the moisture susceptibility of the materials. After a 7-day cure, each specimen was oven-dried at 140°F for 72 hours. The dried specimens were then placed in an ice chest filled to a depth of approximately 0.5 in. with de-ionized water and allowed to imbibe water over a 10-day period. Six surface dielectric readings per specimen were taken each day during the 10-day soaking period. Five readings were taken around the perimeter of the top surface of each specimen, with the sixth reading in the center between the previous five. The highest and lowest of these six daily readings were discarded to reduce variability due to surface imperfections. The four remaining readings were averaged to obtain the average surface dielectric reading for the specimen. The final average dielectric reading was used to rank the moisture susceptibility of each specimen. Figure 3.3 shows the dielectric probe used in the testing.

The moisture susceptibility rating in the TST is an indication of the expected durability of the material. Aggregate base materials with final dielectric values less than 10 in the TST are expected to exhibit superior performance, values between 10 and 16 indicate marginal performance, and values greater than 16 indicate poor performance (*8*).

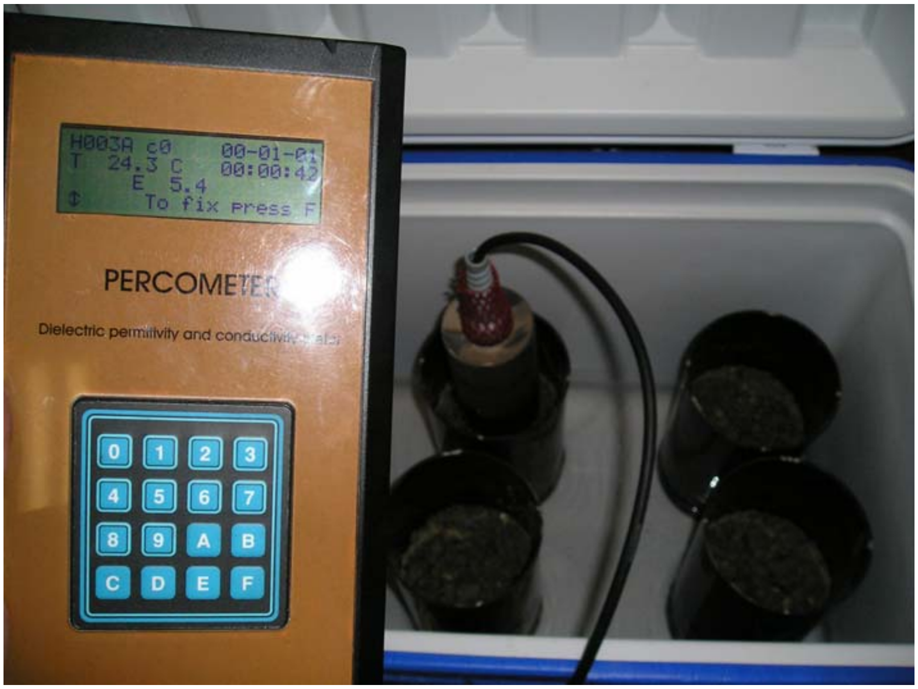

FIGURE 3.3 Dielectric probe used for surface dielectric measurements.

3.4.3 Frost Heave

Frost heave testing was conducted in the environmental chamber of the BYU Highway Materials Laboratory. The frost heave testing apparatus consists of a nine-place specimen bath with a table and specimen collars, a frame to hold the linear variable differential transformers (LVDTs) used to measure vertical displacement of the specimens, thermocouples to measure temperature throughout the test, and a data-logger to automatically record the data. Other elements used in the testing include heat tape to provide a heat source, a pump to circulate water in the bath to ensure uniform water temperature, insulation for the table and each of the test specimens, a variable alternating current device, or variac, and overburden weights.

Frost heave testing consisted of three 10-day tests. One specimen for each material/cement content combination was prepared for each test for a total of eight specimens per batch. A dummy specimen was prepared to fill the ninth location in the bath. The environmental chamber was programmed to maintain a constant room temperature of 19°F, and the data-logger was set to collect readings every 10 minutes. Prior to testing, the frost heave apparatus was cleaned, and the heat tape and the water pump were placed into the bath as shown in Figure 3.4. The bath with the table, table insulation, and collars are shown in Figure 3.5. The heat tape was connected to a variac set at 55 volts during testing to provide a steady supply of heat to the water.

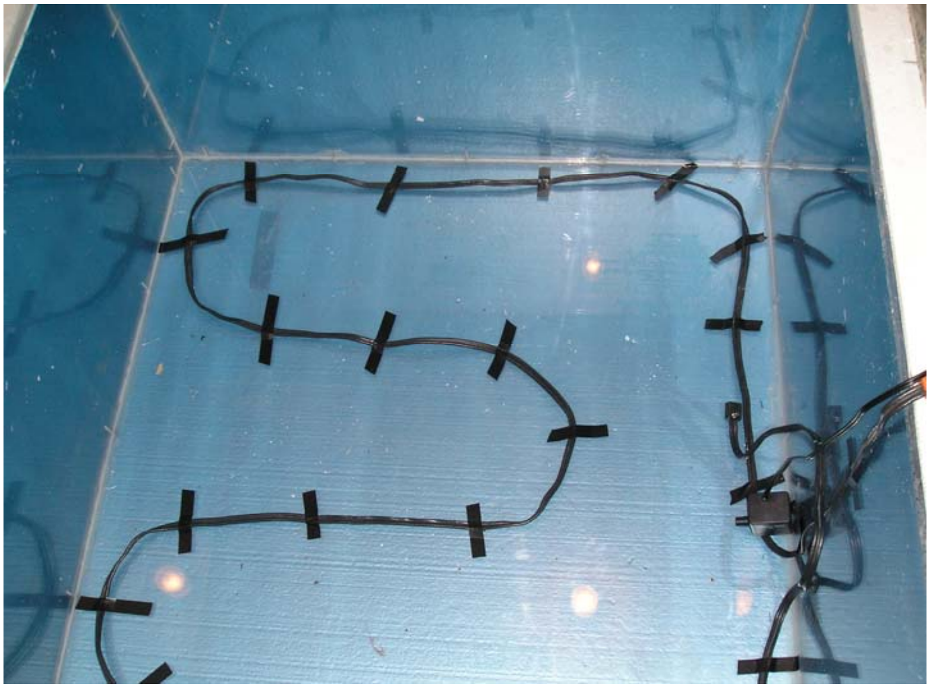

FIGURE 3.4 Heat tape and water pump installation.

FIGURE 3.5 Bath with table and specimen collars.

Approximately 10 gallons of de-ionized water was placed into the bath and allowed to cool in the environmental chamber for approximately 24 hours prior to the start of testing.

Thermocouples were used to monitor temperatures throughout the testing period. Air and water temperatures were monitored using two and three thermocouples, respectively. Additionally, three specimens were instrumented with thermocouples to monitor frost penetration within the specimens. To facilitate the insertion of the thermocouples in each specimen, a 0.188-in.-diameter hole about 1 in. deep was drilled into the specimen, just after compaction, at the bottom of each previously drilled slot in the cylinder molds to allow for vertical movement of the soil during frost heave testing. A thermocouple was inserted into the bottom of each of these seven slots and held in place with duct tape. Figure 3.6 shows a test specimen instrumented with thermocouples.

The specimens instrumented with thermocouples were placed in locations 1, 5, and 6, as depicted in Figure 3.7., for each of the tests performed. Specimens were placed within the bath for frost heave testing using a formal randomization technique. Location assignments for each specimen are given in Table 3.1.

After the thermocouples were inserted into three of the specimens, all of the cured specimens were wrapped in two types of flexible, closed-cell, foam rubber pads used for insulation. The insulation provided control of the direction of frost penetration (*12*). The specimens were then placed into the bath, and a 10-lb overburden weight was placed onto each of the specimens to simulate an overlying pavement surface.

After the specimens had been placed into the bath, LVDTs were positioned into the frame and centered over each of the test specimens. The LVDTs were set to allow for approximately 2 in. of heave. The complete test setup with thermocouples, specimen insulation, and LVDTs is depicted in Figure 3.8.

In addition to automatic data collection using data acquisition equipment, LVDT readings were manually recorded at least once per day throughout the testing period. Temperatures were monitored throughout the test, and adjustments to the setting of the variac were made as necessary to maintain a constant water temperature.

FIGURE 3.6 Test specimen instrumented with thermocouples.

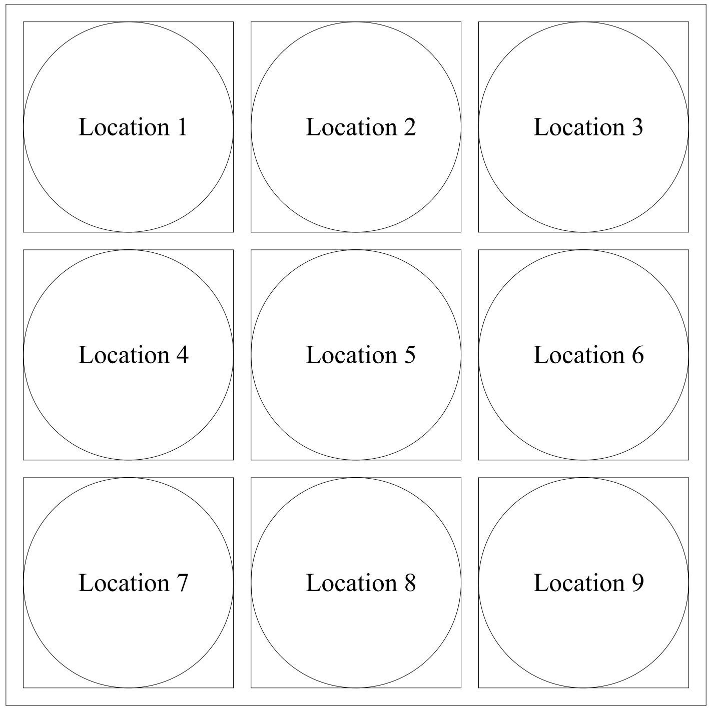

FIGURE 3.7 Specimen locations within the bath.

TABLE 3.1 Specimen Locations for Frost Heave Testing

Material	Cement Content (%)	Specimen Location		
		Test 1	Test 2	Test 3
Dalton	0.0	7	5	8
	0.5	5	9	6
	1.0	3	2	1
	1.5	8	1	4
Elliott	0.0	9	6	9
	1.0	1	4	7
	1.5	2	7	5
	2.0	6	3	2
Dummy	-	4	8	3

FIGURE 3.8 Complete frost heave test setup.

3.5 STATISTICAL ANALYSIS

An ANOVA was used to evaluate the test results obtained in this research. The ANOVA allows for comparison of multiple population means while simultaneously controlling the probability of a Type I error. A Type I error occurs when a true null hypothesis is rejected in favor of a false alternative. The null hypothesis is the assumption that all population means are equal, and the alternative is the assumption that the population means are different. The acceptable probability of occurrence of a Type I error, denoted by α, is assigned by the researcher for any given experiment. The ANOVA generates a level of significance, or *p*-value, which is compared to the value of α. The *p*-value is the probability that the observed differences between the population means occurred by chance. The null hypothesis is rejected in favor of the alternative hypothesis when the *p*-value is less than or equal to α. However, when the *p*-value is greater than α, insufficient evidence exists to reject the null hypothesis. In this study, the standard α value of 0.05 was used in the ANOVA. An α value of 0.05 indicates that only a 5 percent chance exists for incorrectly claiming that a difference exists between any treatments. The response variables evaluated in the ANOVA included 7-day and 28-day UCS values, final average dielectric values in the TST, and frost heave displayed by the materials. Specimens containing different cement contents were treated as samples of different populations.

When the ANOVA indicated that the effect of cement was significant, Tukey's mean separation procedure was performed using statistical software to identify the specific cement contents exhibiting the differences. In each pairwise comparison of sample means, a difference interval was calculated by the software such that a 95 percent probability existed of enclosing the difference between the two population means represented by the two samples. That is, the probability that the difference between the population means would occur outside the interval was only 5 percent. Then, if the interval contained only positive or only negative values, the population means were determined to be different at a 0.05 level of significance. However, if the interval contained zero, then the population means could not be declared different.

3.6 SUMMARY

Characterizations of the base materials evaluated in this research consisted of particle-size distribution, Atterberg limits, specific gravity, absorption, and electrical conductivity. Compacted specimens were prepared to determine OMC and MDD, 7-day and 28-day UCS values, moisture susceptibility, and frost heave behavior. Statistical analyses were performed to evaluate the results of the testing. An ANOVA was used to compare multiple population means, where specimens containing different cement contents were treated as samples of different populations.

CHAPTER 4

RESULTS

4.1 OVERVIEW

This chapter presents the results obtained for material characterizations, UCS tests, moisture susceptibility tests, and frost heave tests.

4.2 MATERIAL CHARACTERIZATION

Classification tests of the materials included a washed sieve analysis, a hydrometer analysis, Atterberg limits, absorption, specific gravity, and electrical conductivity testing. The liquid limit and plasticity index of the Dalton material were found to be 20 and 7, respectively. The Elliott material was found to have a liquid limit of 17 and a plasticity index of 3. The apparent specific gravities of the Dalton and Elliott materials were 3.12 and 2.72, respectively.

The particle-size distribution curves for the Dalton and Elliott materials are shown in Figures 4.1 and 4.2, respectively. The Dalton material was determined to be A-2-4 using the AASHTO classification method and well-graded gravel with sand (GW) using the USCS classification method. The Elliott material was classified as A-1-a using the AASHTO method and poorly-graded gravel with silt and sand (GP-GM) using the USCS method of classification.

The absorptions of the Dalton and Elliott materials were 1.74 and 1.57 percent, respectively. Electrical conductivity readings for the Dalton and Elliott materials stabilized at 28 days with average readings of 92.1 and 75.3 microsiemens per inch, which are both within the range of typical tap water. The relatively low values obtained for these materials were expected, as the soil was obtained from borrow pits and had never been exposed to deicing salts.

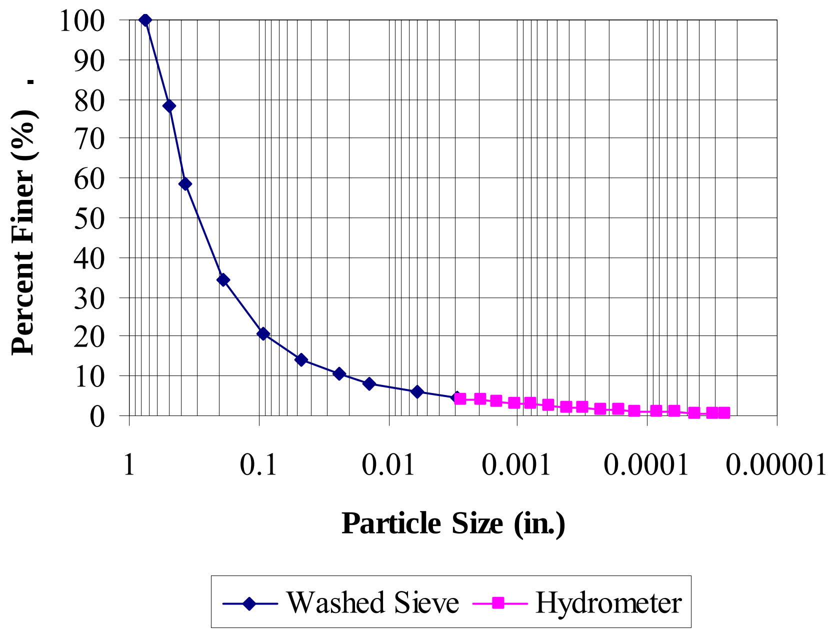

FIGURE 4.1 Particle-size distribution for Dalton material.

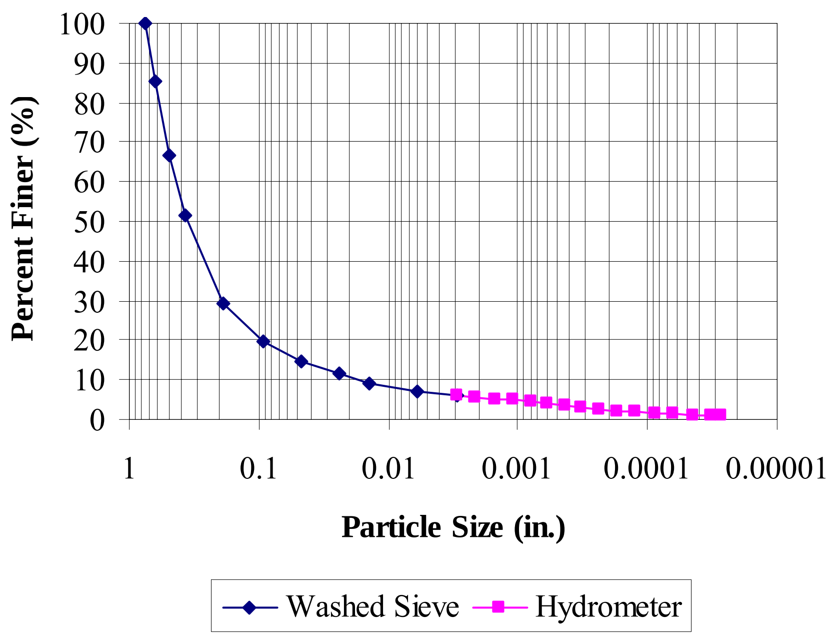

FIGURE 4.2 Particle-size distribution for Elliott material.

4.3 COMPACTION

The following sections present the results obtained from moisture-density testing and UCS testing of trial cement contents used for each of the materials.

4.3.1 Moisture-Density Relations for Untreated Materials

A moisture-density curve was developed for each of the untreated materials to determine the OMC and MDD. The OMC and MDD of the Dalton material were determined to be 4.4 percent and 145.6 pcf, respectively. A moisture-density curve for the Dalton material is shown in Figure 4.3. The Elliott material had an OMC of 5.3 percent and an MDD of 137.3 pcf. A moisture-density curve is shown in Figure 4.4 for the Elliott material. Each specimen prepared for further testing was compacted at the OMC and MDD determined from these tests.

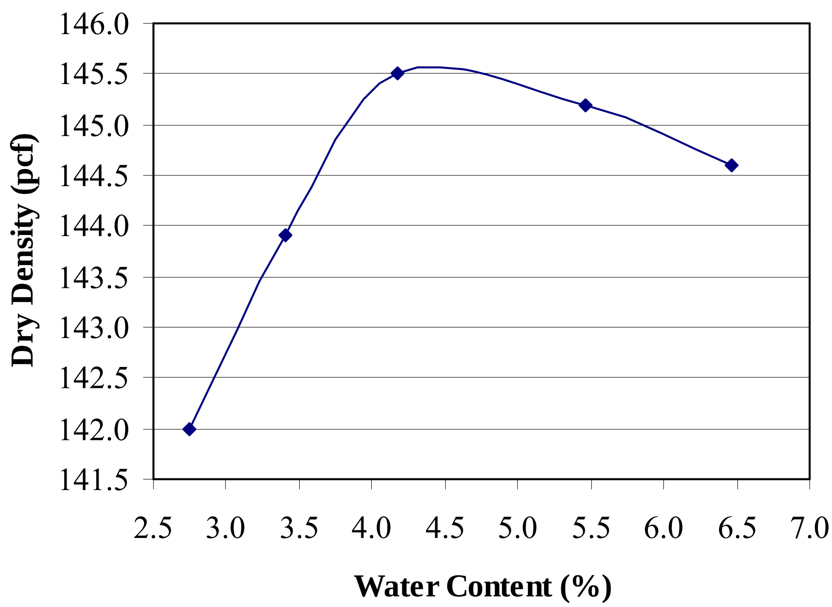

FIGURE 4.3 Moisture-density curve for Dalton material.

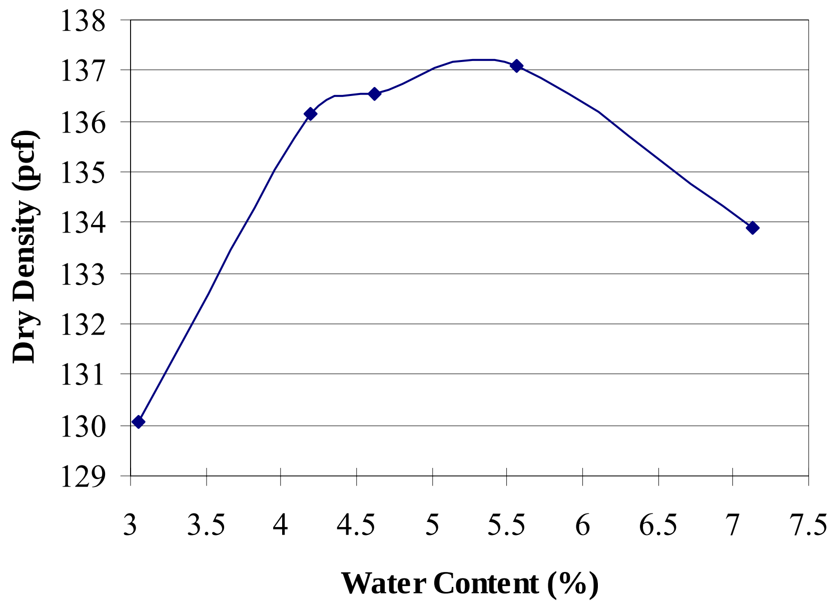

FIGURE 4.4 Moisture-density curve for Elliott material.

4.3.2 Trial Cement Contents

Trial cement contents of 1, 3, 5, and 7 percent by weight of dry aggregate were used for the Dalton material, while trial cement contents of 1, 2, 3, and 4 percent were used for the Elliott material. UCS was plotted against cement content to determine the percent cement needed to achieve 7-day UCS values of 200, 400 and 600 psi. Figures 4.5 and 4.6 display the plots used to determine these strengths. The cement contents corresponding to the UCS target values of 200, 400, and 600 psi for the Dalton material were 0.5, 1.0, and 1.5 percent, and corresponding values for the Elliott material were 1.0, 1.5, and 2.0 percent.

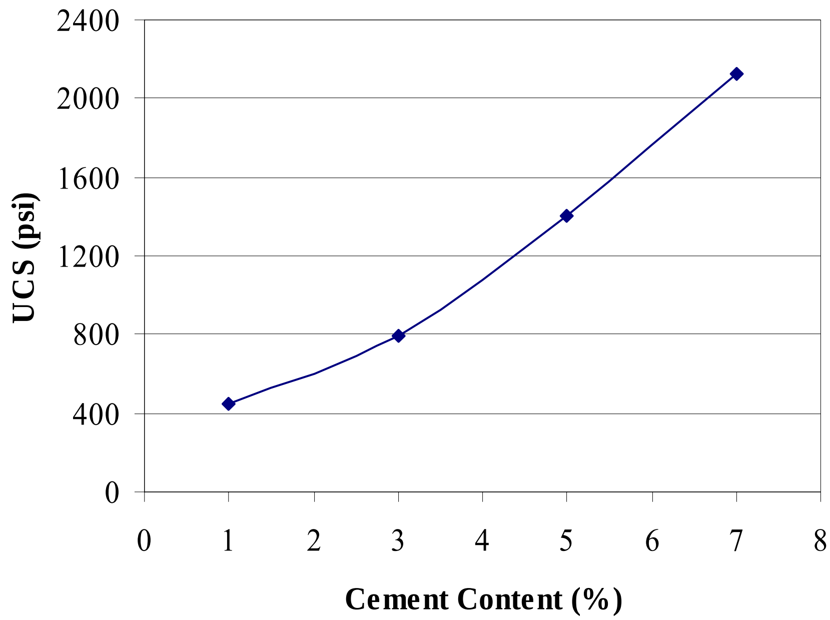

FIGURE 4.5 UCS test results for Dalton material at trial cement contents.

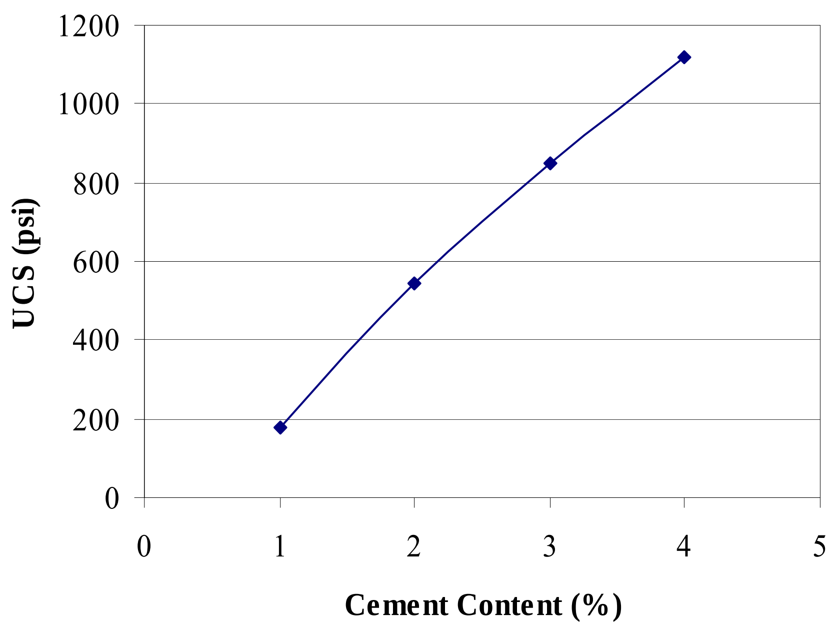

FIGURE 4.6 UCS test results for Elliott material at trial cement contents.

4.4 TESTING

Compacted specimens were prepared and tested for evaluation of UCS, moisture susceptibility, and frost heave behavior. The results from these tests are presented in the following sections.

4.4.1 Unconfined Compressive Strength

The results of UCS testing are shown in Figures 4.7 and 4.8. The Dalton material exhibited a UCS less than the target strengths of 400 and 600 psi for both the 7-day and 28-day tests when 1.0 and 1.5 percent was added to the specimens but exhibited UCS values slightly above the 200 psi target strength for both curing periods when 0.5 percent cement was added. Adding 1 percent cement to the Elliott material produced higher UCS values for both 7-day and 28-day cures than the target strengths of 200 psi. Both 1.5 and 2.0 percent cement resulted in UCS values less than the target values of 400 and 600 psi after a 7-day cure but were close to the target values at 28-day cures.

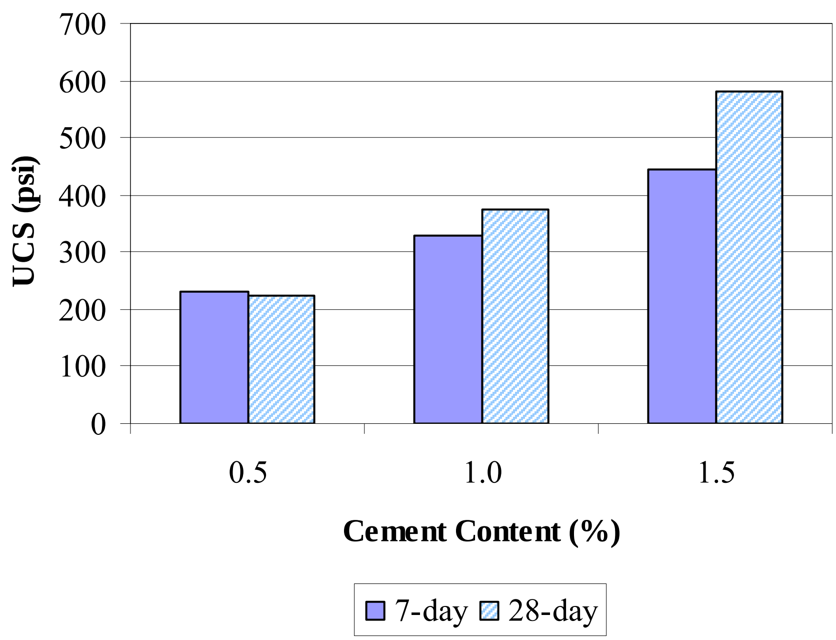

FIGURE 4.7 UCS test results for Dalton material.

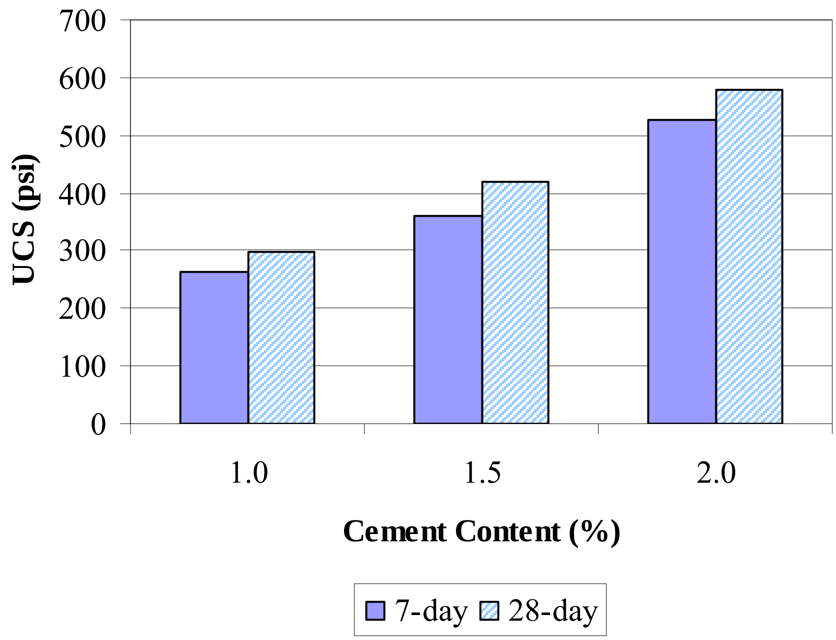

FIGURE 4.8 UCS test results for Elliott material.

4.4.2 Moisture Susceptibility

The TST was performed in order to evaluate moisture susceptibility. Average dielectric values plotted against time for the Dalton and Elliott materials are shown in Figures 4.9 and 4.10, respectively. The final average dielectric values and related ratings for the materials are shown in Table 4.1. Since all of the average final dielectric values were below 10, all of the specimens were rated as superior.

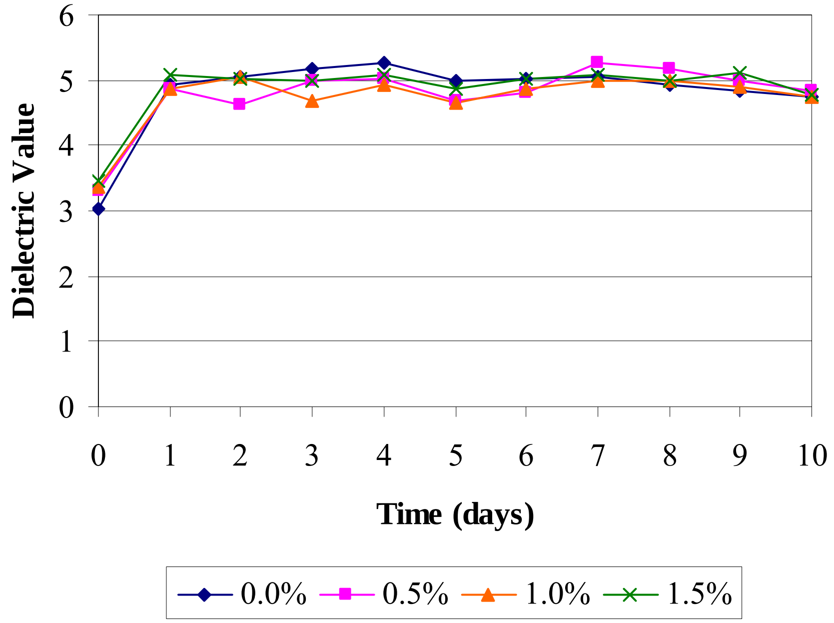

FIGURE 4.9 Average dielectric values for Dalton material.

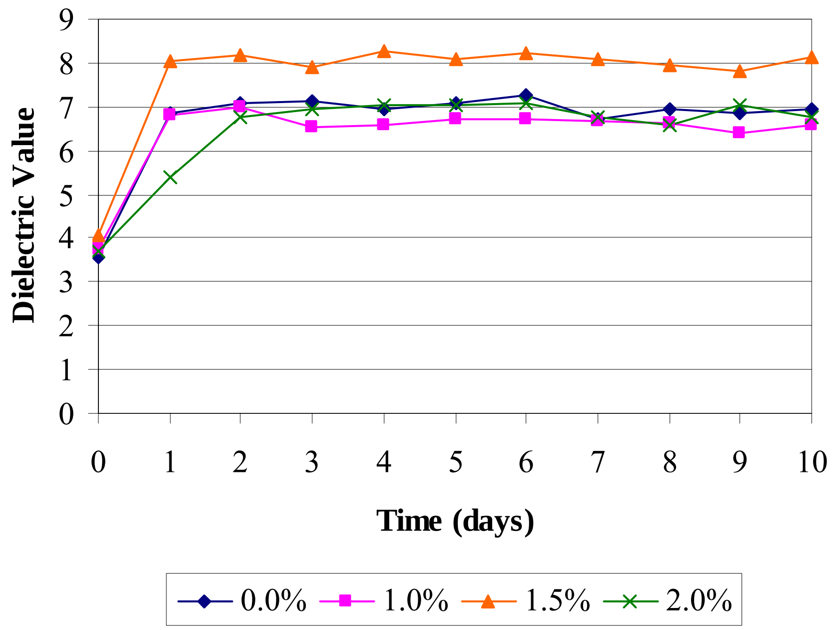

FIGURE 4.10 Average dielectric values for Elliott material.

TABLE 4.1 TST Results

Material	Cement Content (%)	Final Average Dielectric Value	Moisture Susceptibility Rating
Dalton	0.0	4.7	Superior
	0.5	4.9	Superior
	1.0	4.8	Superior
	1.5	4.8	Superior
Elliott	0.0	7.0	Superior
	1.0	6.6	Superior
	1.5	8.2	Superior
	2.0	6.8	Superior

4.4.3 Frost Heave

Three frost heave tests were performed in this research, and three specimens in each test were instrumented with thermocouples to measure frost penetration during freezing. A typical specimen temperature profile recorded during testing is shown in Figure 4.11. The coldest temperatures occurred at 9 in. from the bottom of the specimen, which corresponded to the specimen surface. Conversely, 3 in. from the bottom is the

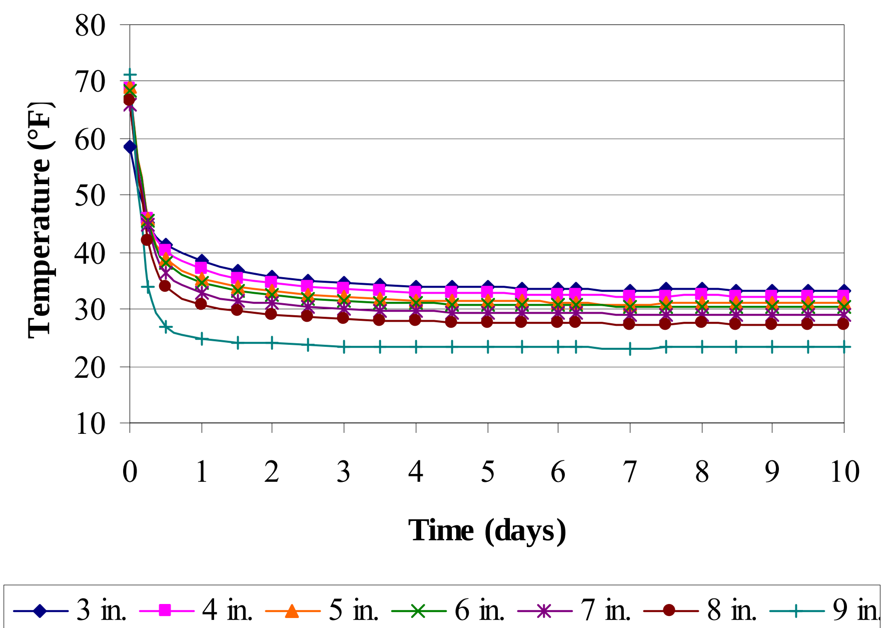

FIGURE 4.11 Specimen temperature profile during frost heave testing.

instrumented location at which the least amount of cooling occurred. Air and water temperatures were also monitored using thermocouples and are displayed in Figure 4.12.

LVDT data collected from the three replicate tests performed on both materials at each cement content were averaged and plotted against time as shown in Figures 4.13 and 4.14 for the Dalton and Elliott materials, respectively. The untreated materials exhibited approximately 0.15 in. of heave. The U.S. Army Corp of Engineers defines a NFS soil as one that exhibits a heave rate ranging from 0 to 0.02 in./day (*7*). The upper end of this range is indicated in Figures 4.13 and 4.14 by the line identified as "NFS Rate." The other labels in these figures indicate the cement content added to the material. The average heave of both materials throughout the 10-day testing period is less than the NFS rate, classifying both materials as NFS. The addition of cement at all levels eliminated any evidence of heave in both materials; in fact, the treated specimens actually decreased in height, probably due to the effects of thermal contraction as the specimens cooled. The minimum amounts of cement needed to eliminate any evidence of heave for the Dalton and Elliott materials are 0.5 and 1.0 percent, respectively, which correspond to the lower limit 7-day UCS of 200 psi. Additional cement beyond this minimum amount has little effect on further reducing heave.

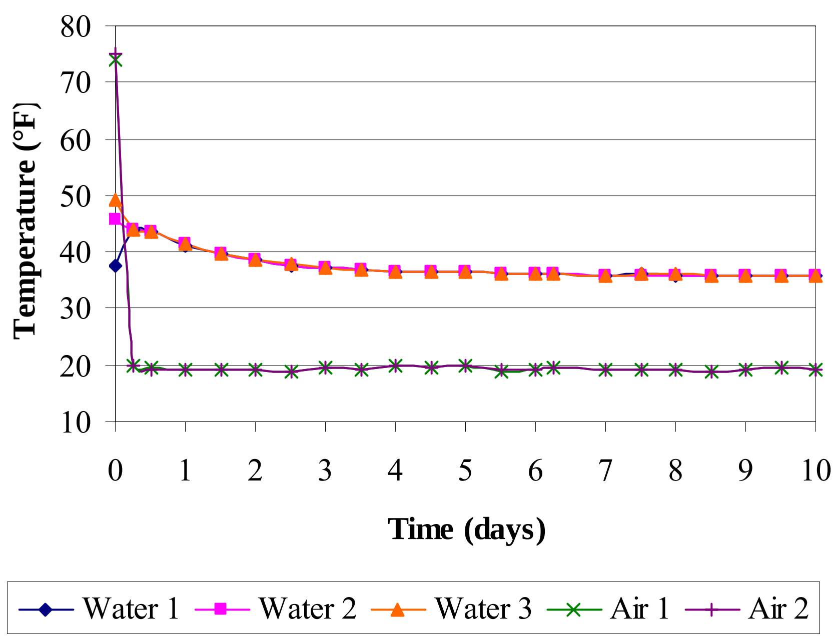

FIGURE 4.12 Typical temperature of air and water over time.

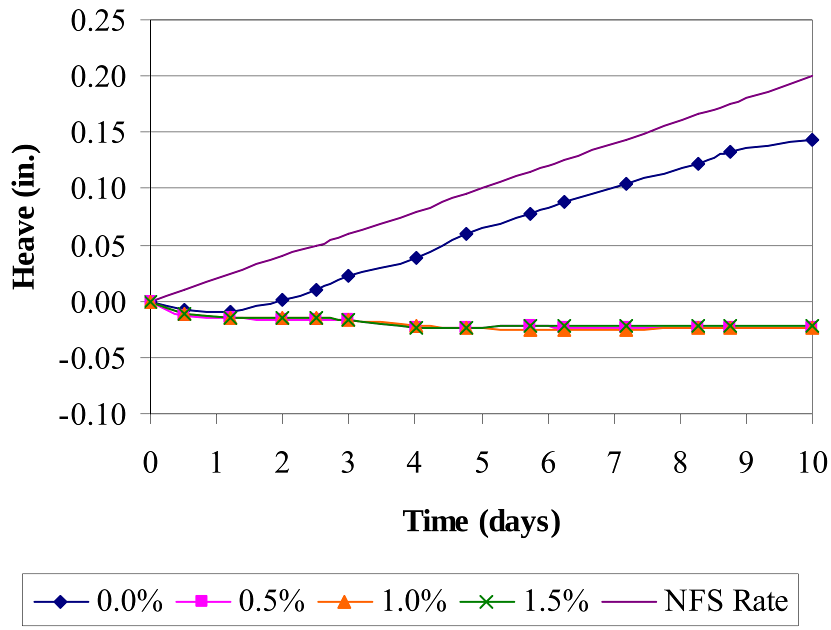

FIGURE 4.13 Average heave for the Dalton material.

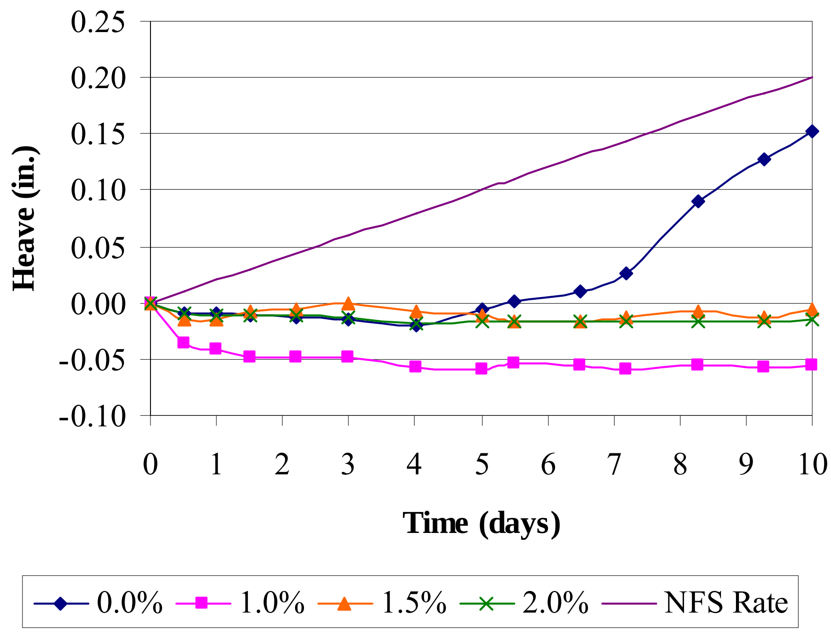

FIGURE 4.14 Average heave for the Elliott material.

Tables 4.2 and 4.3 summarize the frost heave data collected for the Dalton and Elliott specimens, respectively. Unusual heaving behavior was observed in the second test for both untreated materials. While all other specimens were classified as NFS, the frost susceptibility classifications for these two specimens were both determined to be "very low" according to Table 2.1. Although the unusual behavior may not be representative of the materials, the values were averaged with the results of the first and third tests to produce Figures 4.13 and 4.14. The variability associated with the untreated specimens was reduced dramatically with the addition of cement, which also led to reductions in water ingress and final moisture contents after frost heave testing.

The dry density of the specimens increased slightly with the addition of cement, probably attributable to the addition of fines in the form of cement to the total mix. The slight increase in moisture content at compaction is a result of the increased water added to treated materials for cement hydration.

TABLE 4.2 Frost Heave Test Results for Dalton Material

Cement Content (%)	Moisture Content at Compaction (%)	Dry Density at Compaction (pcf)	Initial Height (in)	Change in Height During Test (in)	Weight Gain During Test (lb)	Moisture Content at End of Test (%)
0.0	4.4	142.5	9.11	-0.01	0.20	5.4
	4.4	142.7	9.10	0.39	0.66	7.5
	4.4	146.2	8.89	0.01	0.45	6.6
0.5	4.6	143.1	9.02	0.00	0.22	5.6
	4.5	144.9	9.00	-0.02	0.15	5.2
	4.5	141.0	9.10	-0.05	0.22	5.6
1.0	4.6	147.9	8.90	-0.02	0.05	4.9
	4.6	146.5	8.97	0.00	0.09	5.1
	4.6	146.7	8.95	-0.05	0.05	4.9
1.5	4.7	152.4	8.65	-0.02	0.16	5.5
	4.7	141.9	9.31	0.00	0.19	5.6
	4.7	147.4	8.92	-0.05	0.22	5.8

TABLE 4.3 Frost Heave Test Results for Elliott Material

Cement Content (%)	Moisture Content at Compaction (%)	Dry Density at Compaction (pcf)	Initial Height (in)	Change in Height During Test (in)	Weight Gain During Test (lb)	Moisture Content at End of Test (%)
0.0	5.4	137.9	8.80	0.10	0.11	5.9
	5.3	138.4	8.84	0.25	0.13	6.0
	5.4	139.3	8.75	0.10	0.33	7.0
1.0	5.5	137.1	9.01	-0.01	0.12	6.1
	5.6	138.6	8.86	-0.01	0.09	6.0
	5.6	139.8	8.81	-0.15	0.11	6.1
1.5	5.6	140.5	8.86	-0.01	0.07	6.0
	5.7	139.9	8.86	0.04	0.03	5.8
	5.7	138.7	8.93	-0.05	0.13	6.3
2.0	5.7	140.9	8.88	-0.01	0.09	6.2
	5.7	137.9	9.03	0.00	0.02	5.8
	5.8	141.2	8.80	-0.03	0.03	5.9

4.5 STATISTICAL ANALYSIS

An ANOVA was performed on the collected data to determine the significance of each response variable. A summary of *p*-values obtained from the ANOVA is shown in Table 4.4. The results of the ANOVA indicate that the amount of cement added to the material has a significant effect on UCS. The Dalton material exhibited an increase in 7-day UCS from 230 to 445 psi and an increase in 28-day UCS from 225 to 581 psi as cement content increased from 0.5 to 1.5 percent. The Elliott material exhibited an increase in 7-day UCS from 265 to 527 psi and an increase in 28-day UCS from 299 to 578 psi as the cement content increased from 1.0 to 2.0 percent.

The results of the ANOVA indicate that the effect of cement content with respect to final dielectric value for either material is insignificant. Similarly, results from the ANOVA indicate no significance in cement content with respect to heave for the Dalton material. Therefore, Tukey's mean separation procedure was not performed in these cases. However, the effect of cement content on total heave was significant for the Elliott material. The results of Tukey's mean separation procedure indicated that a significant difference exists between the untreated specimens of Elliott material and those treated with 1 percent cement.

TABLE 4.4 ANOVA Results

Response Variable	*p* -value	
	Dalton	Elliott
7-day UCS	0.001	0.002
28-day UCS	0.000	0.001
Dielectric Value	0.996	0.266
Frost Heave	0.192	0.025

4.6 SUMMARY

The AASHTO classification method identifies the Dalton and Elliott materials as A-2-4 and A-1-a, respectively, while the USCS method classifies the soils as well-graded gravel with sand and poorly-graded gravel with silt and sand, respectively. The cement contents corresponding to target 7-day UCS values of 200, 400, and 600 psi were determined to be 0.5, 1.0, and 1.5 percent for the Dalton material and 1.0, 1.5, and 2.0 percent for the Elliott material.

As summarized in Tables 4.5 and 4.6, material testing included 7-day and 28-day UCS, moisture susceptibility, and frost heave behavior. The UCS test results show that the amounts of cement needed to eliminate the small amount of heave experienced by the Dalton and Elliott materials are 0.5 and 1.0 percent, respectively, which correspond to 7-day UCS values of approximately 200 psi. In addition, the collected data suggest that, once a sufficient amount of cement has been added to reduce frost heave, the addition of more cement has little effect on further reducing heave. The final average dielectric values of all specimens were less than 10, corresponding to superior moisture susceptibility ratings, and the average frost heave rates for all test specimens yielded NFS classifications.

Results from this research in connection with previous research performed on frost-susceptible silt from Montana are shown in Figure 4.15 as a comparison of good and poor materials. Each point on the graph indicates a different specimen. The two vertical lines in the graph indicate the boundaries between the moisture susceptibility ratings in the TST. Dielectric values less than 10 designate superior performers, dielectric values between 10 and 16 indicate marginal performers, and values greater than 16 indicate poor materials. Although several NFS specimens have dielectric values greater than 10, only two specimens having a dielectric value less than 10 exhibited a frost heave rate higher than the permissible limit for NFS materials specified by the U.S. Army Corps of Engineers. This chart therefore suggests that the TST may be used to positively identify NFS materials, including those treated with cement.

TABLE 4.5 Summary of Results for Dalton Material

Cement Content (%)	Specimen	7-day UCS (psi)	28-day UCS (psi)	Dielectric Value	Frost Heave (in.)
0.0	1	-	-	4.4	-0.01
	2	-	-	4.8	0.39
	3	-	-	5.0	0.01
0.5	1	239	253	4.8	0.00
	2	199	239	5.7	-0.02
	3	251	185	4.0	-0.05
1.0	1	335	362	5.0	-0.02
	2	324	401	4.5	0.00
	3	325	365	4.8	-0.05
1.5	1	378	516	4.8	-0.02
	2	469	602	5.1	0.00
	3	489	626	4.4	-0.05

TABLE 4.6 Summary of Results for Elliott Material

Cement Content (%)	Specimen	7-day UCS (psi)	28-day UCS (psi)	Dielectric Value	Frost Heave (in.)
0.0	1	-	-	8.0	0.10
	2	-	-	6.2	0.25
	3	-	-	6.7	0.10
1.0	1	266	307	6.9	-0.01
	2	305	294	6.2	-0.01
	3	224	296	6.6	-0.15
1.5	1	339	410	8.6	-0.01
	2	446	438	6.4	0.04
	3	302	414	9.5	-0.05
2.0	1	518	494	7.4	-0.01
	2	551	616	6.2	0.00
	3	512	625	6.7	-0.03

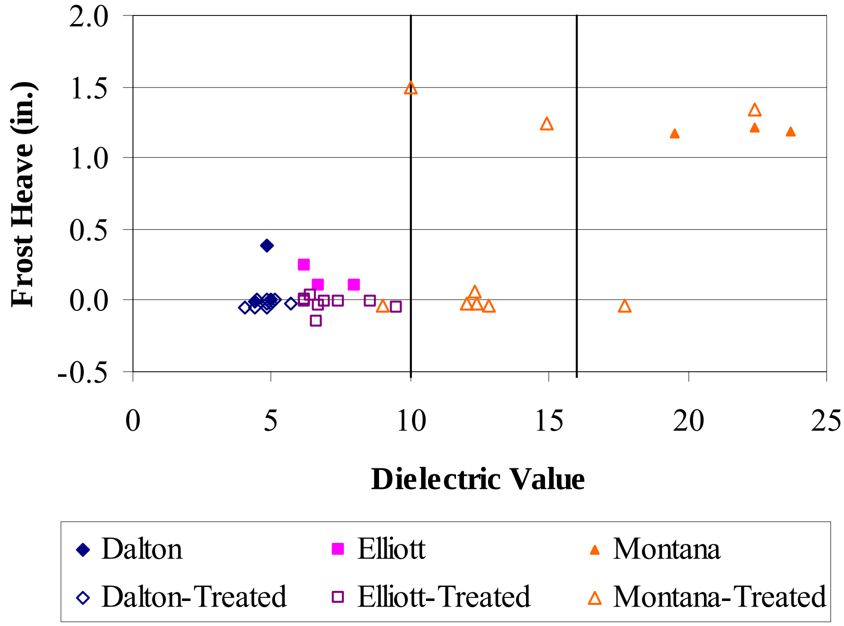

FIGURE 4.15 Comparison of dielectric value and frost heave.

CHAPTER 5

CONCLUSION

5.1 SUMMARY

Frost heave is a primary mechanism of pavement distress in cold regions. The distress exhibited is dependent on the frost susceptibility of the soil within the depth of frost penetration, the availability of subsurface water, and the duration of freezing surface temperatures. Cement stabilization is one method used to mitigate the effects of frost heave.

Determination of the frost susceptibility of soils in the laboratory is expensive and time-consuming. Therefore, a reliable, inexpensive, and relatively rapid method is needed for characterizing both untreated and cement-treated materials to differentiate between those that are frost-susceptible and those that are not. The TST is one possible method to accomplish this objective. The purpose of this research was to assess the utility of using the TST to identify NFS materials stabilized with cement.

This research investigated two aggregate base materials provided by the Alaska Department of Transportation and Public Facilities that have exhibited negligible frost susceptibility in the field. The materials were sampled from milepost 26 along the Dalton Highway and milepost 134 along the Elliott Highway in Alaska. The UCS, final dielectric value in the TST, and frost heave of each material at three levels of cement treatment and in the untreated condition were evaluated. A statistical analysis was then performed to determine the effect of cement treatment on the test results.

5.2 FINDINGS

The Dalton material was classified as A-2-4 and well-graded gravel with sand using the AASHTO and USCS methods, respectively, while the Elliot material was classified as A-1-a and poorly-graded gravel with silt and sand.

The data collected in this research indicate that, for the two known NFS materials included in this study, the TST is a good indicator of frost heave behavior. The total heave of the untreated materials was approximately 0.15 in. at the conclusion of the 10-day freezing period, which classifies these materials as NFS according to the U.S Army Corps of Engineers. The Dalton and Elliott materials both had final dielectric values less than 10, indicating a superior moisture susceptibility rating.

Previous research performed on frost-susceptible Montana silt indicates that the addition of small amounts of cement, corresponding to a 7-day UCS of 200 psi, actually increased the amount of heave that occurred compared to the untreated material. However, addition of small amounts of cement to the NFS materials evaluated in this research did not increase the amount of heave exhibited in the material but actually eliminated the small amount of heave experienced. The minimum amount of cement observed in this research to eliminate heave corresponds to a 7-day UCS of 200 psi. Similar to the results of the tests on Montana silt, the addition of cement beyond the level required to prevent frost heave did not offer significant benefit.

The results of the ANOVA indicate that the amount of cement added to the material has a significant effect on UCS but is insignificant with respect to final dielectric value. Similarly, results from the ANOVA indicate no significance in cement content with respect to heave for the Dalton material. However, due to the marked difference between the untreated specimens of Elliott material and those treated with 1 percent cement, the effect of cement content on total heave was statistically significant.

5.3 RECOMMENDATIONS

The results of this research suggest that the TST should be considered for identifying NFS materials, including those stabilized with cement. Additional testing should be performed on known NFS materials stabilized with cement and other additives to further assess the validity of using the TST to differentiate between frost-susceptible and NFS materials.

Consistent with previous studies, this research indicates that, once a sufficient amount of cement has been added to significantly reduce frost heave, additional cement has only a marginal effect on further reduction. Therefore, to avoid unnecessary expense in construction, the minimum cement content required for preventing frost heave should be identified through laboratory testing and specified by the engineer. In this work, UCS values ranging between 200 psi and 400 psi after a 7-day cure were typically associated with this minimum cement content. Because the scope of this research is limited to two aggregate base materials, further testing is also necessary to validate this finding.

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