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FREEZE-THAW DURABILITY OF PERVIOUS CONCRETE

by

Carson B. DeMille

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil and Environmental Engineering

Brigham Young University

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BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Carson B. DeMille

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

Date	W. Spencer Guthrie, Chair
Date	Mitsuru Saito
Date	A. Woodruff Miller

BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Carson B. DeMille in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

FREEZE-THAW DURABILITY OF PERVIOUS CONCRETE

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Department of Civil and Environmental Engineering

Master of Science

Although the use of pervious concrete is expanding, only a limited number of scholarly papers have been published on the resistance of pervious concrete to deterioration under frost action. Based on this need for additional research on the durability of pervious concrete in cold regions, the objective of this research was to evaluate the resistance of pervious concrete to degradation during freeze-thaw cycling under different soil clogging and water saturation conditions. The laboratory research associated with this project involved three primary measures of pervious concrete performance, including freeze-thaw durability, compressive strength, and permeability. Testing associated with freeze-thaw durability involved two levels of soil clogging, two water saturation conditions, and two curing durations in a full-factorial experimental design. Field testing involved measurements of stiffness, permeability, and compressive strength at a single site in Orem, Utah.

The factor of water saturation and the interaction between the factors of curing condition and clogging condition played significant roles in testing throughout the entire course of freeze-thaw testing. Regarding the factor of water saturation, specimens that were completely submerged in water during freeze-thaw testing were damaged at a notably faster rate than those specimens that were tested in a moist but unsaturated condition for both curing conditions. Regarding the interaction between the factors of curing condition and clogging condition, the effect of clogging on the number of freeze-thaw cycles to failure depended upon the curing condition.

A comparison of in situ modulus values, core modulus values, and core compressive strengths associated with clogged locations and unclogged locations in the field indicated no significant differences in structural properties in the clogged and unclogged locations.

Although the results of this research suggest that pervious concrete similar to that evaluated in this study can be successfully used in cold regions under essentially ideal conditions, further laboratory and field research should be performed to more carefully examine the effect of moisture content on the freeze-thaw durability of moist but unsaturated specimens. Also, given that clogging can reduce the freeze-thaw durability of pervious concrete, the efficacy of maintenance procedures available for cleaning partially clogged pervious concrete slabs should be investigated. Long-term monitoring of and supplementary experimentation on the pervious concrete slab tested in this research should be considered for these purposes. More conclusive data about the performance of pervious concrete in cold regions will be derived from such field tests.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Proper drainage is considered to be one of the most important elements affecting the performance and longevity of pavement structures (*1*). The detrimental effects of water are especially pronounced when pavement structures experience sustained exposure to high levels of water saturation. Water can strip asphalt cement from aggregates in flexible pavements and can also cause durability and map cracking in concrete (*2*). If a roadway or parking lot is not properly graded, water can pond in low spots and create safety hazards such as glare, hydroplaning, and spraying (*3*). Pavement surfaces can also pollute water and cause excess runoff from the site (*3, 4*).

In an effort to reduce the detrimental effects of water on pavements and minimize impacts on the environment, porous pavements were developed. Currently, two commonly used types of porous pavements exist. These include porous asphalt and pervious concrete. Porous asphalt consists of coarse aggregate bound together by asphalt cement, creating interconnected voids throughout the pavement structure. Pervious concrete is defined as a specially formulated mixture of uniform, open-graded coarse aggregate, portland cement, and water. Porous pavements have sufficient interconnectivity among void spaces to allow significant amounts of water to flow through them (*5, 6*). Concerns with asphalt maintenance and how slurry seals may affect porous asphalt have deterred pavement managers in some cities, such as Portland, Oregon, from using porous asphalt; on the other hand, the use of pervious concrete nationwide continues to increase (*7*). The following list gives several applications in which pervious concrete can be used (*3*):

- Low-volume pavements
- Residential roads, alleys, and driveways
- Sidewalks and pathways
- Parking lots
- Low-water crossings
- Tennis courts
- Subbase for conventional concrete pavements
- Patios
- Artificial reefs
- Slope stabilization
- Well linings
- Tree grates in sidewalks
- Foundations and floors for greenhouses, fish hatcheries, aquatic amusement centers, and zoos
- Hydraulic structures
- Swimming pool decks
- Pavement edge drains
- Groins and seawalls
- Noise barriers
- Walls (including load-bearing)

Pervious concrete has become more popular in recent times due to enforcement of increasingly stringent environmental and storm water regulations. The use of pervious concrete is considered a Best Management Practice by the Environmental Protection Agency for the management of storm water runoff (*3, 6*). When used in roadway and parking lot construction, pervious concrete is an attractive material because it reduces runoff, cleans storm water, replenishes aquifers, conserves water, protects streams, and reduces traffic noise (*3, 4, 7, 8, 9, 10*). Pervious concrete is also more attractive than porous asphalt because the former does not require regular maintenance as does the latter (*7*).

Although the use of pervious concrete is expanding for these reasons, only a limited number of scholarly papers have been published on the properties of this product. One topic that especially warrants additional research is the resistance of pervious concrete to deterioration under frost action; use of pervious concrete in cold regions has been limited because of concerns of possible freeze-thaw damage (*5*, *11*). Although research has been conducted to develop a pervious concrete that will withstand freeze-thaw deterioration (*11*), most of this research has been performed primarily on specimens that were completely submerged in water during testing, which does not represent the expected drained condition of pervious concrete in the field. Furthermore, degradation of these specimens was determined solely by mass loss.

The literature does contain a publication describing freeze-thaw testing of pervious concrete in a non-submerged condition (*12*), but those tests were conducted over just 25 freeze-thaw cycles and not according to American Society for Testing and Materials (ASTM) C 666 (Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing) methods. Degradation of these specimens that were tested in a non-submerged condition was determined by mass loss and strength loss (*12*). Furthermore, although research has been conducted on the effects of sand clogging on the permeability of pervious concrete (*13*), effects of clogging have not been previously investigated in conjunction with freeze-thaw testing (*3, 8, 11*, *14*).

Based on this need for additional research on the durability of pervious concrete in cold regions, the objective of this research was to evaluate the resistance of pervious concrete to degradation during freeze-thaw cycling under different clogging and saturation conditions. The data developed in this research will assist members of the pavement industry in understanding the effects of these factors on freeze-thaw durability of pervious concrete and in specifying its use in cold climates. Because of the increasing popularity of pervious concrete, research on this topic is both timely and crucial as projects in northern climates are anticipated.

1.2 SCOPE

The laboratory research associated with this project involved three primary measures of pervious concrete performance, including freeze-thaw durability, compressive strength, and permeability. All testing was performed using one pervious concrete mix design provided by Geneva Rock of Orem, Utah. Testing associated with freeze-thaw durability involved two levels of soil clogging, two water saturation conditions, and two curing durations in a full-factorial experimental design. Four replicate samples were cast for each unique combination by four separate operators, yielding a total of 32 test specimens. Freeze-thaw testing was conducted according to ASTM C 666 Method A.

For laboratory compressive strength and permeability testing, cylindrical specimens each having a 4-in. diameter and an 8-in. length were evaluated. Compressive strength testing involved three different curing durations of 7, 28, and 90 days. Four replicate samples were cast for testing at each curing time by four separate operators for a total of 12 test specimens. For permeability testing, four cylinders were cast by four separate operators, for a total of four cylinders, and then cured for 90 days. Specimens used for compressive strength and permeability testing were cast and cured according to

ASTM C 192 (Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory). Compressive strength was measured according to ASTM C 39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens), and a constant-head apparatus was utilized for laboratory permeability testing.

Field testing involved measurements of stiffness, permeability, and compressive strength at a single site in Orem, Utah. Stiffness was assessed using a portable falling-weight deflectometer (PFWD). Permeability testing was performed using a falling-head permeability setup, and compressive strength testing was performed on 4-in.-diameter cores removed from the field.

1.3 OUTLINE OF REPORT

This report contains five chapters. Chapter 1 presents the objectives and scope of the research. Chapter 2 addresses the results of a literature review focused on pervious concrete placement procedures, explanations of freeze-thaw damage mechanisms, and descriptions of non-destructive testing methods available for assessing the progression of freeze-thaw damage. Descriptions of the experimental plan, laboratory and field testing procedures, and data analyses are given in Chapter 3. Test results are explained in Chapter 4 together with a discussion of the research findings. In Chapter 5, summaries of the procedures, research findings, and recommendations are presented.

CHAPTER 2

BACKGROUND

2.1 OVERVIEW

The following sections present the findings of the literature review conducted in this research, including pervious concrete placement procedures, explanations of freeze-thaw damage mechanisms, and descriptions of non-destructive testing methods available for assessing the progression of freeze-thaw damage.

2.2 PERVIOUS CONCRETE PLACEMENT

Pervious concrete requires the use of special placement procedures in order to provide expected performance characteristics. Furthermore, slopes should be relatively flat in order to prevent runoff from exiting the pavement structure at a lower point in the pavement. If slopes are greater than 1 percent, impervious barriers must be placed in the subbase material beneath the pavement to stop the flow of water downhill (*6, 9*). The pervious concrete must also be placed over a permeable subgrade or subbase. The subbase thickness should be designed to facilitate storage of enough water after a rain event to prevent runoff, or at least to reduce runoff to acceptable amounts. Pervious concrete is placed in forms similar to conventional concrete and is consolidated using a full-width roller screed to obtain the desired voids content. Depending on the weight of the roller used, more than one pass may be necessary. Joints are then placed using a joint roller (*6*, *9*). Immediately after placement of the pervious concrete, plastic is used to cover the pervious concrete to prevent evaporation of water. Further consolidation of the pervious concrete can be completed by using rollers on top of the plastic cover. Typical steel rollers used for consolidation and jointing of the concrete are illustrated in Figures 2.1 and 2.2, respectively; these photographs were taken during placement of an experimental test slab in Orem, Utah, at the Western Star Construction facility. This pervious concrete slab was later tested as part of this research effort.

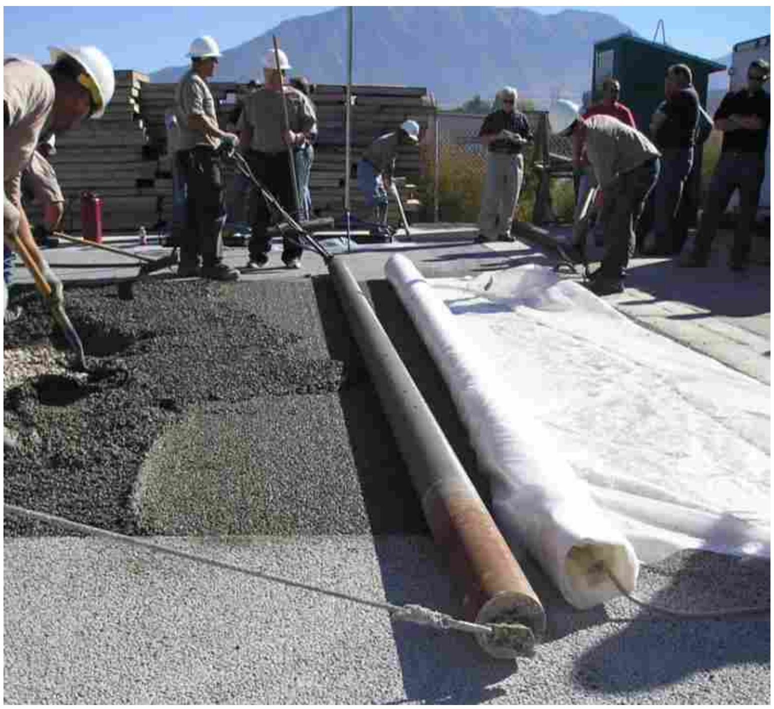

FIGURE 2.1 Steel roller used for consolidation.

FIGURE 2.2 Joint roller used for jointing.

2.3 FREEZE-THAW DAMAGE

A major concern for pervious concrete performance in cold regions is its freeze-thaw durability. Pervious concrete is designed with interconnected pores capable of storing and transmitting water. Although a 5-in.-thick slab of pervious concrete is capable of storing up to an inch of water within its matrix when saturated (*14*), the presence of water exacerbates durability problems.

Three mechanisms of freeze-thaw deterioration can occur within concrete. The first mechanism is hydraulic pressure. As water freezes in large pores or microcracks, it expands by 9 percent (*15*). This pressure expands the cracks and pores and causes eventual deterioration of the concrete.

The second and third mechanisms of freeze-thaw deterioration occur within the microstructure of the concrete, or within the cement paste, as a result of osmotic and vapor pressures. In the second mechanism, as ice begins to form within the concrete, the concentration of solutes in the surrounding supercooled water increases. Because higher solute concentrations increasingly depress the freezing point of water, some amount of liquid water remains in the concrete even at very low temperatures (*16*). Although solutes diffuse in this situation from areas of high concentration to areas of low concentration to achieve equilibrium, water also moves from areas of low concentration to areas of high concentration as a physical response to the osmotic pressure associated with the solute imbalance (*16*). While the incoming water dilutes the solute, it also causes great pore water pressure that can damage the concrete.

Differential vapor pressure is considered the third mechanism of microstructure damage in concrete. Since frozen water has a lower chemical potential than supercooled water, it has a lower vapor pressure. Movement of liquid water towards the freezing site occurs in an attempt to equalize the vapor pressure within the concrete. This movement of water to equilibrate vapor pressure causes damage to the concrete in the same way that osmotic pressure causes damage (*15*).

When properly designed and placed, conventional concrete is practically impervious to external water; therefore, freeze-thaw damage generally occurs from water already within the structure of the concrete material. Although early researchers believed that hydraulic pressure was the main cause of freeze-thaw damage in conventional concrete, later studies demonstrated that the major mechanisms of freeze-thaw damage are those associated with osmotic and vapor pressures (*2*). In an effort to avoid freeze-thaw damage induced by these effects, researchers developed a technique of entraining microscopic air bubbles into concrete. In air-entrained concrete, positive pore water pressures are diminished as moving water is released into these small voids, thus allowing osmosis and/or vapor pressure equilibration to occur while avoiding damage to the concrete (*15*).

Unlike conventional concrete, pervious concrete allows large amounts of water to penetrate its structure, so the possibility exists for the development of immense hydraulic pressures upon freezing. Therefore, since water expands 9 percent in volume upon freezing, the freeze-thaw durability of pervious concrete greatly depends upon the degree of water saturation to which the concrete is subjected. Unlike conventional concrete, pervious concrete should never experience complete saturation; if designed and maintained properly, it should always be drained (*3*, *17*). Nevertheless, the addition of air entrainment has been shown to reduce freeze-thaw damage in pervious concrete in the same manner as conventional concrete (*11*, *17*).

Due to the comparatively large pore sizes characteristic of pervious concrete, soil and debris particles can penetrate the pore structure, clogging the concrete. Typical pervious concrete usually has a porosity of 15 to 30 percent, allowing water to flow through it at rates from 28 in./hr to over 1,400 in./hr (*3*, *18*). However, clogging can greatly reduce the hydraulic conductivity of pervious concrete, even causing the concrete to become impermeable. One study showed that pervious concrete that has been clogged by sand actually exhibits a lower hydraulic conductivity than the sand by which it is clogged, causing the hydraulic conductivity of the pervious concrete to be reduced dramatically (*13*).

Not only does soil clog pervious concrete, restricting the flow of water, but it also retains moisture. A soil mass consists of soil particles and voids, and these voids can be filled with air, water, or a combination of both (19, *20*). Saturated soil particles trapped within the structure of the pervious concrete can greatly affect the level of saturation that the pervious concrete attains. Soils that are saturated with water can experience volumetric expansion of around 2 to 3 percent under freezing conditions (*21*). This expansion can lead to deterioration of the pervious concrete structure as previously explained. Furthermore, soil may also trap water and prevent it from freely draining through the pervious concrete structure. This excess moisture can also cause damage to the pervious concrete when exposed to freezing.

Other factors that greatly affect the freeze-thaw durability of concrete are the rate and temperature at which the pervious concrete is frozen. The standard test method used for concrete freeze-thaw testing is ASTM C 666. Method A in that standard specifies that all specimens be completely saturated during freezing and thawing and that the freeze-thaw cycles occur during a 2- to 5-hour interval, thus allowing up to 12 cycles within a 24-hour period. Method B of the standard specifies that all specimens be frozen in an unsaturated condition and then thawed completely saturated in a water bath. Although these test methods are suitable for certain types of frost exposure, they are considered to be extreme testing conditions for most applications. Research suggests that these tests are useful primarily for comparing the performance of different concrete mixes to one another and do not necessarily predict performance in the field (*22*). Nonetheless, according to the standard, a concrete mix that retains 60 percent of its original dynamic modulus after testing should be adequate for in-field use (*22*).

Studies have shown that the ASTM C 666 method of rapid freeze-thaw testing is much more destructive than slower rates of freeze-thaw testing. Rapid freezing rates lead to greater internal hydraulic pressure (*23*). Pervious concrete specimens subjected to rapid freeze-thaw testing have been shown in previous research to have relative dynamic moduli of less than about 40 percent after only 80 cycles of testing. Conversely, similar specimens tested at slower rates were shown to have relative dynamic moduli of nearly 95 percent after the same number of freeze-thaw cycles (*17*).

2.4 FREEZE-THAW TESTING

Conventional and pervious concrete specimens that are subjected to freeze-thaw testing are regularly tested for transverse and longitudinal frequency following ASTM C 666. The transverse frequency is measured non-destructively by placing a concrete specimen on a support that allows vibration to occur freely and then striking the specimen with a hammer at a right angle to the surface at the center of one of the long sides of the specimen. An accelerometer is placed on the same side of the specimen where the strike occurs and is located next to one end of the specimen. The longitudinal frequency is measured in the same manner, except the strike occurs at one of the specimen end faces and the accelerometer is placed at the center of the opposite end of the specimen. These procedures are executed according to ASTM C 215 (Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens). Figures 2.3 and 2.4 illustrate these two testing configurations.

The purpose of frequency testing is to detect significant changes to specimens during freeze-thaw testing that weighing or visual observation may not detect.

FIGURE 2.3 Longitudinal frequency testing setup.

FIGURE 2.4 Transverse frequency testing setup.

Compression waves generated by the strike of a hammer travel at varying velocities through different materials. Table 2.1 shows typical velocities of waves traveling through various materials. Table 2.1 shows that waves travel much slower through air and water than through rock. Because lower wave velocities correspond to lower frequencies, pervious concrete, being full of voids, will exhibit lower resonant frequencies than conventional concrete. As freeze-thaw testing of either pervious or conventional concrete takes place, damage manifest as microcracks occurs within the concrete. Once these discontinuities and voids are introduced, measured frequencies immediately decrease. Research has shown that density, porosity, fracturing, fluid content, and composition of the rock material all affect the velocities of the compression

TABLE 2.1 Compression Wave Velocities (*24*)

Material	Compressional Wave Velocity (ft/s)
Air	1,080
Water	4,590 - 4,920
Ice	9,840 - 13,120
Water-Saturated Sand	3,940 - 6,230
Clay	3,610 - 8,200
Limestones and Dolomites	11,160 - 19,690

waves materials sustain (*24*). Thus, in addition to freeze-thaw damage and water saturation, clogging would also be expected to affect the resonant frequency measurements.

From the transverse and longitudinal frequencies, both the transverse and longitudinal dynamic moduli of each specimen can be calculated. The initial dynamic modulus of elasticity is calculated before freeze-thaw testing occurs. Later measurements of resonant frequency performed at regular intervals throughout testing are then used to calculate and monitor changes in dynamic modulus. These dynamic moduli are then each divided by the initial dynamic modulus to determine the percentage of the original dynamic modulus retained after each set of freeze-thaw cycles. According to ASTM C 666, testing of a specimen should continue until the transverse dynamic modulus of the specimen falls below 60 percent of the initial transverse dynamic modulus or until the specimen reaches 300 freeze-thaw cycles. If the transverse dynamic modulus of the specimen falls below 60 percent of the initial transverse dynamic modulus before 300 cycles are completed, the specimen fails the test.

Although monitoring dynamic modulus values is the recommended method of evaluating the freeze-thaw durability of concrete specimens in ASTM C 666, some past freeze-thaw research performed on pervious concrete was performed without frequency testing (*11, 12*). In that study, the assumption was made that frequency readings were ambiguous when conducted on pervious concrete. Accordingly, specimen failure was assumed to occur once the specimen weight loss reached 15 percent of its initial weight (*11*). However, other research has shown that the use of frequency measurements is an effective method for calculating the dynamic modulus of pervious concrete specimens; in the latter case, the collected data were effectively used to monitor the degradation of non-clogged, completely saturated pervious concrete specimens during freeze-thaw testing (*17*).

2.5 SUMMARY

In order to provide functional pervious concrete pavement, engineers have developed proper placement procedures and investigated some aspects of pervious concrete durability. The basic mechanisms of freeze-thaw deterioration are more accentuated in pervious concrete, due to its higher porosity, than in conventional concrete, highlighting the need for research on this topic. Although researchers have analyzed the drainage characteristics of pervious concrete under different clogging conditions and performed limited freeze-thaw durability studies, research on the effects of soil clogging and water saturation on the freeze-thaw durability of pervious concrete have not been conducted. Because of its probable sensitivity to these factors, ASTM C 666 seems to be a promising technique for evaluating the progression of deterioration of pervious concrete specimens subjected to freeze-thaw cycling and is the basis for the current research.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 OVERVIEW

This chapter discusses the pervious concrete mix design utilized for this research, explains the laboratory and field testing, and presents the data analyses. In this research, pervious concrete beams were evaluated in a full-factorial laboratory experiment involving two different levels of soil clogging and water saturation. The resulting four combinations, or sets, were tested in the following conditions:

- Set 1: Unclogged, soaked, and completely submerged in water
- Set 2: Clogged, soaked, and completely submerged in water
- Set 3: Unclogged, soaked, drained, and sealed
- Set 4: Clogged, soaked, drained, and sealed

Four replicate specimens were prepared by four different operators for each set for each of two phases of freeze-thaw testing. Thus, a total of 32 beam specimens were evaluated. The first phase was associated with a 28-day cure, while the second phase was associated with a 90-day cure. Sixteen cylinders were also prepared for compressive strength and permeability testing, again consisting of four replicates prepared by each of four different operators.

Field testing consisted of several tests conducted to assess the durability of an experimental pervious concrete slab, including in situ modulus measurements using a PFWD, permeability assessments on clogged and unclogged areas using a falling-head permeameter, modulus measurements of 4-in.-diameter cores removed from clogged and unclogged portions of the concrete, and compressive strength evaluations of the cores.

3.2 MIX DESIGN

So that the data collected in this research would be pertinent to the local area, the pervious concrete mix used in both laboratory and field testing was provided by Geneva Rock, a local concrete producer. The mix, which was designed by Geneva Rock personnel, is detailed in Table 3.1, in which the weight of the aggregate is given as the saturated-surface-dry (SSD) weight. The particle-size distribution of the pea gravel specified in the mix is given in Table 3.2 and displayed graphically in Figure 3.1. The fineness modulus of the pea gravel mixture is 5.82. A total of 2 yd^3 of pervious concrete was delivered to the BYU Highway Materials Laboratory in a mixer truck supplied by Geneva Rock.

TABLE 3.1 Pervious Concrete Mix Design

Ingredient	Design Weight Per Cubic Yard (lb)	Design Volume Per Cubic Yard (yd^3)	Design Weight Per Batch (lb)	Measured-Out Weight Per Batch (lb)
Cement, ASTM C 150	495	0.19	990	978
Fly Ash, ASTM C 618 Type F	120	0.06	240	244
Size No. 4 Pea Gravel, ASTM C 33 (SSD)	2660	1.24	5320	5326
Water	150.15	0.2	300.3	283.6
Total Air (%)	15 +/- 2.5	0.3	30 +/- 5.0	NA
Low Range Water Reducer	10 oz	NA	20 oz	20 oz
Air Entrainment (Daravair 1000)	6 oz	NA	12 oz	12 oz
Total	3425.1	2.0	6850.3	6831.6

TABLE 3.2 Particle-Size Distribution of Pea Gravel

Sieve Size	Percent Passing (%)
3/4 in.	100
1/2 in.	99.9
3/8 in.	95.8
No. 4	16.5
No. 8	1.6
No. 16	1.3
No. 50	1.1
No. 200	0.7

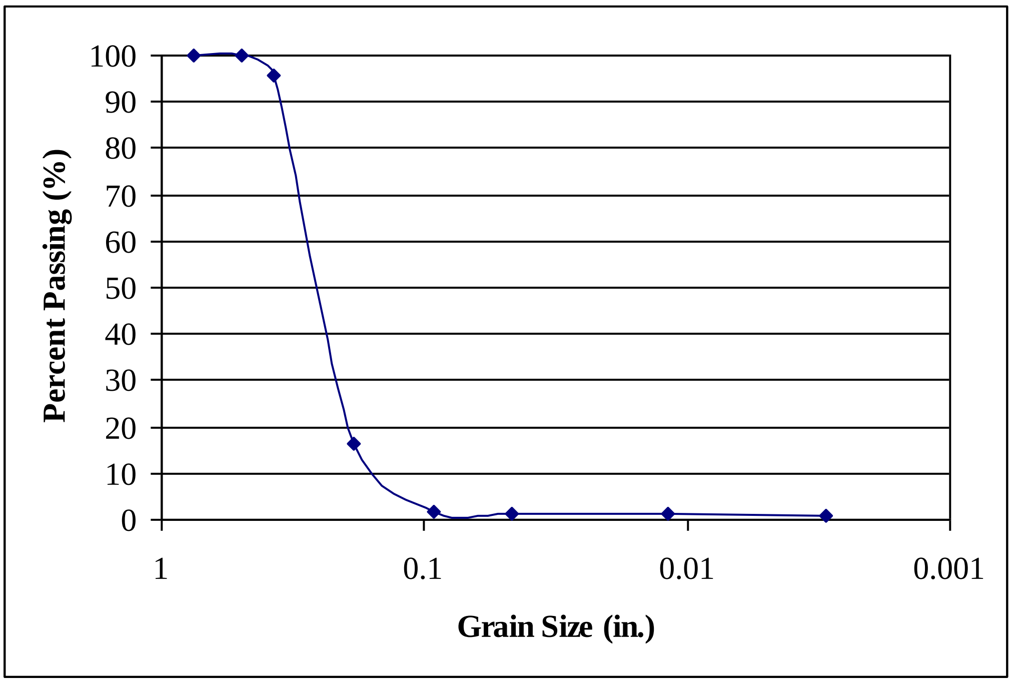

FIGURE 3.1 Particle-size distribution curve for pea gravel.

3.3 LABORATORY TESTING

Upon arrival of the concrete at the laboratory, a slump test was performed following ASTM C 143 (Test Method for Slump of Hydraulic Cement Concrete). Three pervious concrete specimens were then consolidated in two lifts in a pre-weighed beam mold, with each lift being rodded with a 3/8-in.-diameter rod 45 times according to ASTM C 192 standards. Figure 3.2 shows the beam mold used for casting of the concrete; each of the three beams was 3 in. by 3 in. by 15 in. in size.

To simulate the use of a roller screed in the field, the surfaces of the beams were finished with a 1.5-in.-diameter steel pipe that was pulled toward the operator while being manually rotated in the opposite direction. A magnesium trowel was also used to smooth the surfaces of the beam specimens as needed. After the beams were cast, the mold and concrete were then weighed in order to calculate the average density of the specimens. Once the density of the beam specimens was known, another operator cast concrete into a pre-weighed cylinder mold in two lifts, with each lift being rodded with a 3/8-in.-diameter rod 25 times per lift according to ASTM C 192 standards. The cylinder

FIGURE 3.2 Mold for preparing laboratory beam specimens.

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was 4 in. in diameter and 8 in. in height. The cylinder surface was then finished in the same manner as the surfaces of the beams, the cylinder was weighed, and the density was calculated for comparison with the density of the beam specimens. The reason for calculating the densities of the two specimens was to ensure that the ASTM standards for sample placement would produce beam and cylinder specimens of pervious concrete with similar densities.

The densities of the cylinders and the beams were shown to be satisfactorily similar, not different by more than about 2 pcf, so each operator then prepared nine additional beams and four additional cylinders following the same ASTM protocols. All of the molds were oiled prior to being filled with concrete to ensure ease of removal. Each operator also placed a single thermocouple wire in the center of one of the nine beams he prepared so that four beam specimens were instrumented in total; in each case, the tip of the thermocouple wire was inserted through the top surface of the beam and then situated at a depth of 1.5 in. Beams with thermocouple wires were later used as temperature calibration and control specimens during freeze-thaw testing.

After the concrete was placed, the beams and cylinders were covered with plastic and allowed to cure in place for 24 hours. After 24 hours, the beams and cylinders were removed from their molds and labeled using a permanent marker. Specimens were then placed in a fog room for curing according to ASTM C 192 standards.

Following the specified curing period of 28 or 90 days, each beam specimen was removed from the fog room, and a small steel nut was affixed to the center of one end of each beam using epoxy. Another steel nut was then glued about 0.5 in. from the end at the center of one side. These steel nuts were used as attachment points for the magnetically-mounted accelerometer used for transverse and longitudinal testing during freeze-thaw cycling. Figure 3.3 shows the arrangement of these steel nuts on the specimens. Specimens were then dried in an oven at 104°F and weighed to determine the dry density.

The freezer used in testing required a control beam specimen that accommodated insertion of two temperature probes, one in the center of each end of the specimen. Data from one probe were used by the freezer controller to monitor temperature change and initiate heating or cooling at the desired temperature. Data from the other probe were used to record the number of completed freeze-thaw cycles on a circular strip chart. Visual inspection of this chart allowed quick determination of the number of cycles that the freezer had completed at any given time. Since all of the beam molds available in the laboratory were needed for casting of actual freeze-thaw specimens, a second batch of

FIGURE 3.3 Steel nut configurations on laboratory beam specimen.

pervious concrete was prepared to fabricate the additional specimens needed for freezer control. The second batch of concrete was proportioned identically to the first batch but was mixed in the laboratory rather than at a batch plant. Two oiled steel pipes of different diameters were placed in the center of each end of the specimens cast from the second batch of concrete to create two cavities in which the temperature probes could be inserted during testing. In total, six additional beams were cast for testing purposes, and curing was again conducted according to ASTM C 192 standards.

For the first phase of testing, which was associated with a 28-day curing period, four beam specimens were randomly chosen from among those prepared by each of the four operators, for a total of 16 beams. Two additional specimens were also chosen at random to act as temperature control and data collection specimens. One of the two specimens was chosen from the additional beams that were cast to accommodate the probes used by the freezer and the circular strip chart. The other control specimen was chosen from among the four beams that contained embedded thermocouple wires. Unlike the control specimen first mentioned, this control specimen was rotated throughout the freezer during freeze-thaw testing to facilitate monitoring of freezer temperatures. From the 16 beam samples selected for testing, two sets of four specimens each were selected for clogging with soil. To ensure consistency between laboratory and field conditions, clogging was performed using soil collected from the north entrance to the Western Star Construction yard, east of the pervious concrete slab placed earlier at that location; this soil is often carried onto the pervious concrete slab by trucks entering the yard.

For the purpose of characterizing the soil, a washed sieve analysis was conducted on approximately 5.5 lb of soil according to ASTM D 422 (Standard Test Method for Particle-Size Analysis of Soils), Atterberg limits testing was performed according to ASTM D 4318 (Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils), and the Unified soil classifications, and American Association of State Highway and Transportation Officials (AASHTO) were determined following ASTM D 2487 (Standard Practice for Classification of Soils for Engineering Purposes) and AASHTO M 145 (Standard Specifications for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes) respectively. Following classification, the soil sample was separated over a No. 50 sieve, and the fraction that passed the sieve was used for soil clogging in preparation for freeze-thaw testing. The reason for separating the soil over the No. 50 sieve was to ensure that the soil particles would be small enough to enter the void structure of the pervious concrete specimens.

Through experimentation on an extra beam specimen prepared from the first batch of pervious concrete, researchers determined that a maximum of approximately 0.5 lb of soil finer than the No. 50 sieve could be washed into a given specimen. Therefore, this amount of soil was weighed out for each specimen to be clogged, and each soil mass was divided into thirds. The first third was washed into one side of the given specimen with a squirt bottle, and the specimen was then oven-dried at 140°F until all visible surface moisture had evaporated and the soil would remain in place during specimen handling. The second third was then washed into the opposite side of the specimen, and the specimen was again dried. The final third was washed into the top of the specimen. Based on a computed porosity of 21.7 percent for the pervious concrete and an assumed soil specific gravity of 2.65, this level of soil loading corresponds to a condition of about 20 percent clogged; that is, about 20 percent of the entire pore volume of the pervious concrete was filled with soil particles. Thorough washing of the final third into the specimen produced a very wet condition throughout the specimen, and, as a result, the soil was assumed to be essentially saturated in this state. In total, eight specimens were clogged in this manner for freeze-thaw testing.

After being clogged, one of the two specimens prepared by each operator was then allowed to momentarily drain to release all free water, and then the specimen was sealed in plastic wrap so that no further moisture loss could occur during testing. The remaining four clogged specimens were completely submerged in water inside the testing containers.

The other two sets of beams that were not clogged were also submerged in water in order to completely saturate the concrete before testing. One set was then removed from the water and allowed to drain; these four specimens were then sealed in plastic wrap to retain all moisture during testing. The other four specimens were completely submerged in water inside the testing containers for the duration of the testing.

The second phase of freeze-thaw testing commenced at the 90-day cure time, by which point the first phase of testing was completed. This second phase was carried out in a similar manner as the first phase, with the only difference being the cure time. Performing the second phase of testing allowed observation of the effects of a longer curing duration time on freeze-thaw durability of the pervious concrete specimens.

Before testing of the pervious concrete began, the freezer was instrumented with 12 thermocouple wires in order to investigate the uniformity of temperature distribution throughout the freezer. The first five thermocouple wires were distributed evenly across the freezer beneath the center of the beam containers. The next five wires were placed above the same specimen containers and were suspended in air. The remaining two wires were cast in the center of two beam specimens. The two beam specimens were placed at opposite ends of the freezer. One specimen was saturated in water prior to testing, but not submerged during testing, while the other specimen was saturated and submerged in water during testing. The remaining containers were each filled half-way with water during this preliminary evaluation of the spatial variability of temperature within the freezer. The freezer was then allowed to engage in freeze-thaw cycling, and the temperatures across the freezer were monitored. Temperatures measured using the thermocouple wires located beneath the beam containers were found to be uniform and complied with ASTM standards. However, temperature readings recorded from thermocouple wires embedded in the specimens did show variations in temperature because of the different saturation conditions. In preparation for actual testing, adjustments to the freezer controls were performed based on the collected temperature data.

After this preliminary freezer evaluation, the first phase of freeze-thaw testing began at the 28-day cure time, as mentioned previously. A total of four sets of four beams each were situated in the freezer together with two control specimens, one with a thermocouple wire inserted into the center and one with the two probes inserted into either end, for a total of 18 beams. Sets 1 and 2, as defined earlier in this chapter, were tested according to ASTM C 666 Method A, with the exception that set 2 was clogged, through 300 cycles or until tests could not be performed due to specimen degradation.

Sets 3 and 4, also as defined earlier in this chapter, were tested in a similar manner, with the exception that the specimens were not submerged and that set 4 was clogged. These sets were not submerged to simulate the expected condition of porous concrete in the field. While conventional concrete is often designed to be completely submerged, pervious concrete should always be well drained, providing a reasonable justification for this departure from ASTM C 666 standard protocols. This condition also allows for a more realistic analysis of the effects of clogging on freeze-thaw durability.

During freeze-thaw testing, both control specimens were replaced once throughout the duration of each phase of testing to ensure that the temperature probes gave temperature readings representative of the interior conditions of the tested specimens at all times. Progressive rubblization of the control specimens might otherwise have led to skewed temperature readings.

After every 20 freeze-thaw cycles, the freezer was shut off during the thawing mode, and each specimen was removed, photographed, weighed, and tested for longitudinal and transverse frequency. Specimens wrapped with plastic were tested for longitudinal and transverse frequencies with the plastic wrap intact. After testing, the specimens were then repositioned in the freezer according to a pre-determined rotation schedule shown in Figure 3.4. In addition to being rotated, specimens were turned end-for-end in the freezer in accordance with ASTM C666 protocols. Each specimen was tested following this pattern until advanced degradation prevented testing or until the sample underwent 300 cycles. The longitudinal and transverse frequencies were utilized to compute the dynamic modulus of each beam at each testing time using Equations 3.1 and 3.2, which are shown in metric units as they appear in ASTM C 215:

$$E = C \cdot M \cdot n^2 \tag{3.1}$$

where E = transverse elastic modulus, Pa

$C = 0.9464\left(\dfrac{L^3 \cdot T}{b \cdot t^3}\right)$, $N \cdot s^2/(kg \cdot m^2)$

L = length of specimen, m

t, b = dimensions of cross section of prism, m, t being in the direction in which it it is driven

T = correction factor that depends on the ratio of the radius of gyration, K, to the length of the specimen, L, and on Poisson's ratio

$K = \left(\dfrac{t}{3.464}\right)$

M = mass of specimen, kg

n = fundamental transverse frequency, Hz

$$E = D \cdot M \cdot (n')^2 \tag{3.2}$$

where E = longitudinal elastic modulus, Pa

$D = 4\left(\dfrac{L}{bt}\right)$, $N \cdot s^2/(kg \cdot m^2)$

L = length of specimen, m

t, b = dimensions of cross section of prism, m, t being in the direction in which it is driven

M = mass of specimen, kg

n' = fundamental longitudinal frequency, Hz

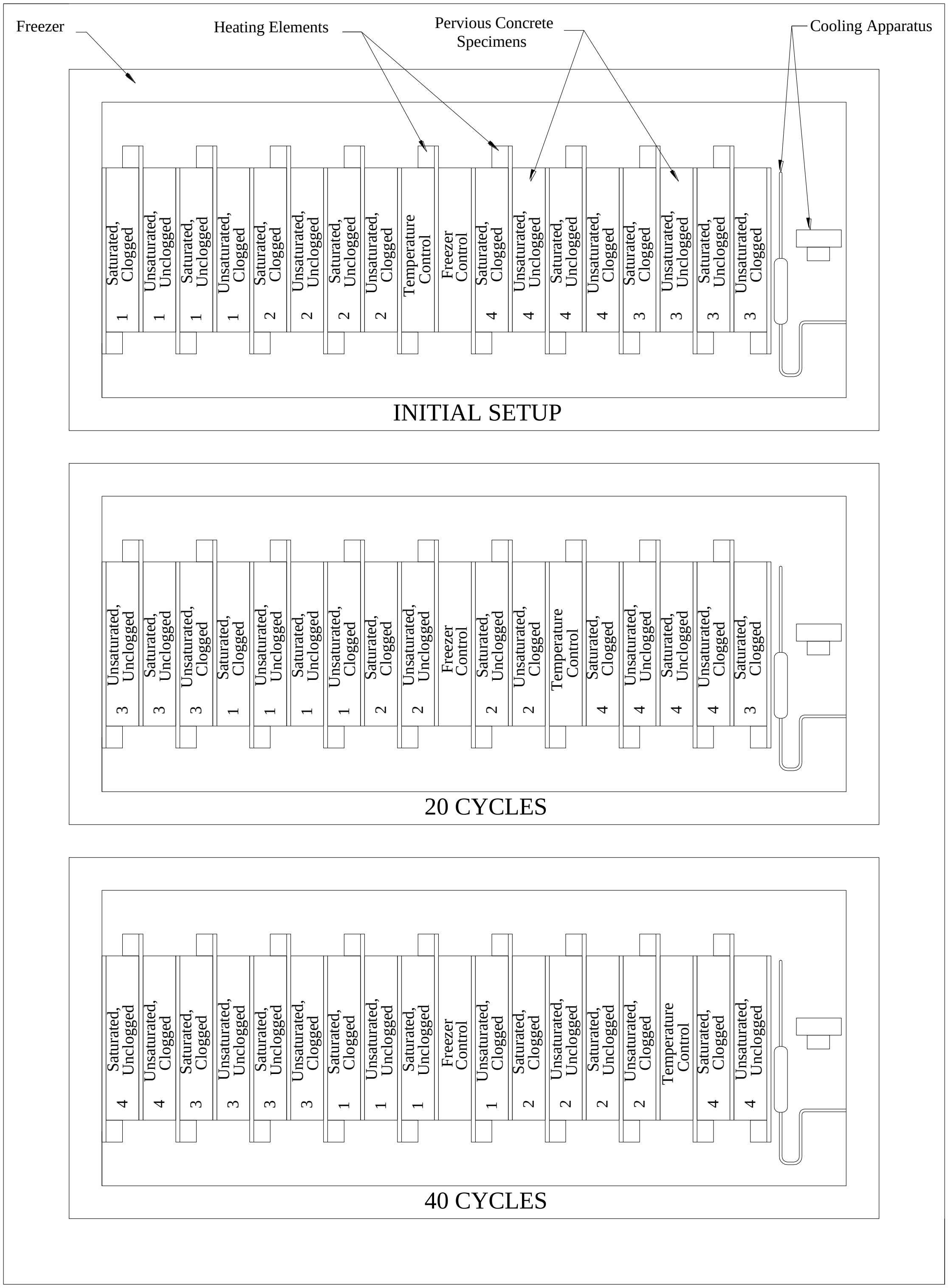

FIGURE 3.4 Specimen rotation schedule for laboratory freeze-thaw testing.

However, in accordance with ASTM C 666 standards, only the dynamic moduli calculated from the transverse frequencies were used to determine whether or not the specimen failed during testing. Longitudinal frequencies were nonetheless included in the statistical analyses performed in this research.

The moisture content of the surviving unsaturated pervious concrete beam specimens was determined by weighing each specimen in its wet condition, carefully removing the plastic wrap, and placing both the wrap and the specimen in an oven to dry. Upon removal from the oven, specimens were again weighed with the plastic wrap, and the moisture content was calculated for each specimen.

Compressive strength and permeability tests were performed on the four sets of cylindrical specimens cast at the same time as the beam specimens. The first set of four cylinders was allowed to cure for 7 days, after which each cylinder was tested for compressive strength according to ASTM C 39. The second and third sets of cylinders were tested in the same manner as the first set except at curing times of 28 and 90 days, respectively. The final set of cylinders was allowed to cure for 90 days in preparation for permeability testing. The top of each specimen was trimmed using a masonry saw to obtain a smooth, uniform surface, while the bottom of each cylinder was also trimmed in order to remove sealed pores caused by placement of the concrete in plastic cylinder molds. Each specimen was then allowed to dry to constant weight on the laboratory bench, after which the weight and height were recorded. Frequency readings were then recorded for each specimen and later used to calculate the specimen modulus values following Equation 3.3:

$$E = \left(\frac{\rho_d \cdot \left(\frac{d}{2} \cdot \frac{L}{12} \cdot n' \right)^2}{\gamma_w \cdot 144 \, \frac{in^2}{ft^2} \cdot 1000 \, \frac{psi}{ksi}} \right) \tag{3.3}$$

where E = longitudinal elastic modulus, ksi

ρ_d = dry density of specimen, pcf

d = diameter of specimen, in.

L = length of specimen, in.

n' = fundamental longitudinal frequency, Hz

γ_w = unit weight of water, pcf

A constant-head permeameter was used to measure the hydraulic conductivity of each specimen as illustrated in Figure 3.5. The apparatus consisted of a 16-in. length of 4-in.-diameter pipe that was connected to a 4-in.-by-2-in. reducer using a rubber sleeve. The remainder of the apparatus was constructed using 2-in.-diameter pipe configured so that the exit end of the pipe would be level with the bottom of a concrete specimen placed inside and flush with the bottom of the 4-in.-diameter pipe section.

Before the cylinders were inserted into the 4-in. pipe section, the sides were first wrapped with three layers of plastic. The plastic was then coated with silicone, and the cylinder was inserted into the pipe using a hydraulic ram. This configuration created a tight fit that was sealed with silicone to ensure that no water was able to pass down the sides of the specimen. Figures 3.6 to 3.9 depict this process.

Each specimen was inserted into separate lengths of pipe that were connected in turn to the permeameter using the rubber sleeve. For testing, each specimen was

FIGURE 3.5 Laboratory permeability testing setup.

FIGURE 3.6 Use of plastic wrap to seal sides of laboratory permeability test specimen.

FIGURE 3.7 Use of silicone for sliding laboratory permeability test specimen into pipe.

immersed in water for a 24-hour period, after which it was attached to the permeameter for testing. The valve at the base of the permeameter was closed to facilitate submersion of the specimen so that any air bubbles in the system could be displaced with water. The constant head was maintained by an external reservoir that kept the depth of water above the specimen constant using a Marriott bottle configuration. Testing was begun by opening the valve and allowing water to flow through the permeameter into a graduated cylinder. The cylinder was allowed to fill to the 100-mL mark to establish a constant flow rate, and then a timer was started. The timer was stopped at the 600-mL mark, and the elapsed time was recorded. This process was completed five times for each specimen, and the average time was used to compute the hydraulic conductivity of each

FIGURE 3.8 Use of hydraulic ram to seat laboratory permeability test specimen into pipe.

FIGURE 3.9 Laboratory permeability test specimen fully inserted into pipe.

specimen. The hydraulic conductivity of each specimen was computed using Equation 3.4 (*19*):

$$k = \frac{Q \cdot L}{A \cdot h \cdot t} \tag{3.4}$$

where k = constant head permeability, in./s

Q = volume of water collected, in.^{3}

A = area of cross section of the soil specimen, in.^{2}

t = duration of water collected, s

h = head, in.

3.4 FIELD TESTING

To supplement the laboratory testing, field testing was conducted on an exterior slab of pervious concrete placed by Geneva Rock at the Western Star Construction facility in Orem, Utah. Placed in October 2005, the slab serves as a driveway and parking area on the east side of the property and is frequently trafficked by trucks loaded with concrete construction equipment. Because the area between the slab and the access road remains unpaved, the trucks track soil from that location onto the pervious concrete. As a result, many places on the pervious concrete slab were clogged at the time of the site visit in June 2007. Figure 3.10 displays the surface condition of the pervious concrete slab at the time it was tested in this research.

The premise of field testing was that reductions in stiffness and strength would likely attend any freeze-thaw damage that may have occurred and that such damage would be more pronounced in clogged areas compared to unclogged areas. Tests selected

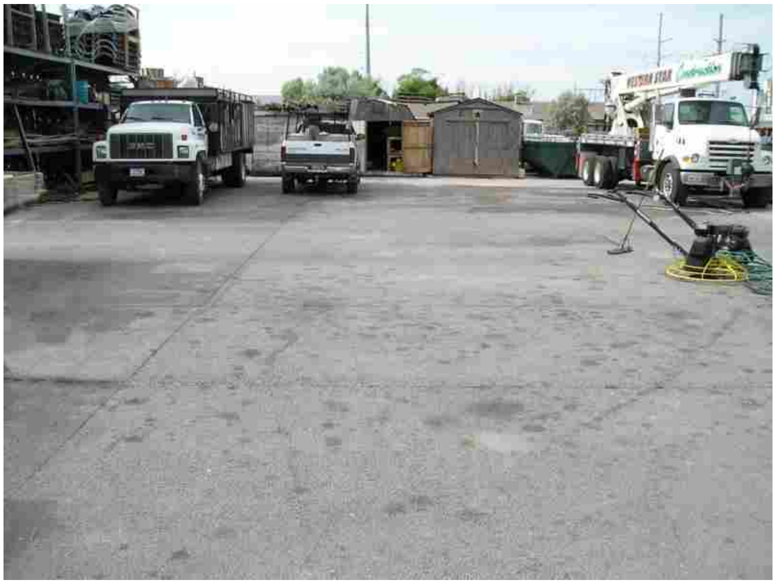

FIGURE 3.10 Pervious concrete test slab in Orem, Utah.

to evaluate the durability of the concrete included in situ modulus measurements using a PFWD, permeability assessments on clogged and unclogged areas using a falling-head permeameter, and compressive strength evaluations of 4-in.-diameter cores removed from clogged and unclogged portions of the concrete. For testing, four clogged and four unclogged locations in the slab were chosen for a total of eight test sites. In order to confirm assumed clogged and unclogged conditions, a water hose was used to flood each location.

At each selected test site, the PFWD was used first to assess the modulus of the concrete. As shown in Figure 3.11, the sensors were spaced 0, 12, and 24 in. from the center of the drop weight and were situated away from any cracks or joints. Set up with a 7.88-in.-diameter load plate, the PFWD weight was then dropped a total of four times on each test site, the first drop being a seating load. The collected PFWD data were analyzed in BAKFAA (*25*), a computer software package, to calculate the in situ

FIGURE 3.11 Field stiffness testing setup.

modulus of the concrete at each location. A two-layer model was used to analyze the data, and the core samples were measured to determine the thickness of the pervious concrete layer at each test location. In BAKFAA, Poisson’s ratios of 0.15 and 0.35 were used for the pervious concrete and subbase/subgrade layers, respectively. The average modulus was calculated for each location by averaging the modulus values determined for the last three drops at each site.

After PFWD testing was completed, permeability testing was performed. As shown in Figure 3.12, the permeameter setup consisted of a 6-in.-diameter stand pipe outside face of the cap to minimize water leakage at the contact between the cap and the concrete surface. For testing, the stand pipe was filled with water and placed directly on the test site. Pressure was applied to the top of the pipe by the operator, and the rubber

FIGURE 3.12 Field permeability testing setup.

stopper was removed by pulling on a wire connected to the rubber stopper inside the stand pipe. The time was then recorded for the water level to drop 6 in within the stand pipe from an initial height of 3.7 ft. Although the apparatus did not allow a true measure of hydraulic conductivity, as the cross-sectional area of the concrete accepting flow could not be determined, the testing did permit relative comparisons of clogged and unclogged areas of the slab.

After permeability testing was completed, one 4-in.-diameter cylinder was removed from each test location using a portable coring rig, shown in Figure 3.13, for a total of eight cores. Following their removal, the cores were returned to the BYU Highway Materials Laboratory, and the ends of each core were trimmed using a masonry

FIGURE 3.13 Field coring setup.

saw to produce a flat surface. The cores were then dried to constant weight in an oven at 104°F. After the length and weight of each trimmed core were measured, the longitudinal frequency and compressive strength were determined as previously described for the cylindrical specimens prepared in the laboratory.

3.5 DATA ANALYSES

The freeze-thaw test results collected every 20 cycles were evaluated using a fixed effects analysis of variance (ANOVA). The null hypothesis of an ANOVA is that the population means of all the treatments are equal. The alternative hypothesis is that at least one population mean is significantly different from the others. The typical Type I error rate of 0.05 was used throughout the analysis. Thus, if the level of significance, or *p*-value, computed in the ANOVA was less than or equal to 0.05, the null hypothesis was rejected, and the alternative hypothesis was accepted. If the *p*-value was greater than 0.05, insufficient evidence existed to reject the null hypothesis.

The response variables associated with this research included fundamental transverse and longitudinal frequencies and freeze-thaw cycles to failure. Factors in the ANOVA included concrete curing time, soil clogging condition, water saturation condition, and concrete density. Because replicate laboratory specimens were consistently prepared by the same operators, the effect of operator could also be evaluated; Tukey's mean separation procedure was utilized for this purpose.

Freeze-thaw test results were also evaluated using the LIFEREG procedure. This procedure fits parametric models to failure time data. A resulting model fitted for a given response variable consists of a linear effect composed of the covariables, or experimental factors, together with a random disturbance term (*26*). Possible distributions of the random disturbance term include the extreme value, normal and logistic distributions, exponential, Weibull, lognormal, loglogistic, and gamma distributions. When the log of the response is the quantity being modeled, these models are equivalent to accelerated failure time models (*26*).

Results from the field testing associated with clogged and unclogged locations were analyzed, where possible, using two-sample *t*-tests to determine if statistically significant differences between clogged and unclogged areas of the pervious concrete existed. Similar to an ANOVA, the *t*-test produces a *p*-value for comparison to a typical

Type I error rate of 0.05, where *p*-values less than or equal to this value indicate that the two populations, in this case, clogged and unclogged, are significantly different.

3.6 SUMMARY

In this research, the freeze-thaw durability of pervious concrete beams was evaluated in a full-factorial laboratory experiment involving four operators, two levels of soil clogging, two levels of water saturation, and two levels of curing time. In order to monitor degradation of the pervious concrete beam specimens, measurement of transverse and longitudinal frequencies of specimens was conducted every 20 freeze-thaw cycles until failure. Additional pervious concrete specimens prepared in the laboratory were tested for compressive strength and permeability using a constant-head setup.

To supplement the laboratory testing, field testing was conducted on an exterior slab of pervious concrete in Orem, Utah. Field testing consisted of in situ modulus testing, permeability testing, and core sampling. Testing was performed at four clogged and four unclogged locations. Modulus testing was conducted using a PFWD, and data were analyzed using a two-layer model. Permeability testing was conducted using a falling-head setup. Pervious concrete cores were removed from each of the eight test locations and were later tested in the laboratory for modulus and compressive strength.

The response variables associated with this research included fundamental transverse and longitudinal frequencies and freeze-thaw cycles to failure. Factors in the ANOVA included concrete curing time, soil clogging condition, water saturation condition, and concrete dry density. Freeze-thaw test results were also evaluated using the LIFEREG procedure, which was specifically utilized to identify the factors that most significantly influenced the number of freeze-thaw cycles to failure of the pervious concrete specimens. Furthermore, when the ANOVA indicated that a factor was significant, Tukey's mean separation procedure was employed to identify the differences. Two-sample *t*-tests were utilized to statistically analyze field data collected on clogged and unclogged areas of the pervious concrete slab.

CHAPTER 4

RESULTS

4.1 OVERVIEW

The following sections present the results of laboratory testing, field testing, and statistical analyses performed on the data collected in this research.

4.2 LABORATORY TESTING

Results of laboratory testing include compressive strength and permeability testing of pervious concrete cylinders, gradation and classification of the soil used in clogging of the beam specimens, and freeze-thaw durability data obtained for pervious concrete beams. Figure 4.1 displays the results of the slump test performed on the pervious concrete utilized in this research; the slump was measured to be 0 in. Results from the 7-, 28-, and 90-day compressive strength testing of the cylinders are reported in Table 4.1. The values are not appreciably different than those associated with standard exterior concrete flatwork.

FIGURE 4.1 Results of slump test.

TABLE 4.1 Results of Strength Tests on Laboratory Specimens

Description	Specimen				Average
	1	2	3	4	
7-day Strength (psi)	3374	4225	3330	2557	3371
28-day Strength (psi)	4379	5178	2508	3556	3905
90-day Strength (psi)	3536	4992	3640	3915	4021

Table 4.2 summarizes the results of stiffness and permeability testing performed on cylinders of pervious concrete prepared in the laboratory. The measured modulus values of the pervious concrete specimens were slightly lower than the typical modulus of conventional concrete, which is about 4000 ksi. Therefore, the pervious concrete evaluated in this research has a lower stiffness than conventional concrete.

TABLE 4.2 Results of Stiffness and Permeability Tests on Laboratory Specimens

Description	Specimen				Average
	1	2	3	4	
Length (in.)	7.0	6.8	7.1	7.0	7.0
Weight (lb)	6.22	6.51	5.97	6.22	6.23
Density (pcf)	122.6	130.7	115.0	121.5	122.4
Resonant Frequency (Hz)	9708	8446	9567	9067	9197
Modulus (ksi)	3369	2616	3209	2968	3041
Hydraulic Conductivity (in./hr)	318	71	295	194	220

The specimen with the lowest hydraulic conductivity had the highest density; however, the specimen with the lowest density did not experience the highest hydraulic conductivity, suggesting that hydraulic conductivity is not based solely on density but also on the interconnectivity of the pores in the concrete.

The particle-size distribution of the soil used to clog the beam specimens is reported in Table 4.3 and displayed graphically in Figure 4.2. This soil was determined to be non-plastic; therefore, Atterberg limits could not be determined. According to the

TABLE 4.3 Particle-Size Distribution of Soil

Sieve Size	Percent Passing (%)
3/4 in.	100
1/2 in.	94.2
3/8 in.	90.8
No. 4	84.0
No. 8	78.9
No. 16	75.0
No. 30	72.2
No. 50	63.2
No. 100	23.7
No. 200	11.7

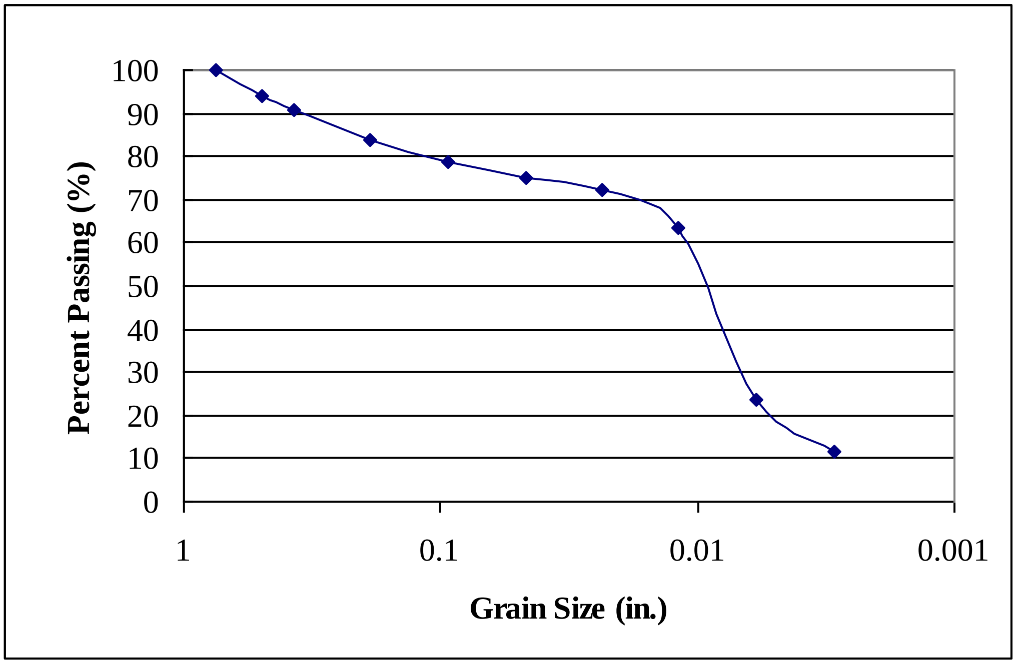

FIGURE 4.2 Particle-size distribution curve for soil.

Unified soil classification system, this soil is classified as SP-SM, or poorly graded sand with silt and gravel. The AASHTO soil classification of this soil is A-2-4.

Temperatures measured throughout freeze-thaw testing for both the 28- and 90-day phases are graphically represented in Figures 4.3 and 4.4, respectively. These plots show the maximum and minimum temperatures for each freeze-thaw cycle. According to ASTM C 666 Method A, internal beam specimen temperatures should cycle between 0°F and 40°F with a variance of plus or minus 3°F. Figures 4.3 and 4.4 show that testing for both phases did not meet this criteria at all times. As noted in Chapter 3, the primary cause of the temperature variation was variable saturation of the specimens tested in each phase; specimens not submerged in water were able to be frozen and thawed more quickly than specimens tested under water. Furthermore, the freeze-thaw cycles for the 90-day specimens occurred at a faster rate than for the 28-day specimens; the 28-day phase of freeze-thaw testing averaged 7.1 cycles per day, while the 90-day phase of testing averaged 7.9 cycles per day. Also, on average, the initial 30 cycles of the 90-day phase had freezing temperatures that were 6.6°F colder than the freezing temperatures of the initial 30 cycles of the 28-day phase and thawing temperatures that were 9.1°F cooler than the thawing temperatures of the 28-day phase. Therefore, despite the efforts of the researchers to ensure uniformity throughout the testing, specimens subjected to freeze-thaw testing in the second phase experienced colder temperatures during the initial freeze-thaw cycles than specimens tested in the first phase.

Graphical representations of the degradation of each beam specimen with increasing numbers of freeze-thaw cycles are shown for the first phase of testing in Figures 4.5 to 4.8 and for the second phase of testing in Figures 4.9 to 4.12. From these plots, the number of cycles to failure can be determined for each specimen through interpolation. Some specimens experienced an apparent increase in the percent of initial modulus during freeze-thaw testing. This increase is most likely due to the sensitivity of the frequency testing to temperature and operator effects and is therefore not given additional consideration in this report. As stated in Chapter 3, only the transverse frequencies were used to map the degradation of the specimens during freeze-thaw testing. The use of longitudinal frequencies was limited to statistical comparisons of the beam specimens.

Graphical representations of modulus variation throughout both phases of freeze-thaw testing show that monitoring modulus values computed from measured frequencies offers great utility in tracking the degradation of the specimens. This result contrasts sharply with the assumption of other researchers that frequency testing produces

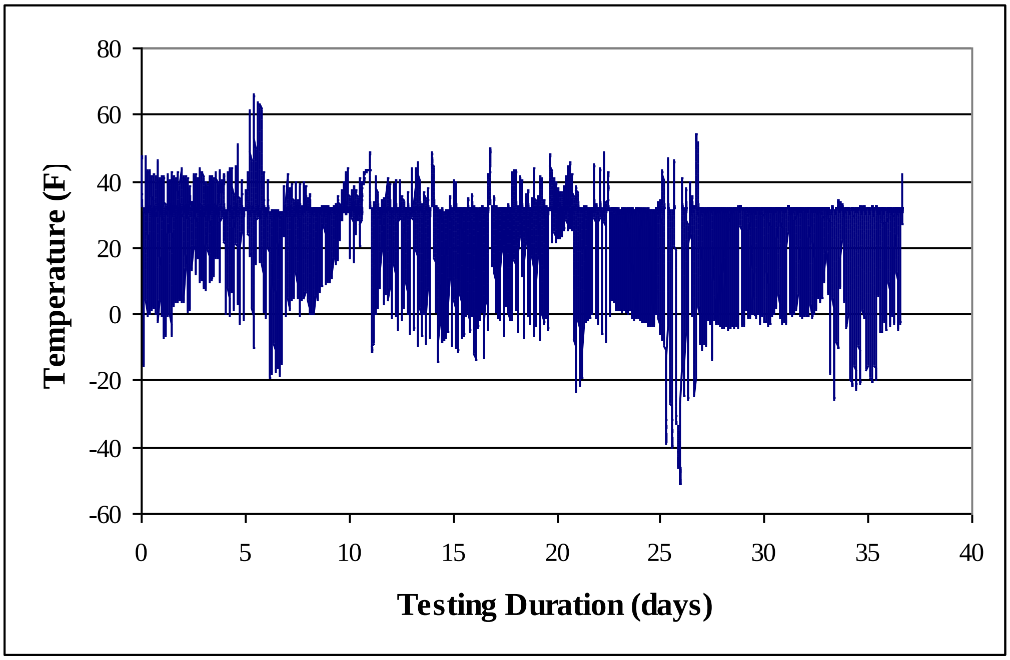

FIGURE 4.3 Temperature data collected during freeze-thaw cycling of specimens cured for 28 days.

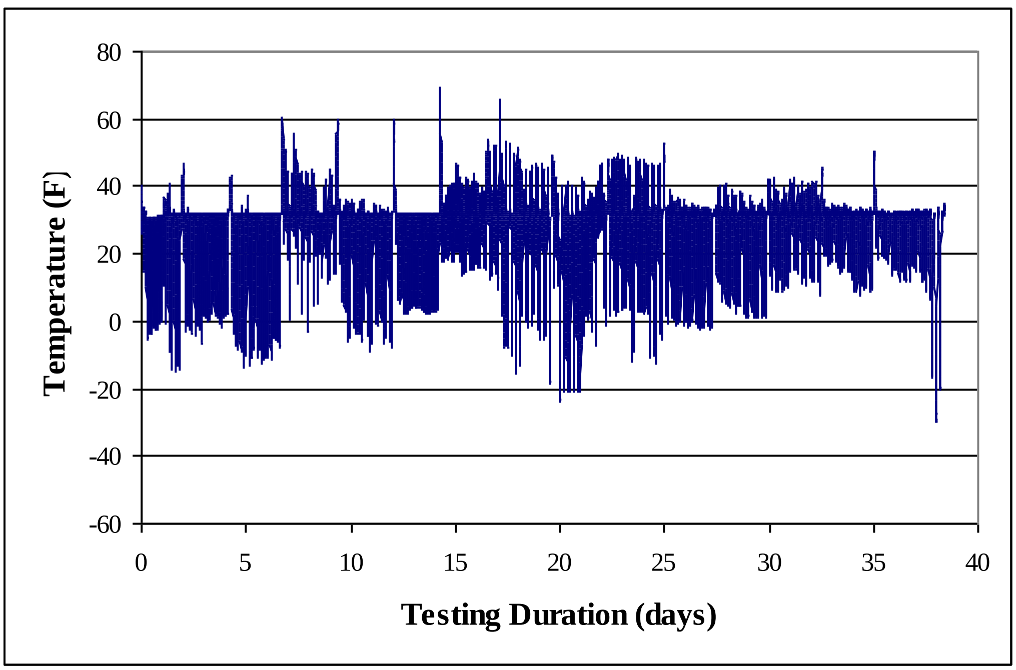

FIGURE 4.4 Temperature data collected during freeze-thaw cycling of specimens cured for 90 days.

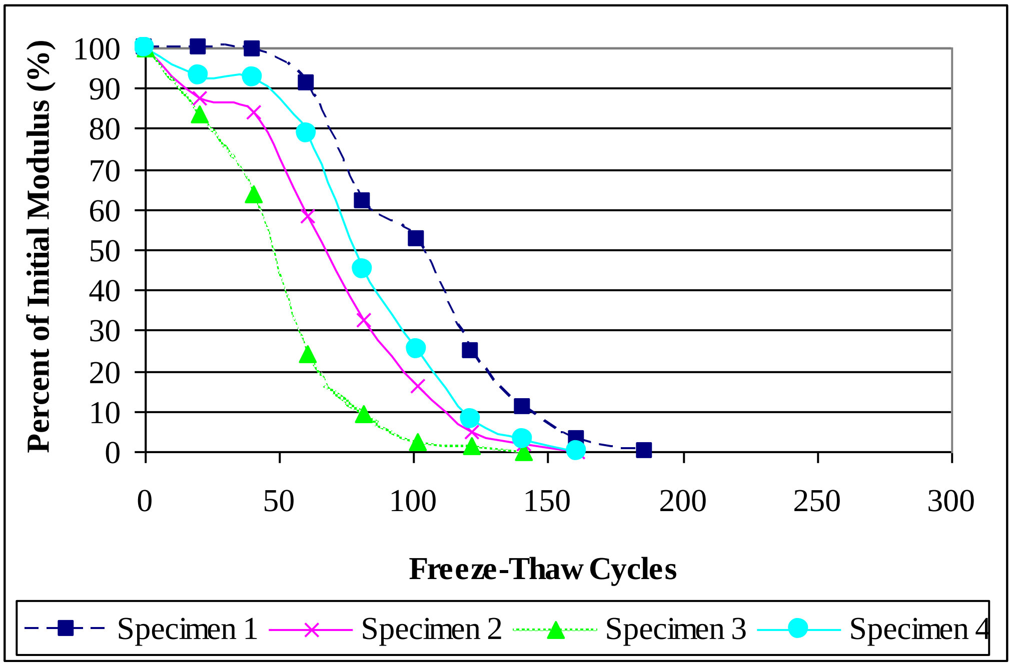

FIGURE 4.5 Freeze-thaw test results for 28-day clogged, saturated beam specimens.

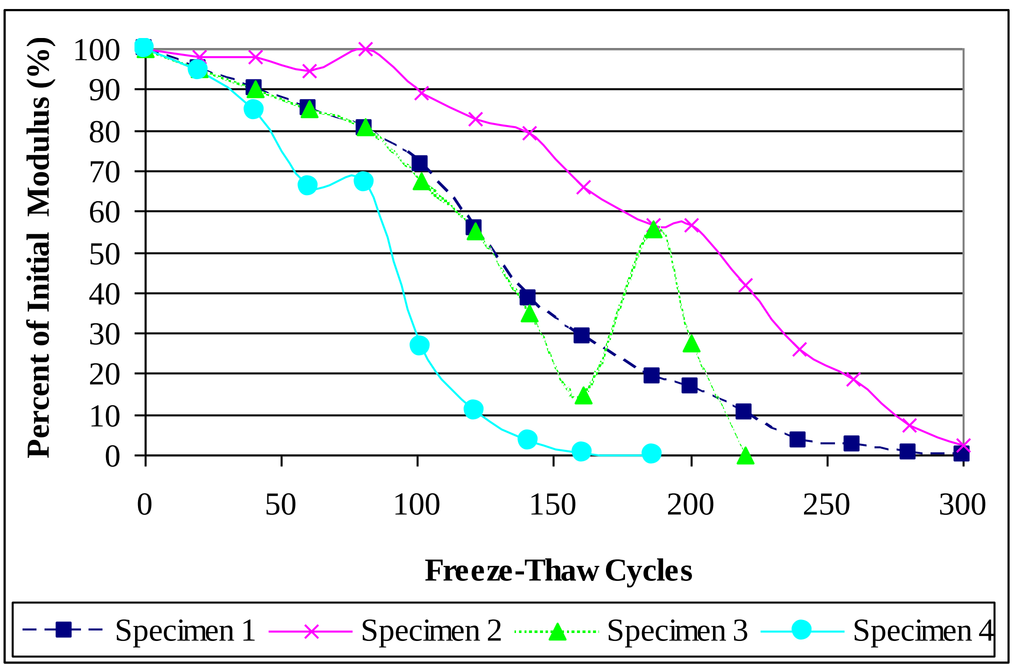

FIGURE 4.6 Freeze-thaw test results for 28-day clogged, unsaturated beam specimens.

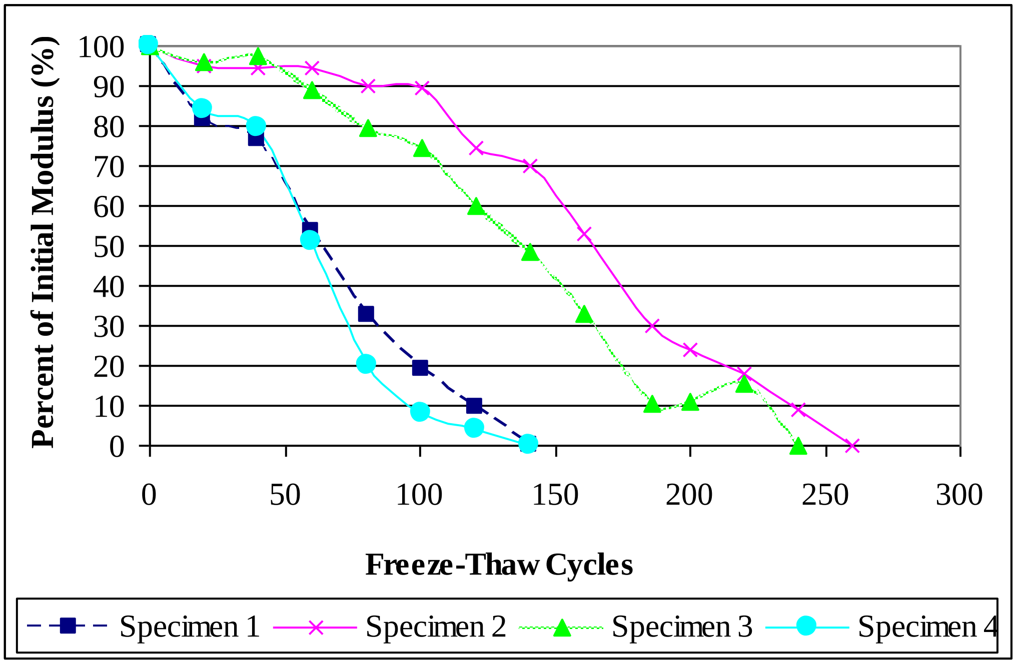

FIGURE 4.7 Freeze-thaw test results for 28-day unclogged, saturated beam specimens.

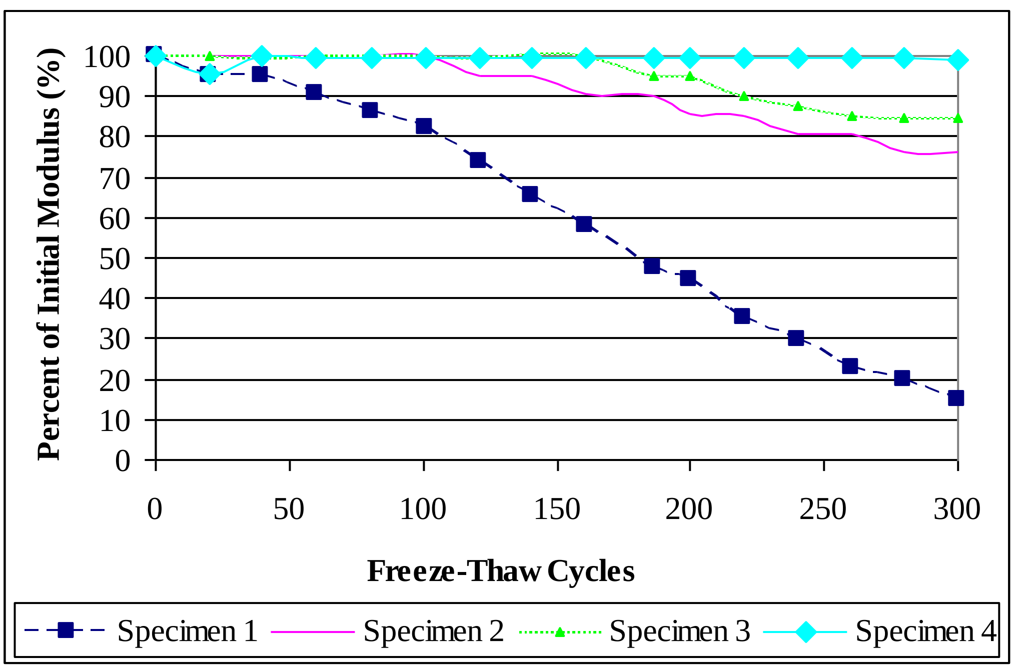

FIGURE 4.8 Freeze-thaw test results for 28-day unclogged, unsaturated beam specimens.

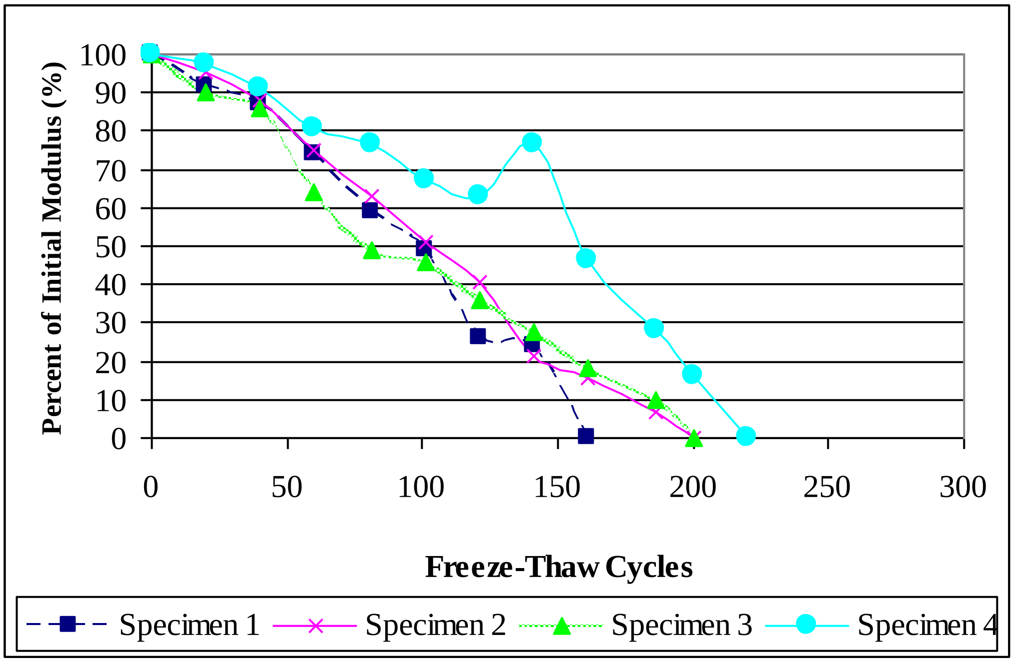

FIGURE 4.9 Freeze-thaw test results for 90-day clogged, saturated beam specimens.

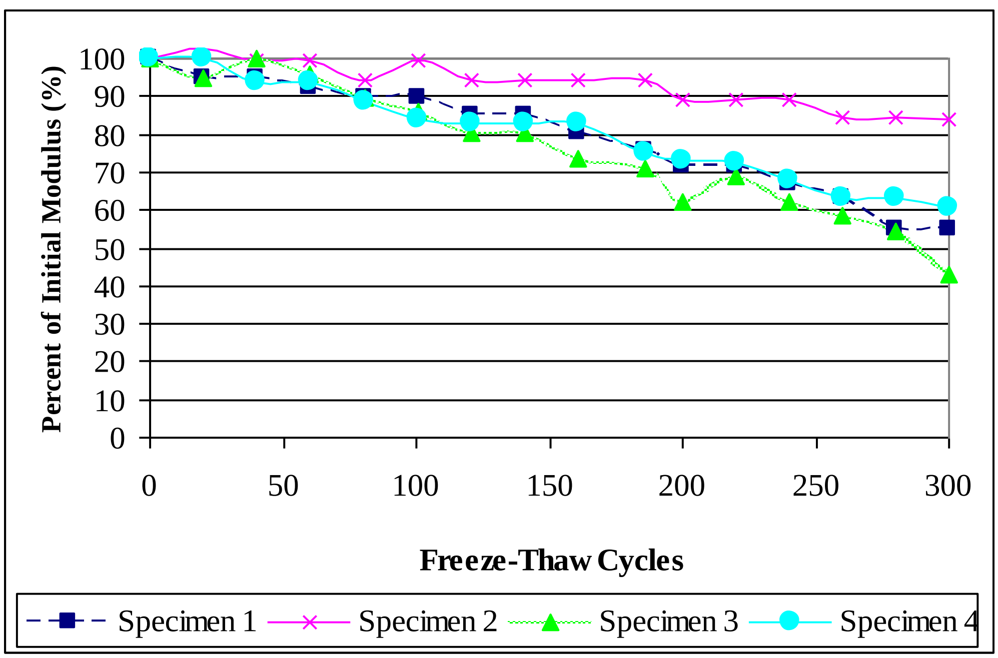

FIGURE 4.10 Freeze-thaw test results for 90-day clogged, unsaturated beam specimens.

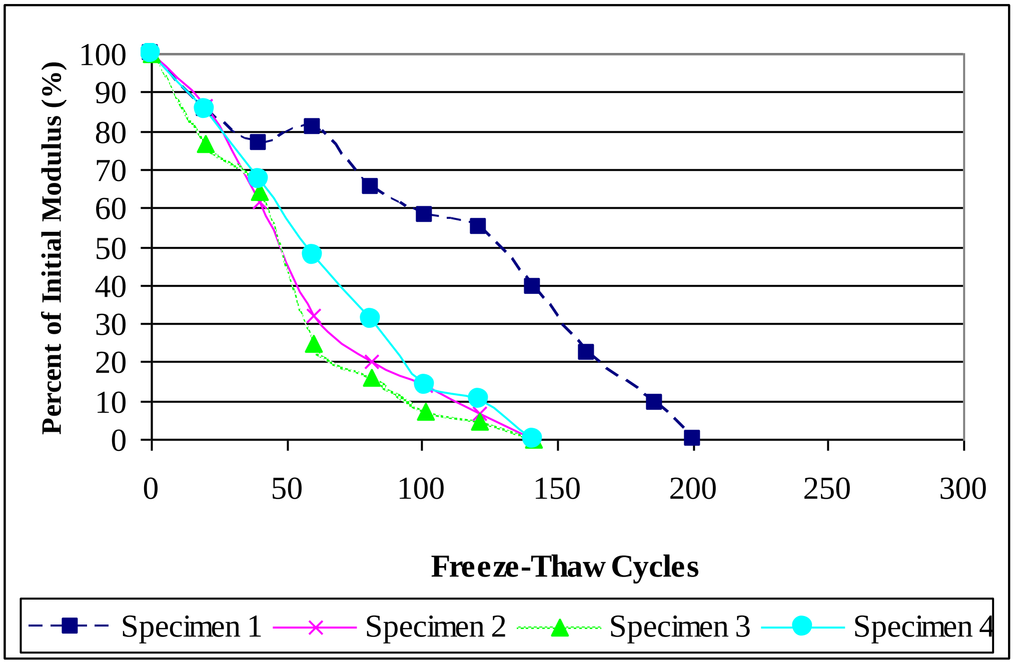

FIGURE 4.11 Freeze-thaw test results for 90-day unclogged, saturated beam specimens.

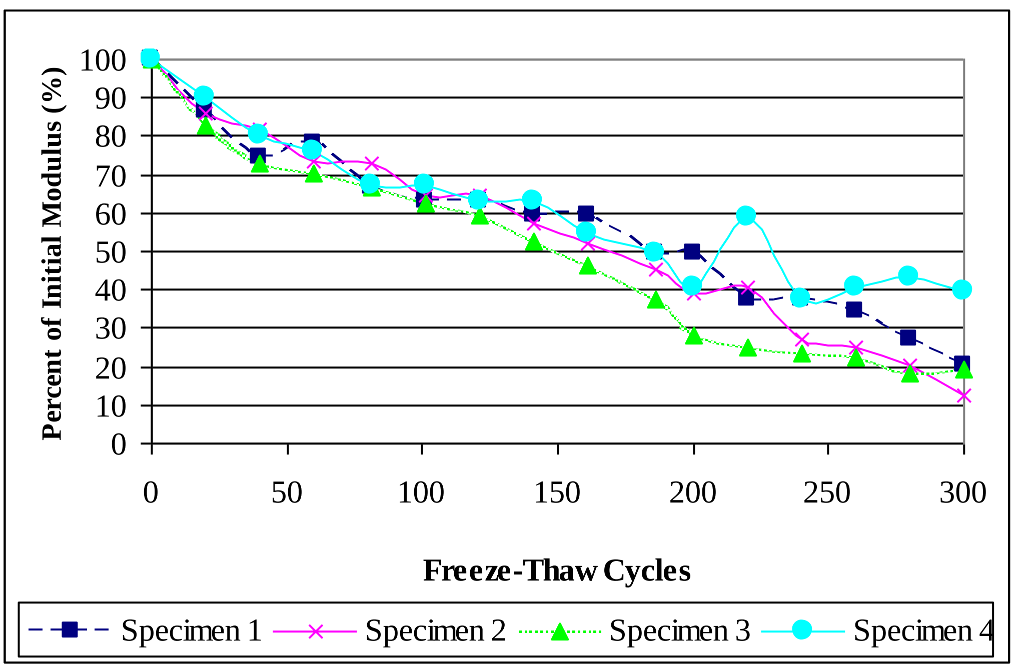

FIGURE 4.12 Freeze-thaw test results for 90-day unclogged, unsaturated beam specimens.

inconsistent modulus values not suitable for mapping the degradation of pervious concrete specimens subjected to freeze-thaw cycling (*11*).

Table 4.4 summarizes the characteristics of the pervious concrete beam specimens and reports the number of freeze-thaw cycles endured by each specimen before failure. Figure 4.13 gives a graphical representation of the average number of freeze-thaw cycles to failure for each specimen treatment.

The initial moisture contents of the beam specimens that remained intact after 300 freeze-thaw cycles for both phases of testing are reported in Table 4.5. Degradation of clogged, unsaturated specimens was so severe during the first phase of testing that a final moisture content could be calculated for just one specimen.

Degradation of the beam specimens during freeze-thaw testing varied between clogged and unclogged specimens. Unclogged specimens experienced gradual degradation with small chunks breaking away each time resonance testing occurred. Clogged specimens did not experience this type of degradation; instead, they remained nearly fully intact until visible failure occurred by the specimen fracturing in half. However, regardless of the physical appearance and/or eventual failure mode of the specimens, frequency readings continued to decrease each time they were tested. More in-depth analyses of the laboratory test results are provided later in this chapter.

Appendices A and B include longitudinal modulus data for beam specimens cured for 28 and 90 days respectively. Appendices C and D include transverse modulus data for beam specimens cured for 28 and 90 day respectively. Missing data in Appendices A, B, C, and D signify that the beam specimen was no longer able to be tested. Photographs of the specimens after each set of 20 freeze-thaw cycles are given in Appendices E, F, G,

TABLE 4.4 Freeze-Thaw Cycles to Failure for Laboratory Beam Specimens

Curing Time (days)	Clogging Condition	Saturation Condition	Specimen	Dry Density (pcf)	Cycles to Failure
28	Clogged	Saturated	1	115.3	82
			2	114.8	59
			3	122.3	42
			4	111.3	71
		Unsaturated	1	117.4	115
			2	114.2	176
			3	120.4	113
			4	116.3	85
	Unclogged	Saturated	1	125.7	54
			2	122.8	153
			3	127.8	121
			4	117.0	54
		Unsaturated	1	127.0	156
			2	123.9	>300
			3	126.7	>300
			4	118.4	>300
90	Clogged	Saturated	1	126.6	79
			2	118.2	85
			3	122.6	64
			4	119.0	151
		Unsaturated	1	119.4	265
			2	120.9	>300
			3	119.2	249
			4	114.0	>300
	Unclogged	Saturated	1	127.6	94
			2	123.8	41
			3	120.9	43
			4	117.9	48
		Unsaturated	1	127.3	134
			2	125.8	134
			3	125.7	118
			4	119.9	149

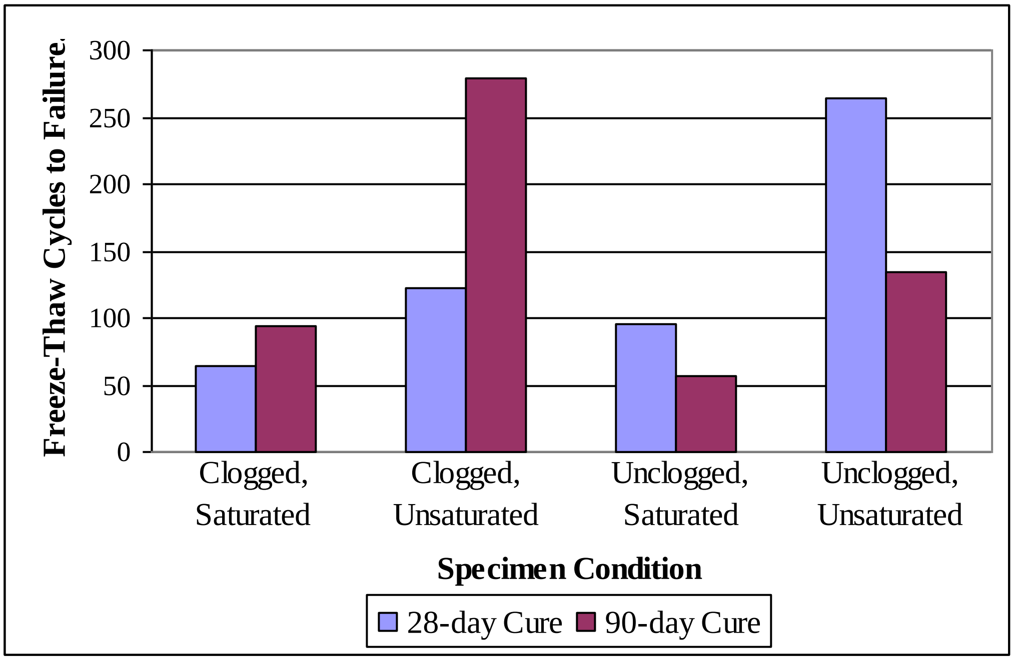

FIGURE 4.13 Freeze-thaw cycles to failure for laboratory beam specimens.

TABLE 4.5 Moisture Contents of Surviving Laboratory Beam Specimens

Curing Time (days)	Clogging Condition	Saturation Condition	Specimen	Moisture Content (%)
28	Clogged	Unsaturated	2	6.1
	Unclogged	Unsaturated	1	3.8
			2	3.9
			3	3.6
			4	4.0
90	Clogged	Unsaturated	1	4.2
			2	3.9
			3	3.4
			4	4.7
	Unclogged	Unsaturated	1	4.0
			2	4.3
			3	4.0
			4	3.0

and H for specimens cured for 28 days, while Appendices I, J, K, and L include photographs of specimens cured for 90 days. Upon failure of a specimen, or after a specimen deteriorated to the point that it could no longer be tested, photographs were no longer recorded for that specimen; hence, some appendices are missing specimen photographs. In all of the appendices, specimen labels are comprised of the initials of the first and last names of the operator who prepared them, followed by a unique number for each specimen. Specimen labels of 1, 2, 3, and 4 used in the text of this report consistently refer to operators having initials of BG, CD, BR, and KS, respectively.

4.3 FIELD TESTING

The results of the field testing include in situ slab modulus, permeability, core modulus, and core compressive strength. Results of the BAKFAA in situ modulus testing are reported in Table 4.6, as well as the concrete slab thickness at each test site. During the field permeability testing, the clogged test sites were observed to be impermeable, while the time to drain at each of the unclogged sites 1, 2, 3, and 4 was 94, 15, 56 and 16 seconds, respectively. Because the time to drain could not be measured on the clogged sites, a statistical comparison of the collected data could not be performed.

Table 4.7 shows the results of testing performed on the cores removed from the pervious concrete slab evaluated in this research, including core modulus and core compressive strength. Inspection of the core holes drilled in clogged locations revealed that the slab was generally only clogged in the upper 1 to 2 in., while the remaining depth of the slab appeared to remain free-draining. Coring also showed that slab thickness decreased from south to north. According to contractors who installed the pervious

TABLE 4.6 Results of Field Stiffness Tests

Condition	Location	Concrete Thickness (in.)	Test	Concrete Modulus (ksi)	Subbase/ Subgrade Modulus (ksi)
Clogged	1	7.0	1	1,784	23
			2	2,462	22
			3	1,998	22
	2	5.9	1	3,750	14
			2	1,665	16
			3	1,361	14
	3	6.6	1	3,723	23
			2	3,957	22
			3	3,779	23
	4	6.6	1	1,416	13
			2	1,276	13
			3	1,372	13
Unclogged	4	7.5	1	386	10
			2	415	9
			3	452	9
	3	6.7	1	1,081	12
			2	1,024	12
			3	826	8
	2	7.4	1	945	10
			2	841	10
			3	924	10
	1	5.2	1	754	6
			2	751	7
			3	613	5

concrete slab, concrete trucks started pouring the pervious concrete at the south end of the slab, driving across the granular subbase to reach the south end. As the concrete trucks exited the site, they caused the subbase aggregates to migrate to the north, thus causing the subbase to be thicker towards the north end of the slab. More in-depth analyses of the field test results are provided later in this chapter.

TABLE 4.7 Results of Laboratory Stiffness and Strength Tests on Field Specimens

Description	Clogged Specimen				Unclogged Specimen			
	1	2	3	4	1	2	3	4
Length (in.)	7.0	5.9	6.6	6.6	5.2	7.4	6.7	7.5
Weight (lb)	6.28	4.95	5.80	5.91	4.40	6.32	5.94	6.36
Dry Density (pcf)	124.0	115.4	120.4	123.6	117.4	117.7	121.8	117.1
Resonant Frequency (Hz)	9535	8817	8977	9439	9548	8977	9266	8324
Modulus (ksi)	3276	1861	2543	2840	1706	3089	2802	2710
Compressive Strength (psi)	3922	2896	2390	3793	3470	3122	4228	2270

4.4 STATISTICAL ANALYSES

Results of the statistical analyses include those obtained from ANOVA and LIFEREG tests of laboratory data and those obtained from *t*-tests of field data. In Tables 4.8 to 4.10, the factors of curing time, clogging condition, and water saturation condition are represented as "age," "soil," and "water," respectively, and all possible two-way interactions among these factors are included. Density was treated as a covariate in the analyses. Tables 4.8 and 4.9 show the *p*-values computed in the ANOVA for each factor included in the models developed for transverse and longitudinal frequencies for each set of 20 freeze-thaw cycles. Statistical analysis results for both transverse and longitudinal frequency readings were nearly identical, with only minor differences in the age and soil factors. Values less than or equal to 0.05 are presented in bold-face font to signify their statistical significance. Hyphens in the tables indicate that insufficient surviving specimens were available for the analyses to be performed.

As shown by the fluctuations in *p*-values, the relative importance of some factors varied as freeze-thaw cycling progressed. Density as a covariate was not statistically significant in any of the analyses, while the factor of age was only significant during the initial stages of freeze-thaw testing. The factor of soil proved to be only intermittently significant. However, the factor of water, as well as the interaction between age and soil, played a significant role in test results throughout the entire course of freeze-thaw testing for both transverse and longitudinal frequency readings. Like the factor of density, neither the interaction between age and water nor the interaction between soil and water was statistically significant in any of the analyses.

TABLE 4.8 Statistical Analyses of Transverse Modulus Values for Laboratory Beam Specimens

Factor	*p* -Values														
No. of Cycles	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300
Density	0.4447	0.3696	0.8676	0.735	0.5514	0.7175	0.1214	0.1459	0.3082	0.2027	0.0949	0.2307	0.1828	0.1421	0.1818
Age	0.1171	**0.0146**	0.3145	0.4638	0.8795	0.5875	0.1935	0.2691	0.2294	0.928	0.3008	0.3565	0.315	0.2707	0.4099
Soil	**0.0444**	0.1089	0.4966	0.4432	0.7148	0.6946	**0.0118**	**0.0274**	0.0837	0.1633	0.0769	0.1468	0.0988	0.0678	0.124
Water	**0.0044**	**0.0021**	**0.0005**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.0008**	**0.0002**	**< 0.0001**	**0.0004**	**0.003**	**0.0098**	-	-	-
Age*Soil	**0.0024**	**< 0.0001**	**0.0068**	**0.0047**	**0.002**	**0.001**	**< 0.0001**	**< 0.0001**	**0.0006**	**0.0005**	**0.0007**	**0.0008**	**0.0012**	**0.0009**	**0.0064**
Age*Water	0.3314	0.9678	0.8539	0.4172	0.7941	0.7986	0.7789	0.7849	0.2115	-	-	-	-	-	-
Soil*Water	0.6037	0.4318	0.5987	0.9648	0.7539	0.7157	0.2317	0.6236	0.1817	-	-	-	-	-	-

TABLE 4.9 Statistical Analysis of Longitudinal Modulus Values for Laboratory Beam Specimens

Factor	*p* -Values														
No. of Cycles	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300
Density	0.546	0.2257	0.2927	0.9327	0.7093	0.7572	0.097	0.1438	0.1155	0.1927	0.1395	0.1988	0.1489	0.0532	0.1372
Age	**0.0209**	**0.0149**	0.1745	0.5169	0.9505	0.5529	0.0863	0.1636	0.0822	0.239	0.1339	0.267	0.3251	0.1274	0.456
Soil	**0.0066**	0.0775	0.9547	0.4588	0.7123	0.9015	**0.0055**	**0.0414**	**0.0195**	0.1487	0.0977	0.1702	0.1373	0.0765	0.1485
Water	**0.0087**	**0.0034**	**0.0045**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.001**	**0.0003**	**< 0.0001**	**0.0022**	**0.0115**	**0.0077**	-	-	-
Age*Soil	**0.001**	**< 0.0001**	**0.0019**	**0.0054**	**0.0035**	**0.0017**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.0004**	**0.0016**	**0.0006**	**0.0008**	**0.0015**	**0.0049**
Age*Water	0.6579	0.6839	0.5429	0.5048	0.8096	0.97	0.9205	0.6751	0.3313	-	-	-	-	-	-
Soil*Water	0.1356	0.2196	0.4688	0.6219	0.5178	0.5265	0.2644	0.7476	0.2166	-	-	-	-	-	-

To facilitate identification of factors that most significantly influenced the number of cycles to failure of the pervious concrete during freeze-thaw testing, the statistical analysis method of LIFEREG was utilized. Results of the LIFEREG analysis, presented in Table 4.10, show that the most influential factors are water and the two-way interaction between age and soil. Regarding the first factor, specimens that were completely submerged in water were damaged at a notably faster rate than those specimens that were tested in a moist but unsaturated condition for both age conditions. Regarding the second factor, the effect of clogging on the number of freeze-thaw cycles to failure depended upon the age. For example, as shown in Figure 4.13, specimens cured for 28 days and tested in a clogged state survived fewer cycles than specimens cured for 28 days and tested in an unclogged state, while the reverse is true for specimens cured for 90 days.

One possible reason for the worse performance of clogged, unsaturated specimens tested in the first phase compared to that of clogged, unsaturated specimens in the second phase is that the specimens in the first phase may have had higher moisture contents than corresponding specimens in the second phase of testing. The moisture content of the single clogged, unsaturated specimen surviving from the first phase was significantly

TABLE 4.10 Statistical Analysis of Freeze-Thaw Cycles to Failure for Laboratory Beam Specimens

Factor	*p* -Value
Density	0.4121
Age	0.9435
Soil	0.3954
Water	< **0.0001**
Age*Soil	< **0.0001**

higher than the moisture contents of similar specimens tested in the second phase. However, since only one specimen of this type survived, the assumption that higher moisture content caused beams in the first phase to perform worse than similar beams in the second phase cannot be supported statistically.

In addition to differing moisture contents, freezer temperatures also varied between the two phases. As discussed earlier in this chapter, the second phase of testing had colder initial freeze-thaw cycles that may have affected the performance of the specimens over the remainder of the test. These colder temperatures during the second phase of testing seem to have deteriorated the unclogged specimens at a much faster rate than clogged specimens tested in the same phase, regardless of the saturation condition.

One possible reason for the worse performance of unclogged specimens in this phase stems from consideration of moisture contents. Although moisture contents could not be computed for any saturated specimens, the average moisture contents of clogged, unsaturated specimens and unclogged, unsaturated specimens evaluated during the second phase of testing were nearly identical at 4.1 and 3.8 percent, respectively, as calculated from data presented in Table 4.5. Since the soil in the clogged specimens most likely retained a considerable portion of the 4.1 percent of moisture, the actual moisture available for freeze-thaw deterioration of the concrete comprising the clogged, unsaturated specimens was most likely significantly lower than the moisture available for freeze-thaw deterioration of the concrete comprising the unclogged, unsaturated specimens. This would explain why the clogged, unsaturated specimens performed much better than similar unclogged, unsaturated specimens in the second phase of testing.

Table 4.10 also shows that the density, curing time, and clogging condition of the pervious concrete did not play a statistically significant role in influencing the number of freeze-thaw cycles required to reach failure. This finding is consistent with the previous ANOVA analyses. These data suggest that pervious concrete similar to that tested in this research should perform satisfactorily in cold regions as long as it remains free of debris and well drained.

As noted in Chapter 3, preparation of the pervious concrete specimens in the laboratory was conducted by four separate operators. As shown in Table 4.11, differences between specimens prepared by different operators were determined to be statistically different in three areas specific to the initial frequency and density measurements obtained from each specimen for both 28- and 90-day phases prior to the start of freeze-thaw cycling and before any clogging and/or saturation treatments were applied.

The results of Tukey's analysis show that differences between operators one, two, and three were not statistically significant in any of the three response variables since none of the *p*-values were less than or equal to 0.05. However, statistically significant differences did exist between operators one and four and two and four for all three response variables, and differences between operators three and four were nearly

TABLE 4.11 Statistical Analyses of Operator Effects

Operator Effects	
Response Variable	*p* -Value
Density	< **0.0001**
Transverse Frequency	< **0.0001**
Longitudinal Frequency	< **0.0001**

statistically significant for longitudinal frequencies with a p-value of 0.0519. From this statistical analysis, operator four is shown to have placed and prepared the pervious concrete in a significantly different manner than other operators, thus affecting the test results.

A comparison of in situ modulus values, core modulus values, and core compressive strengths associated with clogged locations and unclogged locations yielded p-values of 0.969, 0.523, and 0.530, thus indicating no significant differences in structural properties in the clogged and unclogged locations. That is, the stiffness and strength of the clogged and unclogged areas were essentially identical.

4.5 SUMMARY

The factor of water and the interaction between the factors of age and soil played significant roles in testing throughout the entire course of freeze-thaw testing for both transverse and longitudinal frequency readings for specimens cured for both 28 and 90 days. Density as a covariate was not statistically significant in any of the analyses, while the factor of age was only significant during the initial stages of freeze-thaw testing. The factor of soil proved to be only intermittently significant.

Regarding the factor of water, specimens that were completely submerged in water during freeze-thaw testing were damaged at a notably faster rate than those specimens that were tested in a moist but unsaturated condition for both age conditions. Regarding the interaction between the factors of age and soil, the effect of clogging on the number of freeze-thaw cycles to failure depended upon the age. This dependency may be explained by variations in the specimen moisture contents and freezer temperatures during the two phases; clogged, unsaturated specimens cured for 28 days had higher moisture contents than those cured for 90 days, and initial freeze-thaw cycles were much colder during the second phase of testing than during the first phase. In addition, for the second phase of testing, the presence of soil in clogged, unsaturated specimens may have reduced the amount of moisture available for freeze-thaw deterioration of the concrete compared to that available in the unclogged, unsaturated specimens evaluated in the same phase.

A comparison of in situ modulus values, core modulus values, and core compressive strengths associated with clogged locations and unclogged locations in the field indicated no significant differences in structural properties in the clogged and unclogged locations. That is, the stiffness and strength of the clogged and unclogged areas were essentially identical. These data suggest that pervious concrete similar to that tested in this research should perform satisfactorily in cold regions as long as it remains free of debris and well drained.

CHAPTER 5

CONCLUSION

5.1 SUMMARY

Although the use of pervious concrete is expanding, only a limited number of scholarly papers have been published on the properties of this product. One topic that especially warrants additional research is the resistance of pervious concrete to deterioration under frost action. Based on this need for additional research on the durability of pervious concrete in cold regions, the objective of this research was to evaluate the resistance of pervious concrete to degradation during freeze-thaw cycling under different clogging and saturation conditions. The laboratory research associated with this project involved three primary measures of pervious concrete performance, including freeze-thaw durability, compressive strength, and permeability. Testing associated with freeze-thaw durability involved two levels of soil clogging, two water saturation conditions, and two curing durations in a full-factorial experimental design. Compressive strength testing involved three different curing durations of 7, 28, and 90 days. For permeability testing, a constant-head apparatus was utilized.

Field testing involved measurements of stiffness, permeability, and compressive strength at a single site in Orem, Utah. Stiffness was assessed using a PFWD. Permeability testing was performed using a falling-head permeability setup, and compressive strength testing was performed on 4-in.-diameter cores removed from the field.

5.2 FINDINGS

The factor of water and the interaction between the factors of age and soil played significant roles in testing throughout the entire course of freeze-thaw testing for both transverse and longitudinal frequency readings for specimens cured for both 28 and 90 days. Density as a covariate was not statistically significant in any of the analyses, while the factor of age was only significant during the initial stages of freeze-thaw testing. The factor of soil proved to be only intermittently significant.

Regarding the factor of water, specimens that were completely submerged in water during freeze-thaw testing were damaged at a notably faster rate than those specimens that were tested in a moist but unsaturated condition for both age conditions. Regarding the interaction between the factors of age and soil, the effect of clogging on the number of freeze-thaw cycles to failure depended upon the age. This dependency may be explained by variations in the specimen moisture contents and freezer temperatures during the two phases; clogged, unsaturated specimens cured for 28 days had higher moisture contents than those cured for 90 days, and initial freeze-thaw cycles were much colder during the second phase of testing than during the first phase. In addition, for the second phase of testing, the presence of soil in clogged, unsaturated specimens may have reduced the amount of moisture available for freeze-thaw deterioration of the concrete compared to that available in the unclogged, unsaturated specimens evaluated in the same phase.

A comparison of in situ modulus values, core modulus values, and core compressive strengths associated with clogged locations and unclogged locations in the field indicated no significant differences in structural properties in the clogged and unclogged locations. That is, the stiffness and strength of the clogged and unclogged areas were essentially identical. These data suggest that pervious concrete similar to that tested in this research should perform satisfactorily in cold regions as long as it remains free of debris and well drained.

5.3 RECOMMENDATIONS

Although the results of this research suggest that pervious concrete similar to that evaluated in this study can be successfully used in cold regions under essentially ideal conditions, further laboratory and field research should be performed to more carefully examine the effect of moisture content on the freeze-thaw durability of moist but unsaturated specimens. Also, given that clogging can reduce the freeze-thaw durability of pervious concrete, the effects of different types of soils on performance and the efficacy of maintenance procedures available for cleaning partially clogged pervious concrete slabs should be investigated. Long-term monitoring of and supplementary experimentation on the pervious concrete slab tested in this research should be considered for these purposes. Instrumentation of test slabs with thermocouples could also be performed to investigate the ability of the concrete to behave as an insulator in cold regions and thus reduce the depth of frost penetration below the concrete. More conclusive data about the performance of pervious concrete in cold regions will be derived from such field tests.

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APPENDIX A:

LONGITUDINAL MODULUS DATA FOR

BEAM SPECIMENS CURED FOR

28 DAYS

Table A.1 Longitudinal Modulus Data after 28-day Cure and before Treatment

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.76	10.06	9.82	9.92	9.75	9.93	9.60	9.68	10.09	10.18	9.98	9.90	9.44	9.92	9.14	9.25
Density (pcf)	124.9	128.8	125.7	127.0	124.8	127.1	122.8	123.9	129.2	130.3	127.8	126.7	120.9	127.0	117.0	118.4
Average Frequency (Hz)	4127	4421	4537	4691	4069	4152	4306	4492	4421	4383	4537	4345	3851	4063	4152	4075
Average Modulus (MPa)	19784	23422	24058	25984	19215	20383	21186	23250	23488	23276	24456	22246	16672	19498	18770	18290
Average Modulus (ksi)	2869	3397	3489	3769	2787	2956	3073	3372	3407	3376	3547	3227	2418	2828	2722	2653

Table A.2 Longitudinal Modulus Data after 28-day Cure and after Treatment

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.76	10.06	9.82	9.92	9.75	9.93	9.60	9.68	10.09	10.18	9.98	9.90	9.44	9.92	9.14	9.25
Density (pcf)	124.9	128.8	125.7	127.0	124.8	127.1	122.8	123.9	129.2	130.3	127.8	126.7	120.9	127.0	117.0	118.4
Average Frequency (Hz)	4127	4421	4537	4691	4069	4152	4306	4492	4421	4383	4537	4345	3851	4063	4152	4075
Average Modulus (MPa)	19784	23422	24058	25984	19215	20383	21186	23250	23488	23276	24456	22246	16672	19498	18770	18290
Average Modulus (ksi)	2869	3397	3489	3769	2787	2956	3073	3372	3407	3376	3547	3227	2418	2828	2722	2653

Table A.3 Longitudinal Modulus Data after 28-day Cure and 20 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.76	10.06	9.82	9.92	9.75	9.93	9.60	9.68	10.09	10.18	9.98	9.90	9.44	9.92	9.14	9.25
Density (pcf)	124.9	128.8	125.7	127.0	124.8	127.1	122.8	123.9	129.2	130.3	127.8	126.7	120.9	127.0	117.0	118.4
Average Frequency (Hz)	4082	4268	4075	4537	3922	4075	4229	4421	4139	4306	4421	4345	3806	3928	3870	4075
Average Modulus (MPa)	19356	21822	19414	24308	17848	19635	20436	22526	20588	22466	23228	22246	16286	18228	16307	18290
Average Modulus (ksi)	2807	3165	2816	3526	2589	2848	2964	3267	2986	3258	3369	3227	2362	2644	2365	2653
Modulus Retained (%)	97.8	93.2	80.7	93.5	92.9	96.3	96.5	96.9	87.7	96.5	95.0	100.0	97.7	93.5	86.9	100.0

Table A.4 Longitudinal Modulus Data after 28-day Cure and 40 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.69	10.05	9.76	9.91	9.70	9.90	9.56	9.66	10.09	10.17	9.95	9.87	9.37	9.93	9.06	9.24
Density (pcf)	124.0	128.7	124.9	126.8	124.1	126.8	122.4	123.7	129.1	130.2	127.4	126.4	120.0	127.2	115.9	118.2
Average Frequency (Hz)	4114	4223	4011	4498	3838	4075	4242	4421	3826	4152	4421	4345	3774	3755	3768	4114
Average Modulus (MPa)	19519	21342	18700	23872	17011	19583	20484	22493	17573	20878	23157	22183	15894	16677	15305	18611
Average Modulus (ksi)	2831	3095	2712	3462	2467	2840	2971	3262	2549	3028	3359	3217	2305	2419	2220	2699
Modulus Retained (%)	98.7	91.1	77.7	91.9	88.5	96.1	96.7	96.7	74.8	89.7	94.7	99.7	95.3	85.5	81.5	101.8

Table A.5 Longitudinal Modulus Data after 28-day Cure and 60 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.99	10.06	9.82	9.92	9.98	9.93	9.57	9.68	10.36	10.18	10.06	9.89	9.67	9.95	9.25	9.22
Density (pcf)	127.9	128.7	125.7	127.0	127.7	127.1	122.5	123.9	132.6	130.3	128.8	126.6	123.8	127.4	118.4	118.1
Average Frequency (Hz)	3845	4075	3460	4421	3576	4037	4229	4421	2634	4037	4306	4345	3537	3319	4140	4114
Average Modulus (MPa)	17582	19885	13998	23085	15190	19261	20375	22525	8554	19744	22217	22228	14403	13052	18863	18585
Average Modulus (ksi)	2550	2884	2030	3348	2203	2794	2955	3267	1241	2864	3222	3224	2089	1893	2736	2696
Modulus Retained (%)	88.9	84.9	58.2	88.8	79.1	94.5	96.2	96.9	36.4	84.8	90.8	99.9	86.4	66.9	100.5	101.6

Table A.6 Longitudinal Modulus Data after 28-day Cure and 81 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.95	10.04	9.76	9.91	9.81	9.94	9.61	9.68	10.26	10.18	9.96	9.90	9.43	9.99	9.03	9.22
Density (pcf)	127.4	128.6	124.9	126.8	125.6	127.2	123.0	123.8	131.4	130.3	127.4	126.7	120.7	127.8	115.6	118.0
Average Frequency (Hz)	3422	3922	2640	4306	2768	4075	4095	4421	1935	3999	4095	4383	2884	3326	2140	4152
Average Modulus (MPa)	13871	18388	8099	21876	8953	19648	19184	22517	4576	19376	19871	22640	9338	13150	4927	18926
Average Modulus (ksi)	2012	2667	1175	3173	1298	2850	2782	3266	664	2810	2882	3284	1354	1907	715	2745
Modulus Retained (%)	70.1	78.5	33.7	84.2	46.6	96.4	90.6	96.8	19.5	83.2	81.2	101.8	56.0	67.4	26.2	103.5

Table A.7 Longitudinal Modulus Data after 28-day Cure and 101 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.86	10.05	9.55	9.97	9.80	9.90	9.56	9.67	10.24	10.18	9.91	9.88	9.57	10.00	8.74	9.21
Density (pcf)	126.2	128.6	122.2	127.6	125.5	126.8	122.3	123.8	131.1	130.4	126.8	126.4	122.4	127.9	111.9	117.9
Average Frequency (Hz)	3191	3768	1967	4184	2089	3845	4043	4383	1070	3576	3999	4335	2063	2198	1173	4114
Average Modulus (MPa)	11954	16977	4400	20783	5093	17429	18600	22123	1396	15502	18863	22092	4849	5747	1431	18565
Average Modulus (ksi)	1734	2462	638	3014	739	2528	2698	3209	202	2248	2736	3204	703	833	208	2693
Modulus Retained (%)	60.4	72.5	18.3	80.0	26.5	85.5	87.8	95.2	5.9	66.6	77.1	99.3	29.1	29.5	7.6	101.5

Table A.8 Longitudinal Modulus Data after 28-day Cure and 121 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.75	10.13	9.22	9.94	9.82	9.90	9.49	9.66	10.05	10.17	9.90	9.87	9.38	10.00	8.18	9.20
Density (pcf)	124.8	129.6	118.0	127.3	125.6	126.7	121.5	123.7	128.7	130.2	126.7	126.3	120.1	128.0	104.7	117.7
Average Frequency (Hz)	2871	3345	1615	4037	1288	3736	3787	4383	308	3262	3672	4383	1288	1455	577	4114
Average Modulus (MPa)	9568	13491	2861	19293	1939	16452	16208	22094	113	12882	15885	22571	1853	2518	324	18528
Average Modulus (ksi)	1388	1957	415	2798	281	2386	2351	3205	16	1868	2304	3274	269	365	47	2687
Modulus Retained (%)	48.4	57.6	11.9	74.2	10.1	80.7	76.5	95.0	0.5	55.3	65.0	101.5	11.1	12.9	1.7	101.3

Table A.9 Longitudinal Modulus Data after 28-day Cure and 141 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.78	10.15		9.91	9.80	9.88	9.50	9.68		10.23	9.90	9.93	9.23	9.96		9.22
Density (pcf)	125.2	129.9		126.9	125.5	126.4	121.5	123.9		130.9	126.7	127.1	118.1	127.5		118.0
Average Frequency (Hz)	1596	2518		3768	852	3653	3672	4345		2057	3345	4345	769	827		4152
Average Modulus (MPa)	2964	7662		16752	847	15686	15238	21748		5152	13180	22306	650	810		18925
Average Modulus (ksi)	430	1111		2430	123	2275	2210	3154		747	1912	3235	94	117		2745
Modulus Retained (%)	15.0	32.7		64.5	4.4	77.0	71.9	93.5		22.1	53.9	100.3	3.9	4.2		103.5

Table A.10 Longitudinal Modulus Data after 28-day Cure and 161 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.61	10.07		9.91		9.95	9.38	9.67		10.25	9.85	9.91		9.93		9.21
Density (pcf)	123.0	128.9		126.8		127.4	120.1	123.8		131.2	126.0	126.8		127.2		117.8
Average Frequency (Hz)	577	2307		3146		3185	3262	4268		1974	2473	4306		385		4133
Average Modulus (MPa)	380	6380		11676		12019	11886	20974		4755	7171	21875		175		18722
Average Modulus (ksi)	55	925		1693		1743	1724	3042		690	1040	3173		25		2715
Modulus Retained (%)	1.9	27.2		44.9		59.0	56.1	90.2		20.4	29.3	98.3		0.9		102.4

Table A.11 Longitudinal Modulus Data after 28-day Cure and 186 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.06		9.91		9.87	9.35	9.66		10.24	9.88	9.93				9.20
Density (pcf)		128.8		126.9		126.3	119.7	123.6		131.0	126.4	127.0				117.8
Average Frequency (Hz)		1794		3018		2992	2326	4229		1608	2102	4268				4152
Average Modulus (MPa)		3857		10751		10518	6023	20568		3153	5194	21521				18885
Average Modulus (ksi)		559		1559		1526	874	2983		457	753	3121				2739
Modulus Retained (%)		16.5		41.4		51.6	28.4	88.5		13.5	21.2	96.7				103.2

Table A.12 Longitudinal Modulus Data after 28-day Cure and 200 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.06		9.90		9.85	9.22	9.64		10.25	9.74	9.89				9.19
Density (pcf)		128.8		126.7		126.1	118.1	123.3		131.2	124.7	126.6				117.6
Average Frequency (Hz)		1826		1922		1999	1903	4191		1269	2211	4229				4152
Average Modulus (MPa)		3994		4356		4687	3977	20146		1964	5669	21060				18864
Average Modulus (ksi)		579		632		680	577	2922		285	822	3054				2736
Modulus Retained (%)		17.1		16.8		23.0	18.8	86.6		8.4	23.2	94.7				103.1

Table A.13 Longitudinal Modulus Data after 28-day Cure and 220 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.04		9.91		9.84	9.07	9.62			9.65	9.90				9.21
Density (pcf)		128.5		126.8		126.0	116.1	123.1			123.5	126.7				117.9
Average Frequency (Hz)		1826		2159		1692	1307	4114			2147	4165				4114
Average Modulus (MPa)		3986		5500		3353	1846	19383			5293	20441				18552
Average Modulus (ksi)		578		798		486	268	2811			768	2965				2691
Modulus Retained (%)		17.0		21.2		16.4	8.7	83.4			21.6	91.9				101.4

Table A.14 Longitudinal Modulus Data after 28-day Cure and 240 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.04		9.89		9.85	8.76	9.61				9.88				9.20
Density (pcf)		128.5		126.5		126.1	112.1	123.0				126.5				117.7
Average Frequency (Hz)		1224		2217		1660	577	4050				4101				4114
Average Modulus (MPa)		1790		5785		3230	347	18770				19791				18532
Average Modulus (ksi)		260		839		468	50	2722				2870				2688
Modulus Retained (%)		7.6		22.3		15.8	1.6	80.7				89.0				101.3

Table A.15 Longitudinal Modulus Data after 28-day Cure and 260 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.05		9.88		9.86		9.61				9.86				9.22
Density (pcf)		128.6		126.4		126.2		123.0				126.3				118.1
Average Frequency (Hz)		807		2006		1775		4037				4075				4114
Average Modulus (MPa)		780		4730		3697		18638				19504				18583
Average Modulus (ksi)		113		686		536		2703				2829				2695
Modulus Retained (%)		3.3		18.2		18.1		80.2				87.7				101.6

Table A.16 Longitudinal Modulus Data after 28-day Cure and 280 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.04		9.88		9.84		9.60				9.84				9.20
Density (pcf)		128.5		126.4		125.9		122.8				126.0				117.7
Average Frequency (Hz)		333		1660		1448		3922				4075				4114
Average Modulus (MPa)		133		3240		2456		17569				19465				18527
Average Modulus (ksi)		19		470		356		2548				2823				2687
Modulus Retained (%)		0.6		12.5		12.0		75.6				87.5				101.3

Table A.17 Longitudinal Modulus Data after 28-day Cure and 300 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)				9.864		9.813		9.6				9.859				9.172
Density (pcf)				126.3		125.6		122.9				126.2				117.4
Average Frequency (Hz)				1807		1256		3902				3986				4114
Average Modulus (MPa)				3835		1843		17405				18646				18480
Average Modulus (ksi)				556		267		2524				2704				2680
Modulus Retained (%)				14.8		9.0		74.9				83.8				101.0

APPENDIX B:

LONGITUDINAL MODULUS DATA FOR

BEAM SPECIMENS CURED FOR

90 DAYS

Table B.1 Longitudinal Modulus Data after 90-day Cure and before Treatment

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	9.89	9.33	9.97	9.94	9.23	9.45	9.67	9.83	9.58	9.31	9.45	9.82	9.30	8.91	9.21	9.37
Density (pcf)	126.6	119.4	127.6	127.3	118.2	120.9	123.8	125.8	122.6	119.2	120.9	125.7	119.0	114.0	117.9	119.9
Average Frequency (Hz)	4998	4652	4883	4729	4460	4575	4633	4691	4729	4498	4441	4768	4383	4152	4268	4345
Average Modulus (MPa)	29406	24041	28286	26470	21859	23543	24722	25741	25503	22428	22177	26583	21261	18281	19978	21047
Average Modulus (ksi)	4265	3487	4103	3839	3170	3415	3586	3733	3699	3253	3217	3856	3084	2651	2898	3053

Table B.2 Longitudinal Modulus Data after 90-day Cure and after Treatment

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.45	10.09	9.97	9.94	9.90	10.23	9.67	9.83	10.23	10.01	9.45	9.82	10.01	9.69	9.21	9.37
Density (pcf)	133.8	129.2	127.6	127.3	126.7	131.0	123.8	125.8	130.9	128.2	120.9	125.7	128.1	124.1	117.9	119.9
Average Frequency (Hz)	4755	4383	4896	4729	4152	4274	4633	4691	4511	4306	4441	4768	4120	3896	4268	4345
Average Modulus (MPa)	28137	23082	28435	26470	20319	22256	24722	25741	24776	22104	22177	26583	20223	17513	19978	21047
Average Modulus (ksi)	4081	3348	4124	3839	2947	3228	3586	3733	3594	3206	3217	3856	2933	2540	2898	3053

Table B.3 Longitudinal Modulus Data after 90-day Cure and 20 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.52	10.07	10.02	9.93	9.84	10.23	9.71	9.82	10.24	10.01	9.48	9.82	10.02	9.68	9.23	9.36
Density (pcf)	134.7	128.9	128.3	127.1	126.0	130.9	124.3	125.7	131.0	128.1	121.4	125.7	128.2	123.8	118.2	119.7
Average Frequency (Hz)	4588	4293	4530	4421	4095	4268	4306	4383	4345	4229	3922	4441	3999	3845	3845	4037
Average Modulus (MPa)	26369	22097	24492	23111	19645	22178	21442	22464	23005	21315	17363	23050	19068	17026	16247	18151
Average Modulus (ksi)	3824	3205	3552	3352	2849	3217	3110	3258	3337	3092	2518	3343	2766	2469	2356	2633
Modulus Retained (%)	93.7	95.7	86.1	87.3	96.7	99.6	86.7	87.3	92.8	96.4	78.3	86.7	94.3	97.2	81.3	86.2

Table B.4 Longitudinal Modulus Data after 90-day Cure and 40 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.49	10.08	9.97	9.91	9.88	10.19	9.65	9.79	10.11	10.02	9.52	9.78	9.93	9.64	9.20	9.35
Density (pcf)	134.3	129.1	127.6	126.8	126.5	130.4	123.6	125.4	129.5	128.2	121.8	125.2	127.0	123.4	117.8	119.7
Average Frequency (Hz)	4415	4287	4402	4268	3960	4268	3864	4268	4248	4216	3672	4210	3981	3864	3614	3922
Average Modulus (MPa)	24348	22063	23007	21479	18449	22093	17158	21237	21732	21197	15276	20646	18725	17130	14312	17127
Average Modulus (ksi)	3531	3200	3337	3115	2676	3204	2489	3080	3152	3074	2216	2995	2716	2485	2076	2484
Modulus Retained (%)	86.5	95.6	80.9	81.1	90.8	99.3	69.4	82.5	87.7	95.9	68.9	77.7	92.6	97.8	71.6	81.4

Table B.5 Longitudinal Modulus Data after 90-day Cure and 60 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.41	10.06	10.00	9.92	9.79	10.17	9.56	9.79	10.21	10.02	9.45	9.75	9.86	9.63	9.14	9.35
Density (pcf)	133.3	128.8	128.0	127.0	125.2	130.2	122.3	125.3	130.7	128.3	120.9	124.8	126.2	123.2	117.0	119.7
Average Frequency (Hz)	4095	4236	4441	4204	3755	4191	2948	4075	3864	4191	2653	4075	3845	3768	3133	3806
Average Modulus (MPa)	20783	21491	23477	20869	16426	21273	9886	19360	18150	20951	7915	19283	17345	16267	10689	16135
Average Modulus (ksi)	3014	3117	3405	3027	2382	3085	1434	2808	2632	3039	1148	2797	2516	2359	1550	2340
Modulus Retained (%)	73.9	93.1	82.6	78.8	80.8	95.6	40.0	75.2	73.3	94.8	35.7	72.5	85.8	92.9	53.5	76.7

Table B.6 Longitudinal Modulus Data after 90-day Cure and 80 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.49	10.06	9.95	9.90	9.91	10.18	9.52	9.77	10.19	10.02	9.43	9.76	9.94	9.64	9.04	9.33
Density (pcf)	134.2	128.8	127.3	126.7	126.8	130.3	121.9	125.1	130.5	128.3	120.7	124.9	127.3	123.3	115.7	119.4
Average Frequency (Hz)	3576	4191	3999	3960	3537	4152	2403	3902	3422	4133	2192	4075	3710	3691	2653	3614
Average Modulus (MPa)	15962	21038	18931	18478	14760	20888	6548	17713	14209	20383	5393	19289	16294	15629	7572	14509
Average Modulus (ksi)	2315	3051	2746	2680	2141	3030	950	2569	2061	2956	782	2798	2363	2267	1098	2104
Modulus Retained (%)	56.7	91.1	66.6	69.8	72.6	93.9	26.5	68.8	57.3	92.2	24.3	72.6	80.6	89.2	37.9	68.9

Table B.7 Longitudinal Modulus Data after 90-day Cure and 100 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.52	10.05	9.94	9.89	9.91	10.17	9.49	9.72	10.23	10.13	9.21	9.74	9.98	9.63	8.72	9.35
Density (pcf)	134.6	128.6	127.2	126.5	126.8	130.1	121.4	124.4	131.0	129.7	117.9	124.7	127.7	123.2	111.7	119.7
Average Frequency (Hz)	3217	4152	3787	3877	3198	4152	1961	3845	3313	3960	1608	3883	3480	3653	1878	3576
Average Modulus (MPa)	12956	20626	16974	17690	12058	20867	4343	17100	13370	18920	2837	17489	14378	15287	3661	14237
Average Modulus (ksi)	1879	2992	2462	2566	1749	3027	630	2480	1939	2744	412	2537	2085	2217	531	2065
Modulus Retained (%)	46.0	89.4	59.7	66.8	59.3	93.8	17.6	66.4	54.0	85.6	12.8	65.8	71.1	87.3	18.3	67.6

Table B.8 Longitudinal Modulus Data after 90-day Cure and 120 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.49	10.07	9.97	9.87	9.94	10.17	9.28	9.71	10.15	10.07	9.05	9.78	9.98	9.61	8.64	9.34
Density (pcf)	134.3	128.8	127.6	126.3	127.2	130.2	118.8	124.3	129.9	128.9	115.8	125.2	127.7	123.0	110.6	119.5
Average Frequency (Hz)	2652	4172	3729	3947	2845	4152	1115	3768	3037	3960	1230	3768	3307	3672	1615	3492
Average Modulus (MPa)	8785	20852	16500	18301	9577	20876	1374	16415	11149	18795	1631	16533	12985	15417	2683	13558
Average Modulus (ksi)	1274	3024	2393	2654	1389	3028	199	2381	1617	2726	237	2398	1883	2236	389	1966
Modulus Retained (%)	31.2	90.3	58.0	69.1	47.1	93.8	5.6	63.8	45.0	85.0	7.4	62.2	64.2	88.0	13.4	64.4

Table B.9 Longitudinal Modulus Data after 90-day Cure and 140 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.56	10.06	9.96	9.85	9.93	10.17		9.71	10.21	10.06		9.77	9.99	9.60		9.31
Density (pcf)	135.2	128.7	127.5	126.1	127.2	130.1		124.3	130.7	128.8		125.1	127.8	122.9		119.2
Average Frequency (Hz)	2422	4133	3242	3941	2083	4191		3653	2691	3941		3665	3537	3653		3460
Average Modulus (MPa)	7379	20454	12466	18214	5130	21259		15428	8802	18602		15633	14876	15254		13274
Average Modulus (ksi)	1070	2967	1808	2642	744	3083		2238	1277	2698		2267	2158	2212		1925
Modulus Retained (%)	26.2	88.6	43.8	68.8	25.2	95.5		59.9	35.5	84.2		58.8	73.6	87.1		63.1

Table B.10 Longitudinal Modulus Data after 90-day Cure and 160 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.05	9.87	9.88	9.78	10.16		9.70	10.18	10.04		9.75	9.85	9.61		9.31
Density (pcf)		128.7	126.4	126.4	125.1	130.1		124.2	130.3	128.5		124.8	126.1	123.0		119.1
Average Frequency (Hz)		4037	2115	3761	1730	4133		3441	2345	3806		3409	2960	3614		3223
Average Modulus (MPa)		19504	5257	16633	3483	20665		13680	6664	17317		13492	10281	14941		11509
Average Modulus (ksi)		2829	762	2412	505	2997		1984	967	2512		1957	1491	2167		1669
Modulus Retained (%)		84.5	18.5	62.8	17.1	92.8		53.1	26.9	78.3		50.8	50.8	85.3		54.7

Table B.11 Longitudinal Modulus Data after 90-day Cure and 180 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.06	9.63	9.86	9.78	10.16		9.70	10.11	10.05		9.75	9.71	9.60		9.29
Density (pcf)		128.8	123.3	126.3	125.1	130.1		124.2	129.4	128.6		124.8	124.3	122.9		118.9
Average Frequency (Hz)		3896	1250	3306	1250	4088		3210	1724	3768		3005	2300	3454		2999
Average Modulus (MPa)		18184	1790	12839	1817	20220		11902	3575	16978		10482	6117	13633		9947
Average Modulus (ksi)		2637	260	1862	264	2933		1726	518	2462		1520	887	1977		1443
Modulus Retained (%)		78.8	6.3	48.5	8.9	90.9		46.2	14.4	76.8		39.4	30.2	77.8		47.3

Table B.12 Longitudinal Modulus Data after 90-day Cure and 200 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.06		9.87		10.15		9.70		10.03		9.75	9.66	9.60		9.29
Density (pcf)		128.7		126.4		129.9		124.1		128.4		124.8	123.7	122.9		118.9
Average Frequency (Hz)		3806		2711		4056		2896		3608		2659	1679	3447		2762
Average Modulus (MPa)		17348		8635		19877		9686		15540		8206	3242	13589		8433
Average Modulus (ksi)		2516		1252		2883		1405		2254		1190	470	1971		1223
Modulus Retained (%)		75.2		32.6		89.3		37.6		70.3		30.9	16.0	77.6		40.1

Table B.13 Longitudinal Modulus Data after 90-day Cure and 220 Freeze-Thaw Cycles

Property	Specimen														
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.04		9.86		10.14		9.69		10.01		9.74		9.59		9.29
Density (pcf)		128.6		126.2		129.8		124.0		128.2		124.6		122.7		118.9
Average Frequency (Hz)		3845		2768		4075		2845		3653		2531		3383		3653
Average Modulus (MPa)		17674		8997		20053		9338		15903		7426		13066		14759
Average Modulus (ksi)		2563		1305		2908		1354		2307		1077		1895		2141
Modulus Retained (%)		76.6		34.0		90.1		36.3		71.9		27.9		74.6		70.1

Table B.14 Longitudinal Modulus Data after 90-day Cure and 240 Freeze-Thaw Cycles

Property	Specimen														
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.03		9.85		10.16		9.76		10.01		9.73		9.57		9.28
Density (pcf)		128.4		126.0		130.1		124.9		128.1		124.6		122.5		118.8
Average Frequency (Hz)		3729		2352		4082		2454		3556		2364		3300		2640
Average Modulus (MPa)		16612		6482		20158		6995		15068		6478		12404		7703
Average Modulus (ksi)		2409		940		2924		1015		2185		940		1799		1117
Modulus Retained (%)		72.0		24.5		90.6		27.2		68.2		24.4		70.8		36.6

Table B.15 Longitudinal Modulus Data after 90-day Cure and 260 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.07		9.85		10.19		9.74		10.03		9.72		9.59		9.27
Density (pcf)		128.9		126.0		130.4		124.7		128.4		124.4		122.8		118.7
Average Frequency (Hz)		3665		2166		3960		2089		3499		2300		3192		2685
Average Modulus (MPa)		16103		5499		19019		5061		14616		6123		11632		7957
Average Modulus (ksi)		2336		798		2758		734		2120		888		1687		1154
Modulus Retained (%)		69.8		20.8		85.5		19.7		66.1		23.0		66.4		37.8

Table B.16 Longitudinal Modulus Data after 90-day Cure and 281 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.05		9.85		10.17		9.73		10.01		9.72		9.57		9.06
Density (pcf)		128.7		126.1		130.1		124.5		128.2		124.4		122.5		115.9
Average Frequency (Hz)		3447		1890		3986		1974		3403		2083		3172		2807
Average Modulus (MPa)		14226		4192		19226		4511		13804		5018		11464		8494
Average Modulus (ksi)		2063		608		2789		654		2002		728		1663		1232
Modulus Retained (%)		61.6		15.8		86.4		17.5		62.4		18.9		65.5		40.4

Table B.17 Longitudinal Modulus Data after 90-day Cure and 306 Freeze-Thaw Cycles

Property	Specimen														
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.03		9.85		10.15		9.72		10.00		9.74		9.55		9.05
Density (pcf)		128.4		126.1		130.0		124.5		128.1		124.6		122.3		115.9
Average Frequency (Hz)		3364		1679		3934		1647		3114		2070		3121		2723
Average Modulus (MPa)		13516		3305		18712		3139		11551		4966		11077		7993
Average Modulus (ksi)		1960		479		2714		455		1675		720		1607		1159
Modulus Retained (%)		58.6		12.5		84.1		12.2		52.3		18.7		63.2		38.0

APPENDIX C:

TRANSVERSE MODULUS DATA FOR

BEAM SPECIMENS CURED FOR

28 DAYS

Table C.1 Transverse Modulus Data after 28-day Cure and before Treatment

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.01	9.18	9.82	9.92	8.97	8.92	9.60	9.68	9.55	9.40	9.98	9.90	8.70	9.08	9.14	9.25
Density (pcf)	115.33	117.45	125.67	126.98	114.81	114.21	122.84	123.89	122.28	120.37	127.75	126.72	111.30	116.28	117.04	118.40
Average Frequency (Hz)	1391	1499	1576	1615	1461	1461	1461	1576	1589	1570	1596	1499	1371	1480	1461	1461
Average Modulus (MPa)	15482	18331	21678	22986	17013	16925	18203	21371	21439	20596	22590	19778	14530	17686	17344	17545
Average Modulus (ksi)	2245	2659	3144	3334	2468	2455	2640	3100	3109	2987	3276	2869	2107	2565	2516	2545

Table C.2 Transverse Modulus Data after 28-day Cure and after Treatment

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.76	10.06	9.82	9.92	9.75	9.93	9.60	9.68	10.09	10.18	9.98	9.90	9.44	9.92	9.14	9.25
Density (pcf)	124.9	128.8	125.7	127.0	124.8	127.1	122.8	123.9	129.2	130.3	127.8	126.7	120.9	127.0	117.0	118.4
Average Frequency (Hz)	1384	1499	1576	1615	1423	1423	1461	1576	1506	1499	1596	1499	1314	1423	1461	1461
Average Modulus (MPa)	16612	20106	21678	22986	17531	17858	18203	21371	20335	20332	22590	19778	14478	17845	17344	17545
Average Modulus (ksi)	2409	2916	3144	3334	2543	2590	2640	3100	2949	2949	3276	2869	2100	2588	2516	2545

Table C.3 Transverse Modulus Data after 28-day Cure and 20 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.76	10.06	9.82	9.92	9.75	9.93	9.60	9.68	10.09	10.18	9.98	9.90	9.44	9.92	9.14	9.25
Density (pcf)	124.9	128.8	125.7	127.0	124.8	127.1	122.8	123.9	129.2	130.3	127.8	126.7	120.9	127.0	117.0	118.4
Average Frequency (Hz)	1384	1461	1423	1576	1333	1410	1423	1576	1378	1461	1564	1499	1269	1384	1339	1429
Average Modulus (MPa)	16612	19089	17657	21903	15389	17537	17259	21371	17022	19304	21680	19778	13507	16893	14575	16785
Average Modulus (ksi)	2409	2769	2561	3177	2232	2544	2503	3100	2469	2800	3144	2869	1959	2450	2114	2434
Modulus Retained (%)	100.0	94.9	81.4	95.3	87.8	98.2	94.8	100.0	83.7	94.9	96.0	100.0	93.3	94.7	84.0	95.7

Table C.4 Transverse Modulus Data after 28-day Cure and 40 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.69	10.05	9.76	9.91	9.70	9.90	9.56	9.66	10.09	10.17	9.95	9.87	9.37	9.93	9.06	9.24
Density (pcf)	124.0	128.7	124.9	126.8	124.1	126.8	122.4	123.7	129.1	130.2	127.4	126.4	120.0	127.2	115.9	118.2
Average Frequency (Hz)	1384	1423	1384	1576	1307	1410	1423	1576	1205	1423	1576	1499	1269	1307	1307	1461
Average Modulus (MPa)	16492	18079	16618	21880	14727	17490	17195	21339	13008	18291	21969	19722	13407	15085	13750	17521
Average Modulus (ksi)	2392	2622	2410	3173	2136	2537	2494	3095	1887	2653	3186	2860	1945	2188	1994	2541
Modulus Retained (%)	99.3	89.9	76.7	95.2	84.0	97.9	94.5	99.9	64.0	90.0	97.3	99.7	92.6	84.5	79.3	99.9

Table C.5 Transverse Modulus Data after 28-day Cure and 60 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.99	10.06	9.82	9.92	9.98	9.93	9.57	9.68	10.36	10.18	10.06	9.89	9.67	9.95	9.25	9.22
Density (pcf)	127.9	128.7	125.7	127.0	127.7	127.1	122.5	123.9	132.6	130.3	128.8	126.6	123.8	127.4	118.4	118.1
Average Frequency (Hz)	1307	1384	1153	1538	1077	1384	1423	1576	731	1384	1499	1499	1153	1153	1038	1461
Average Modulus (MPa)	15171	17120	11608	20847	10277	16898	17208	21370	4912	17323	20106	19762	11430	11763	8855	17496
Average Modulus (ksi)	2200	2483	1684	3024	1491	2451	2496	3099	712	2513	2916	2866	1658	1706	1284	2538
Modulus Retained (%)	91.3	85.1	53.5	90.7	58.6	94.6	94.5	100.0	24.2	85.2	89.0	99.9	78.9	65.9	51.1	99.7

Table C.6 Transverse Modulus Data after 28-day Cure and 81 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.95	10.04	9.76	9.91	9.81	9.94	9.61	9.68	10.26	10.18	9.96	9.90	9.43	9.99	9.03	9.22
Density (pcf)	127.4	128.6	124.9	126.8	125.6	127.2	123.0	123.8	131.4	130.3	127.4	126.7	120.7	127.8	115.6	118.0
Average Frequency (Hz)	1077	1346	904	1499	807	1423	1384	1576	461	1346	1423	1499	884	1160	654	1461
Average Modulus (MPa)	10247	16161	7080	19797	5685	17870	16361	21362	1942	16381	17903	19776	6555	11937	3429	17488
Average Modulus (ksi)	1486	2344	1027	2871	825	2592	2373	3098	282	2376	2597	2868	951	1731	497	2536
Modulus Retained (%)	61.7	80.4	32.7	86.1	32.4	100.1	89.9	100.0	9.5	80.6	79.3	100.0	45.3	66.9	19.8	99.7

Table C.7 Transverse Modulus Data after 28-day Cure and 101 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.86	10.05	9.55	9.97	9.80	9.90	9.56	9.67	10.24	10.18	9.91	9.88	9.57	10.00	8.74	9.21
Density (pcf)	126.2	128.6	122.2	127.6	125.5	126.8	122.3	123.8	131.1	130.4	126.8	126.4	122.4	127.9	111.9	117.9
Average Frequency (Hz)	1000	1269	692	1461	577	1346	1384	1576	231	1230	1384	1499	654	731	423	1461
Average Modulus (MPa)	8755	14370	4065	18911	2897	15938	16268	21358	484	13699	16870	19732	3631	4740	1389	17477
Average Modulus (ksi)	1270	2084	590	2743	420	2312	2359	3098	70	1987	2447	2862	527	687	201	2535
Modulus Retained (%)	52.7	71.5	18.8	82.3	16.5	89.2	89.4	99.9	2.4	67.4	74.7	99.8	25.1	26.6	8.0	99.6

Table C.8 Transverse Modulus Data after 28-day Cure and 121 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.75	10.13	9.22	9.94	9.82	9.90	9.49	9.66	10.05	10.17	9.90	9.87	9.38	10.00	8.18	9.20
Density (pcf)	124.8	129.6	118.0	127.3	125.6	126.7	121.5	123.7	128.7	130.2	126.7	126.3	120.1	128.0	104.7	117.7
Average Frequency (Hz)	692	1115	500	1384	308	1294	1269	1538	192	1115	1243	1499	365	461	308	1461
Average Modulus (MPa)	4151	11190	2046	16927	825	14742	13580	20304	330	11237	13591	19716	1112	1891	688	17442
Average Modulus (ksi)	602	1623	297	2455	120	2138	1970	2945	48	1630	1971	2860	161	274	100	2530
Modulus Retained (%)	25.0	55.7	9.4	73.6	4.7	82.6	74.6	95.0	1.6	55.3	60.2	99.7	7.7	10.6	4.0	99.4

Table C.9 Transverse Modulus Data after 28-day Cure and 141 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.78	10.15		9.91	9.80	9.88	9.50	9.68		10.23	9.90	9.93	9.23	9.96		9.22
Density (pcf)	125.2	129.9		126.9	125.5	126.4	121.5	123.9		130.9	126.7	127.1	118.1	127.5		118.0
Average Frequency (Hz)	461	923		1307	192	1269	1230	1538		884	1115	1499	231	269		1461
Average Modulus (MPa)	1850	7677		15051	322	14129	12771	20341		7107	10932	19831	437	641		17487
Average Modulus (ksi)	268	1114		2183	47	2049	1852	2950		1031	1585	2876	63	93		2536
Modulus Retained (%)	11.1	38.2		65.5	1.8	79.1	70.2	95.2		35.0	48.4	100.3	3.0	3.6		99.7

Table C.10 Transverse Modulus Data after 28-day Cure and 161 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)	9.61	10.07		9.91		9.95	9.38	9.67		10.25	9.85	9.91		9.93		9.21
Density (pcf)	123.0	128.9		126.8		127.4	120.1	123.8		131.2	126.0	126.8		127.2		117.8
Average Frequency (Hz)	231	807		1230		1153	1077	1499		577	923	1499		115		1461
Average Modulus (MPa)	454	5834		13326		11767	9664	19325		3030	7449	19796		117		17462
Average Modulus (ksi)	66	846		1933		1707	1402	2803		439	1080	2871		17		2533
Modulus Retained (%)	2.7	29.0		58.0		65.9	53.1	90.4		14.9	33.0	100.1		0.7		99.5

Table C.11 Transverse Modulus Data after 28-day Cure and 186 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.06		9.91		9.87	9.35	9.66		10.24	9.88	9.93				9.20
Density (pcf)		128.8		126.9		126.3	119.7	123.6		131.0	126.4	127.0				117.8
Average Frequency (Hz)		654		1115		1077	807	1499		1115	519	1461				1461
Average Modulus (MPa)		3821		10953		10160	5416	19297		11309	2364	18826				17450
Average Modulus (ksi)		554		1589		1474	786	2799		1640	343	2730				2531
Modulus Retained (%)		19.0		47.6		56.9	29.8	90.3		55.6	10.5	95.2				99.5

Table C.12 Transverse Modulus Data after 28-day Cure and 200 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.06		9.90		9.85	9.22	9.64		10.25	9.74	9.89				9.19
Density (pcf)		128.8		126.7		126.1	118.1	123.3		131.2	124.7	126.6				117.6
Average Frequency (Hz)		615		1077		1077	731	1461		788	538	1461				1461
Average Modulus (MPa)		3383		10195		10143	4374	18276		5658	2508	18759				17431
Average Modulus (ksi)		491		1479		1471	634	2651		821	364	2721				2528
Modulus Retained (%)		16.8		44.4		56.8	24.0	85.5		27.8	11.1	94.8				99.4

Table C.13 Transverse Modulus Data after 28-day Cure and 220 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.04		9.91		9.84	9.07	9.62			9.65	9.90				9.21
Density (pcf)		128.5		126.8		126.0	116.1	123.1			123.5	126.7				117.9
Average Frequency (Hz)		481		961		923	634	1461			641	1423				1461
Average Modulus (MPa)		2061		8134		7445	3244	18247			3520	17799				17465
Average Modulus (ksi)		299		1180		1080	471	2647			511	2581				2533
Modulus Retained (%)		10.2		35.4		41.7	17.8	85.4			15.6	90.0				99.5

Table C.14 Transverse Modulus Data after 28-day Cure and 240 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.04		9.89		9.85	8.76	9.61				9.88				9.20
Density (pcf)		128.5		126.5		126.1	112.1	123.0				126.5				117.7
Average Frequency (Hz)		288		884		731	461	1423				1403				1461
Average Modulus (MPa)		741		6869		4671	1657	17288				17297				17446
Average Modulus (ksi)		108		996		677	240	2507				2509				2530
Modulus Retained (%)		3.7		29.9		26.2	9.1	80.9				87.5				99.4

Table C.15 Transverse Modulus Data after 28-day Cure and 260 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.05		9.88		9.86		9.61				9.86				9.22
Density (pcf)		128.6		126.4		126.2		123.0				126.3				118.1
Average Frequency (Hz)		231		769		615		1423				1384				1461
Average Modulus (MPa)		475		5188		3315		17275				16792				17494
Average Modulus (ksi)		69		753		481		2506				2435				2537
Modulus Retained (%)		2.4		22.6		18.6		80.8				84.9				99.7

Table C.16 Transverse Modulus Data after 28-day Cure and 280 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)		10.04		9.88		9.84		9.60				9.84				9.20
Density (pcf)		128.5		126.4		125.9		122.8				126.0				117.7
Average Frequency (Hz)		115		724		385		1384				1384				1461
Average Modulus (MPa)		119		4602		1292		16336				16758				17441
Average Modulus (ksi)		17		667		187		2369				2431				2530
Modulus Retained (%)		0.6		20.0		7.2		76.4				84.7				99.4

Table C.17 Transverse Modulus Data after 28-day Cure and 300 Freeze-Thaw Cycles

Property	Specimen															
	BG 1	BG 2	BG 4	BG 5	CD 1	CD 2	CD 5	CD 6	BR 3	BR 4	BR 7	BR 9	KS 2	KS 4	KS 7	KS 9
Weight (lb)				9.864		9.813		9.6				9.859				9.172
Density (pcf)				126.3		125.6		122.9				126.2				117.4
Average Frequency (Hz)				629		231		1384				1384				1461
Average Modulus (MPa)				3469		464		16343				16784				17397
Average Modulus (ksi)				503		67		2370				2434				2523
Modulus Retained (%)				15.1		2.6		76.5				84.9				99.2

APPENDIX D:

TRANSVERSE MODULUS DATA FOR

BEAM SPECIMENS CURED FOR

90 DAYS

Table D.1 Transverse Modulus Data after 90-day Cure and before Treatment

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	9.89	9.33	9.97	9.94	9.23	9.45	9.67	9.83	9.58	9.31	9.45	9.82	9.30	8.91	9.21	9.37
Density (pcf)	126.6	119.4	127.6	127.3	118.2	120.9	123.8	125.8	122.6	119.2	120.9	125.7	119.0	114.0	117.9	119.9
Average Frequency (Hz)	1769	1615	1711	1692	1576	1608	1615	1615	1653	1576	1538	1692	1499	1461	1499	1499
Average Modulus (MPa)	27482	21620	25922	25284	20382	21717	22417	22771	23264	20556	19854	24984	18572	16893	18407	18712
Average Modulus (ksi)	3986	3136	3760	3667	2956	3150	3251	3303	3374	2981	2880	3624	2694	2450	2670	2714

Table D.2 Transverse Modulus Data after 90-day Cure and after Treatment

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.45	10.09	9.97	9.94	9.90	10.23	9.67	9.83	10.23	10.01	9.45	9.82	10.01	9.69	9.21	9.37
Density (pcf)	133.8	129.2	127.6	127.3	126.7	131.0	123.8	125.8	130.9	128.2	120.9	125.7	128.1	124.1	117.9	119.9
Average Frequency (Hz)	1653	1499	1711	1692	1455	1461	1615	1615	1538	1461	1538	1692	1403	1346	1499	1499
Average Modulus (MPa)	25391	20163	25922	25284	18612	19411	22417	22771	21493	18993	19854	24984	17511	15596	18407	18712
Average Modulus (ksi)	3683	2924	3760	3667	2699	2815	3251	3303	3117	2755	2880	3624	2540	2262	2670	2714

Table D.3 Transverse Modulus Data after 90-day Cure and 20 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.52	10.07	10.02	9.93	9.84	10.23	9.71	9.82	10.24	10.01	9.48	9.82	10.02	9.68	9.23	9.36
Density (pcf)	134.7	128.9	128.3	127.1	126.0	130.9	124.3	125.7	131.0	128.1	121.4	125.7	128.2	123.8	118.2	119.7
Average Frequency (Hz)	1576	1461	1576	1576	1423	1480	1499	1499	1461	1423	1346	1538	1384	1346	1384	1423
Average Modulus (MPa)	23232	19100	22132	21925	17700	19914	19405	19622	19418	18002	15260	20636	17053	15569	15717	16824
Average Modulus (ksi)	3370	2770	3210	3180	2567	2888	2814	2846	2816	2611	2213	2993	2473	2258	2280	2440
Modulus Retained (%)	91.5	94.7	85.4	86.7	95.1	102.6	86.6	86.2	90.3	94.8	76.9	82.6	97.4	99.8	85.4	89.9

Table D.4 Transverse Modulus Data after 90-day Cure and 40 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.49	10.08	9.97	9.91	9.88	10.19	9.65	9.79	10.11	10.02	9.52	9.78	9.93	9.64	9.20	9.35
Density (pcf)	134.3	129.1	127.6	126.8	126.5	130.4	123.6	125.4	129.5	128.2	121.8	125.2	127.0	123.4	117.8	119.7
Average Frequency (Hz)	1538	1461	1499	1461	1365	1461	1269	1461	1435	1461	1230	1448	1346	1307	1230	1346
Average Modulus (MPa)	22051	19127	19922	18789	16357	19326	13809	18577	18517	18996	12797	18235	15972	14634	12379	15053
Average Modulus (ksi)	3198	2774	2889	2725	2372	2803	2003	2694	2686	2755	1856	2645	2317	2123	1795	2183
Modulus Retained (%)	86.8	94.9	76.9	74.3	87.9	99.6	61.6	81.6	86.2	100.0	64.5	73.0	91.2	93.8	67.3	80.4

Table D.5 Transverse Modulus Data after 90-day Cure and 60 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.41	10.06	10.00	9.92	9.79	10.17	9.56	9.79	10.21	10.02	9.45	9.75	9.86	9.63	9.14	9.35
Density (pcf)	133.3	128.8	128.0	127.0	125.2	130.2	122.3	125.3	130.7	128.3	120.9	124.8	126.2	123.2	117.0	119.7
Average Frequency (Hz)	1423	1442	1538	1499	1269	1461	923	1384	1230	1429	769	1423	1269	1307	1038	1307
Average Modulus (MPa)	18725	18588	21017	19818	13998	19298	7231	16668	13734	18182	4963	17538	14100	14615	8757	14204
Average Modulus (ksi)	2716	2696	3048	2874	2030	2799	1049	2417	1992	2637	720	2544	2045	2120	1270	2060
Modulus Retained (%)	73.7	92.2	81.1	78.4	75.2	99.4	32.3	73.2	63.9	95.7	25.0	70.2	80.5	93.7	47.6	75.9

Table D.6 Transverse Modulus Data after 90-day Cure and 80 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.49	10.06	9.95	9.90	9.91	10.18	9.52	9.77	10.19	10.02	9.43	9.76	9.94	9.64	9.04	9.33
Density (pcf)	134.2	128.8	127.3	126.7	126.8	130.3	121.9	125.1	130.5	128.3	120.7	124.9	127.3	123.3	115.7	119.4
Average Frequency (Hz)	1269	1423	1384	1384	1153	1423	731	1384	1077	1384	615	1384	1230	1269	846	1230
Average Modulus (MPa)	15002	18095	16932	16848	11714	18300	4516	16632	10497	17063	3172	16607	13373	13786	5745	12549
Average Modulus (ksi)	2176	2624	2456	2444	1699	2654	655	2412	1522	2475	460	2409	1940	1999	833	1820
Modulus Retained (%)	59.1	89.7	65.3	66.6	62.9	94.3	20.1	73.0	48.8	89.8	16.0	66.5	76.4	88.4	31.2	67.1

Table D.7 Transverse Modulus Data after 90-day Cure and 100 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.52	10.05	9.94	9.89	9.91	10.17	9.49	9.72	10.23	10.13	9.21	9.74	9.98	9.63	8.72	9.35
Density (pcf)	134.6	128.6	127.2	126.5	126.8	130.1	121.4	124.4	131.0	129.7	117.9	124.7	127.7	123.2	111.7	119.7
Average Frequency (Hz)	1153	1423	1307	1346	1038	1461	615	1307	1038	1346	423	1346	1153	1237	577	1230
Average Modulus (MPa)	12433	18071	15095	15910	9486	19283	3191	14755	9798	16307	1464	15677	11793	13082	2578	12581
Average Modulus (ksi)	1803	2621	2189	2307	1376	2797	463	2140	1421	2365	212	2274	1710	1897	374	1825
Modulus Retained (%)	49.0	89.6	58.2	62.9	51.0	99.3	14.2	64.8	45.6	85.9	7.4	62.7	67.3	83.9	14.0	67.2

Table D.8 Transverse Modulus Data after 90-day Cure and 120 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.49	10.07	9.97	9.87	9.94	10.17	9.28	9.71	10.15	10.07	9.05	9.78	9.98	9.61	8.64	9.34
Density (pcf)	134.3	128.8	127.6	126.3	127.2	130.2	118.8	124.3	129.9	128.9	115.8	125.2	127.7	123.0	110.6	119.5
Average Frequency (Hz)	846	1384	1269	1346	923	1423	423	1307	923	1307	346	1307	1115	1230	500	1192
Average Modulus (MPa)	6670	17134	14255	15877	7518	18290	1475	14748	7680	15286	963	14854	11021	12920	1918	11788
Average Modulus (ksi)	967	2485	2068	2303	1090	2653	214	2139	1114	2217	140	2154	1598	1874	278	1710
Modulus Retained (%)	26.3	85.0	55.0	62.8	40.4	94.2	6.6	64.8	35.7	80.5	4.8	59.5	62.9	82.8	10.4	63.0

Table D.9 Transverse Modulus Data after 90-day Cure and 140 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)	10.56	10.06	9.96	9.85	9.93	10.17		9.71	10.21	10.06		9.77	9.99	9.60		9.31
Density (pcf)	135.2	128.7	127.5	126.1	127.2	130.1		124.3	130.7	128.8		125.1	127.8	122.9		119.2
Average Frequency (Hz)	801	1384	1077	1307	673	1423		1230	807	1307		1230	1230	1230		1192
Average Modulus (MPa)	6024	17122	10256	14958	3996	18285		13066	5914	15277		13147	13433	12918		11755
Average Modulus (ksi)	874	2483	1488	2170	580	2652		1895	858	2216		1907	1948	1874		1705
Modulus Retained (%)	23.7	84.9	39.6	59.2	21.5	94.2		57.4	27.5	80.4		52.6	76.7	82.8		62.8

Table D.10 Transverse Modulus Data after 90-day Cure and 160 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.05	9.87	9.88	9.78	10.16		9.70	10.18	10.04		9.75	9.85	9.61		9.31
Density (pcf)		128.7	126.4	126.4	125.1	130.1		124.2	130.3	128.5		124.8	126.1	123.0		119.1
Average Frequency (Hz)		1346	807	1307	577	1423		1173	654	1250		1153	961	1230		1115
Average Modulus (MPa)		16177	5720	14995	2889	18273		11858	3863	13930		11524	8090	12923		10280
Average Modulus (ksi)		2346	830	2175	419	2650		1720	560	2020		1671	1173	1874		1491
Modulus Retained (%)		80.2	22.1	59.3	15.5	94.1		52.1	18.0	73.3		46.1	46.2	82.9		54.9

Table D.11 Transverse Modulus Data after 90-day Cure and 180 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.06	9.63	9.86	9.78	10.16		9.70	10.11	10.05		9.75	9.71	9.60		9.29
Density (pcf)		128.8	123.3	126.3	125.1	130.1		124.2	129.4	128.6		124.8	124.3	122.9		118.9
Average Frequency (Hz)		1307	538	1192	385	1423		1096	481	1230		1038	756	1173		1057
Average Modulus (MPa)		15279	2480	12453	1284	18275		10349	2074	13512		9335	4932	11730		9228
Average Modulus (ksi)		2216	360	1806	186	2651		1501	301	1960		1354	715	1701		1338
Modulus Retained (%)		75.8	9.6	49.3	6.9	94.1		45.5	9.7	71.1		37.4	28.2	75.2		49.3

Table D.12 Transverse Modulus Data after 90-day Cure and 200 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.06		9.87		10.15		9.70		10.03		9.75	9.66	9.60		9.29
Density (pcf)		128.7		126.4		129.9		124.1		128.4		124.8	123.7	122.9		118.9
Average Frequency (Hz)		1269		1192		1384		1019		1153		897	577	1153		961
Average Modulus (MPa)		14389		12462		17276		8946		11856		6971	2855	11354		7625
Average Modulus (ksi)		2087		1807		2506		1297		1720		1011	414	1647		1106
Modulus Retained (%)		71.4		49.3		89.0		39.3		62.4		27.9	16.3	72.8		40.7

Table D.13 Transverse Modulus Data after 90-day Cure and 220 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.04		9.86		10.14		9.69		10.01		9.74		9.59		9.29
Density (pcf)		128.6		126.2		129.8		124.0		128.2		124.6		122.7		118.9
Average Frequency (Hz)		1269		1039		1384		1038		1211		846		1153		1153
Average Modulus (MPa)		14367		9459		17265		9279		13051		6190		11334		10985
Average Modulus (ksi)		2084		1372		2504		1346		1893		898		1644		1593
Modulus Retained (%)		71.3		37.4		88.9		40.8		68.7		24.8		72.7		58.7

Table D.14 Transverse Modulus Data after 90-day Cure and 240 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.03		9.85		10.16		9.76		10.01		9.73		9.57		9.28
Density (pcf)		128.4		126.0		130.1		124.9		128.1		124.6		122.5		118.8
Average Frequency (Hz)		1230		1038		1384		846		1153		827		1115		923
Average Modulus (MPa)		13494		9428		17300		6201		11829		5910		10569		7023
Average Modulus (ksi)		1957		1367		2509		899		1716		857		1533		1019
Modulus Retained (%)		66.9		37.3		89.1		27.2		62.3		23.7		67.8		37.5

Table D.15 Transverse Modulus Data after 90-day Cure and 260 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.07		9.85		10.19		9.74		10.03		9.72		9.59		9.27
Density (pcf)		128.9		126.0		130.4		124.7		128.4		124.4		122.8		118.7
Average Frequency (Hz)		1192		1000		1346		807		1115		807		1077		962
Average Modulus (MPa)		12710		8743		16392		5643		11080		5630		9876		7619
Average Modulus (ksi)		1843		1268		2378		818		1607		816		1432		1105
Modulus Retained (%)		63.0		34.6		84.4		24.8		58.3		22.5		63.3		40.7

Table D.16 Transverse Modulus Data after 90-day Cure and 281 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.05		9.85		10.17		9.73		10.01		9.72		9.57		9.06
Density (pcf)		128.7		126.1		130.1		124.5		128.2		124.4		122.5		115.9
Average Frequency (Hz)		1115		884		1346		731		1077		731		1077		1000
Average Modulus (MPa)		11107		6847		16359		4612		10313		4608		9856		8042
Average Modulus (ksi)		1611		993		2373		669		1496		668		1429		1166
Modulus Retained (%)		55.1		27.1		84.3		20.3		54.3		18.4		63.2		43.0

Table D.17 Transverse Modulus Data after 90-day Cure and 306 Freeze-Thaw Cycles

Property	Specimen															
	BG 7	BG 6	BG 8	BG 9	CD 3	CD 7	CD 9	CD 4	BR 5	BR 6	BR 1	BR 2	KS 6	KS 1	KS 8	KS 5
Weight (lb)		10.03		9.85		10.15		9.72		10.00		9.74		9.55		9.05
Density (pcf)		128.4		126.1		130.0		124.5		128.1		124.6		122.3		115.9
Average Frequency (Hz)		1115		769		1346		577		961		750		1057		961
Average Modulus (MPa)		11082		5175		16339		2874		8214		4863		9491		7432
Average Modulus (ksi)		1607		751		2370		417		1191		705		1377		1078
Modulus Retained (%)		55.0		20.5		84.2		12.6		43.2		19.5		60.9		39.7

APPENDIX E:

PICTORAL RESULTS OF SPECIMENS CURED FOR 28 DAYS AND TESTED IN A CLOGGED, SATURATED CONDITION

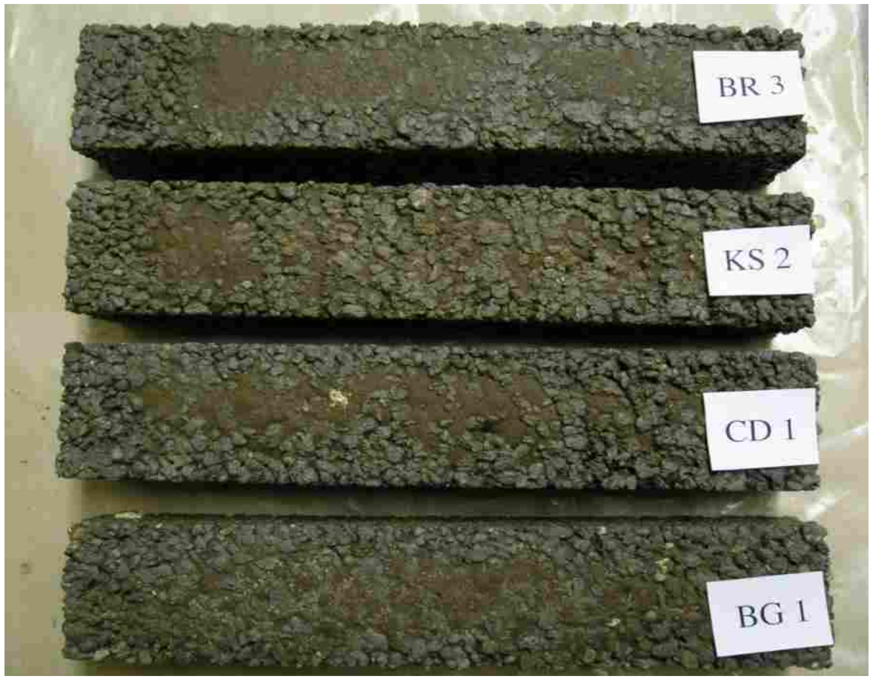

Figure E.1 Clogged, saturated specimens after 28-day cure and 20 freeze-thaw cycles.

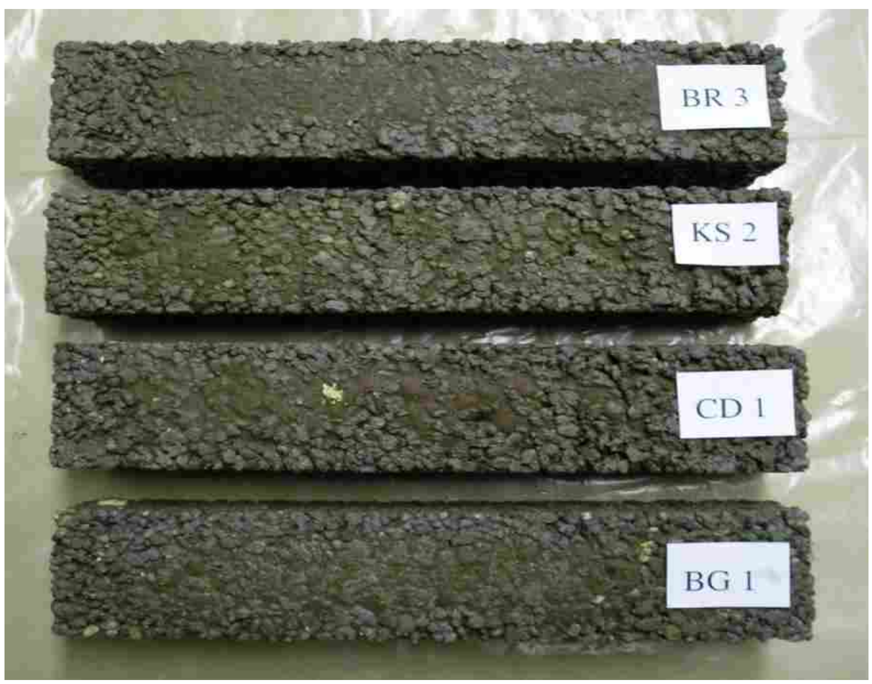

Figure E.2 Clogged, saturated specimens after 28-day cure and 40 freeze-thaw cycles.

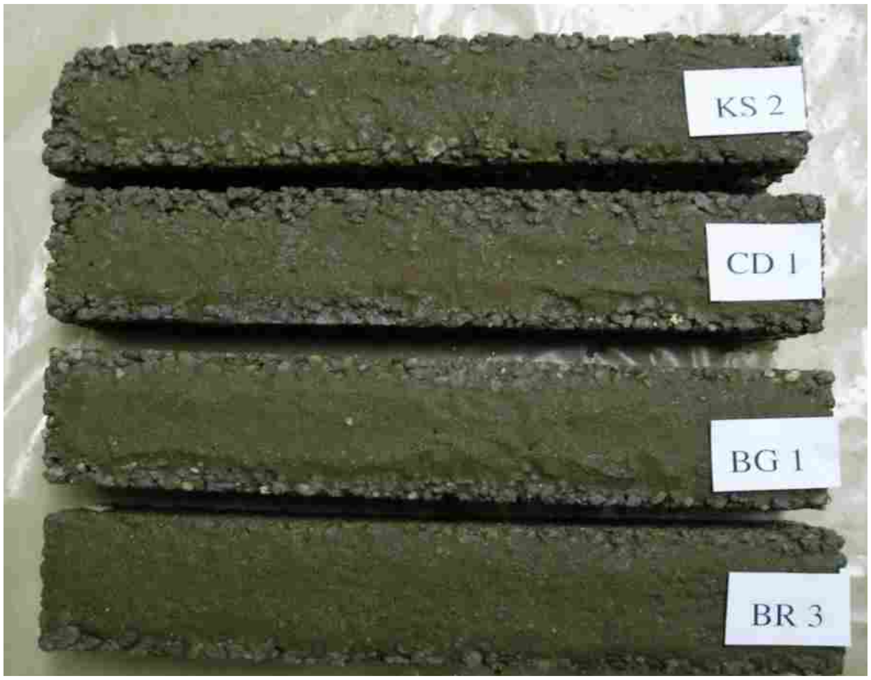

Figure E.3 Clogged, saturated specimens after 28-day cure and 60 freeze-thaw cycles.

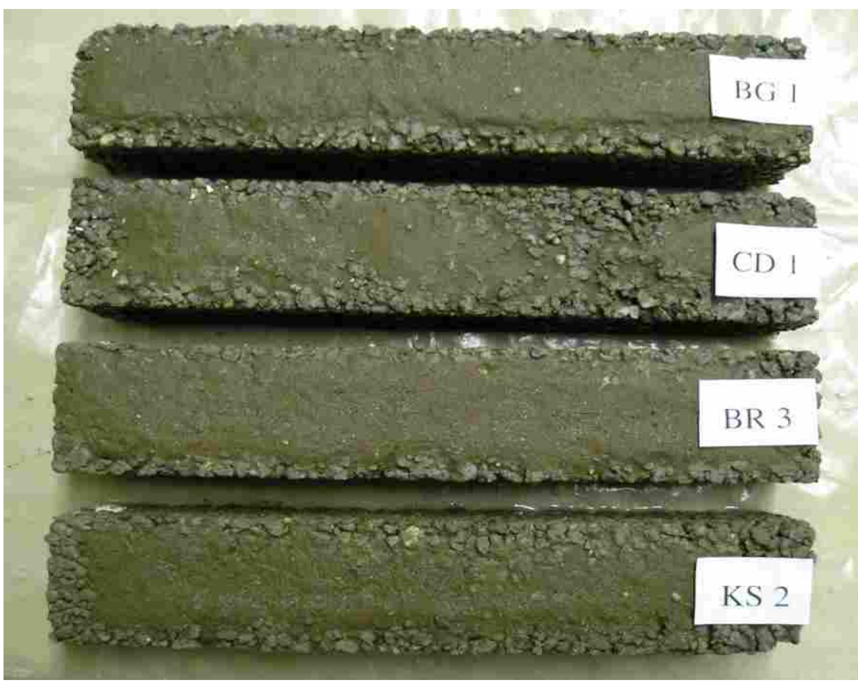

Figure E.4 Clogged, saturated specimens after 28-day cure and 81 freeze-thaw cycles.

Figure E.5 Clogged, saturated specimens after 28-day cure and 101 freeze-thaw cycles.

Figure E.6 Clogged, saturated specimens after 28-day cure and 121 freeze-thaw cycles.

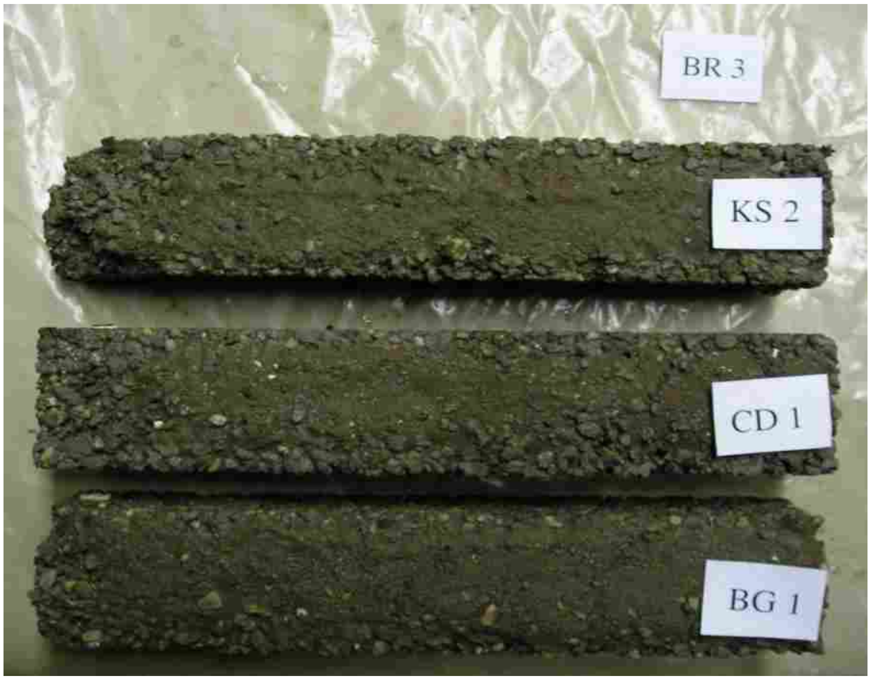

Figure E.7 Clogged, saturated specimens after 28-day cure and 141 freeze-thaw cycles.

Figure E.8 Clogged, saturated specimens after 28-day cure and 161 freeze-thaw cycles.

APPENDIX F:

PICTORAL RESULTS OF SPECIMENS CURED FOR 28 DAYS AND TESTED IN A CLOGGED, UNSATURATED CONDITION

Figure F.1 Unsaturated, clogged specimens after 28-day cure and 20 freeze-thaw cycles.

Figure F.2 Unsaturated, clogged specimens after 28-day cure and 40 freeze-thaw cycles.

Figure F.3 Unsaturated, clogged specimens after 28-day cure and 60 freeze-thaw cycles.

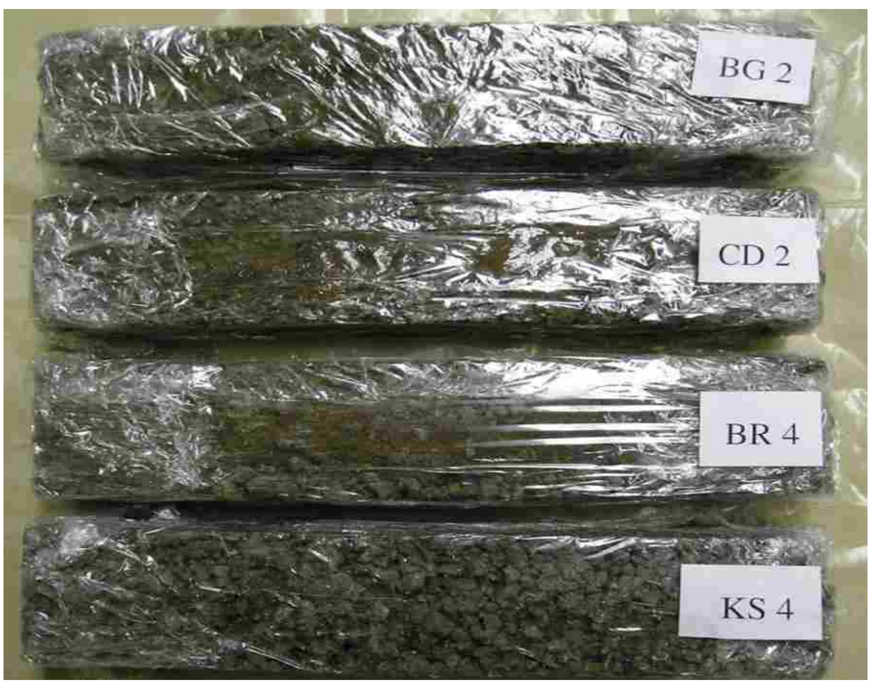

Figure F.4 Unsaturated, clogged specimens after 28-day cure and 81 freeze-thaw cycles.

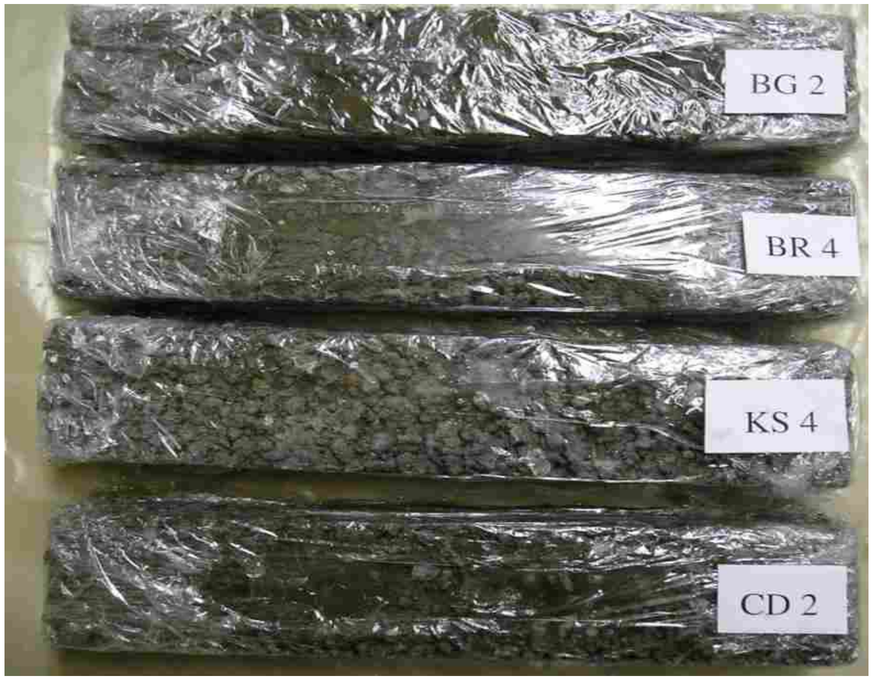

Figure F.5 Unsaturated, clogged specimens after 28-day cure and 101 freeze-thaw cycles.

Figure F.6 Unsaturated, clogged specimens after 28-day cure and 121 freeze-thaw cycles.

Figure F.7 Unsaturated, clogged specimens after 28-day cure and 141 freeze-thaw cycles.

Figure F.8 Unsaturated, clogged specimens after 28-day cure and 161 freeze-thaw cycles.

Figure F.9 Unsaturated, clogged specimens after 28-day cure and 186 freeze-thaw cycles.

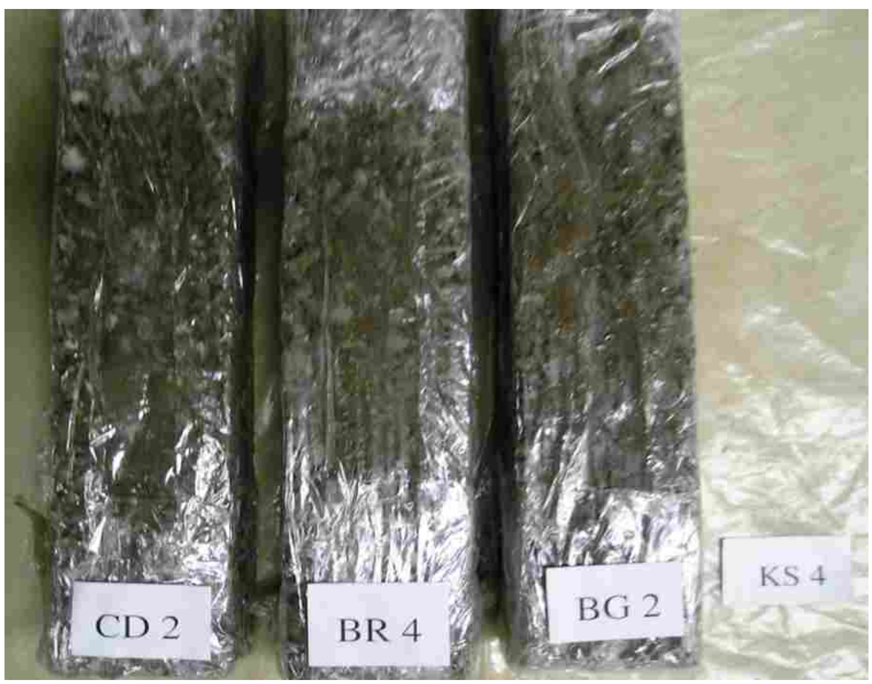

Figure F.10 Unsaturated, clogged specimens after 28-day cure and 200 freeze-thaw cycles.

Figure F.11 Unsaturated, clogged specimens after 28-day cure and 220 freeze-thaw cycles.

Figure F.12 Unsaturated, clogged specimens after 28-day cure and 240 freeze-thaw cycles.

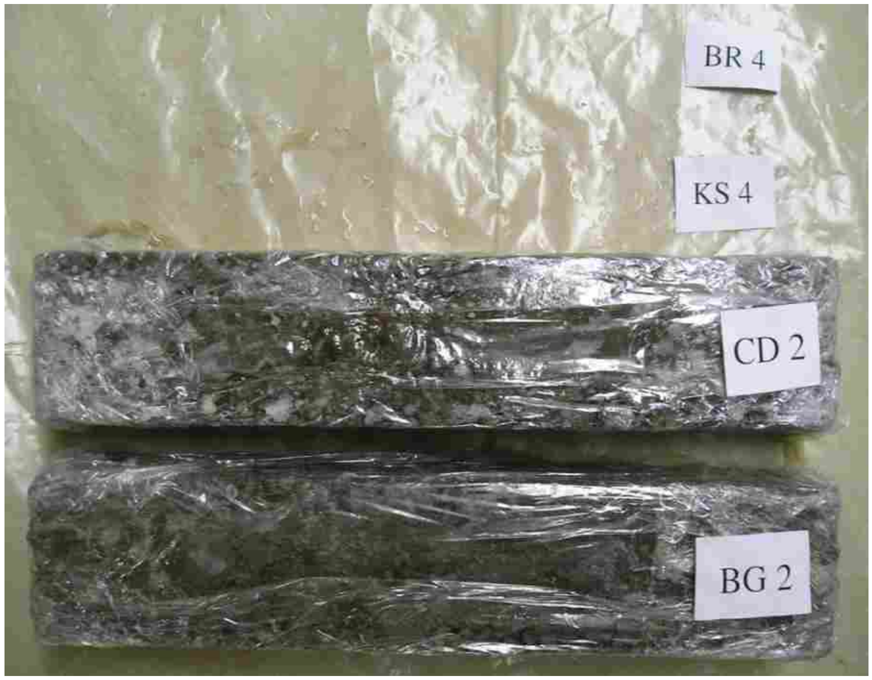

Figure F.13 Unsaturated, clogged specimens after 28-day cure and 260 freeze-thaw cycles.

Figure F.14 Unsaturated, clogged specimens after 28-day cure and 280 freeze-thaw cycles.

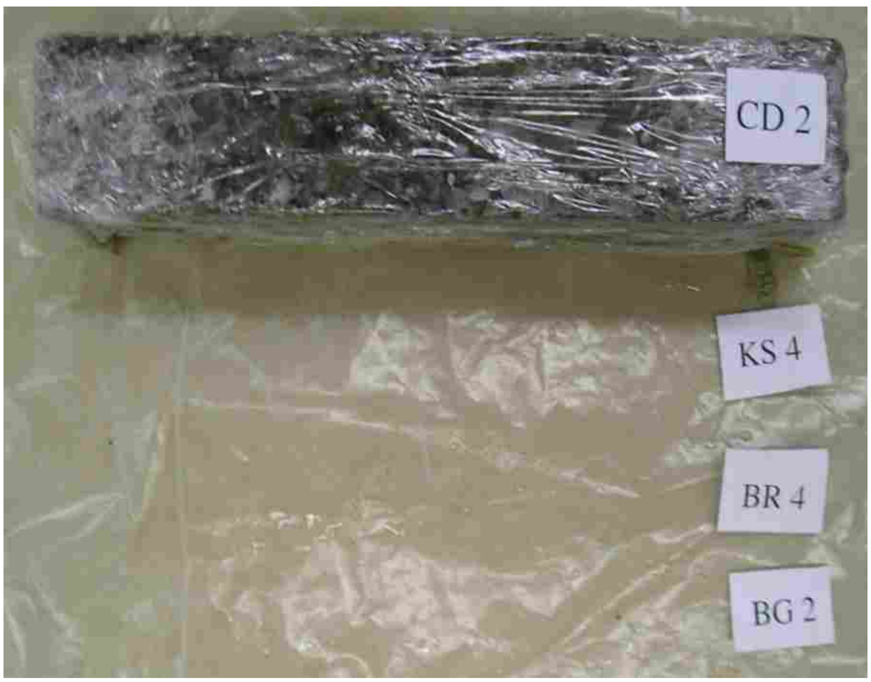

Figure F.15 Unsaturated, clogged specimens after 28-day cure and 300 freeze-thaw cycles.

APPENDIX G:

PICTORAL RESULTS OF SPECIMENS CURED FOR 28 DAYS AND TESTED IN A UNCLOGGED, SATURATED CONDITION

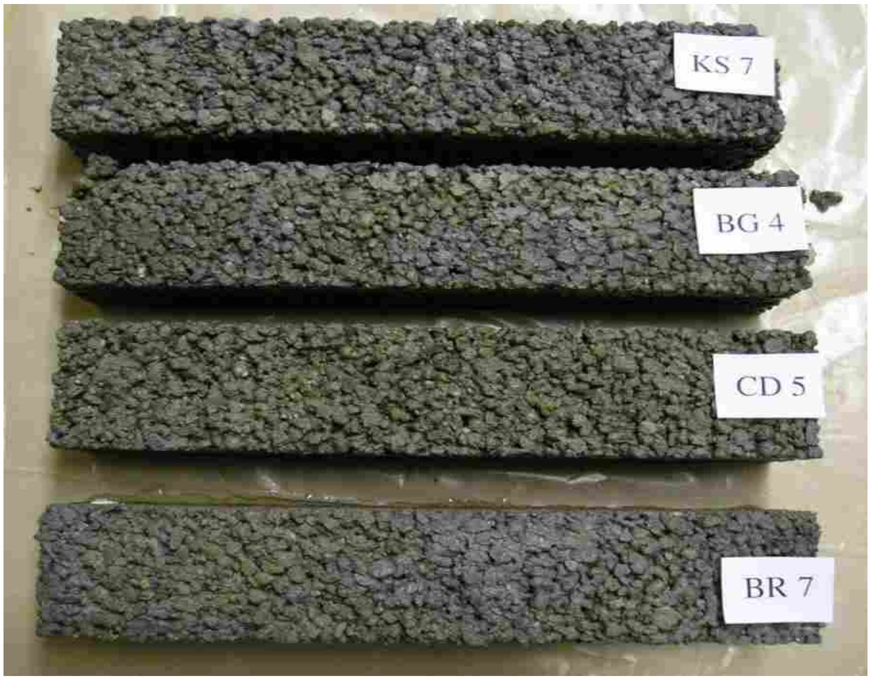

Figure G.1 Unclogged, saturated specimens after 28-day cure and 20 freeze-thaw cycles.

Figure G.2 Unclogged, saturated specimens after 28-day cure and 40 freeze-thaw cycles.

Figure G.3 Unclogged, saturated specimens after 28-day cure and 60 freeze-thaw cycles.

Figure G.4 Unclogged, saturated specimens after 28-day cure and 81 freeze-thaw cycles.

Figure G.5 Unclogged, saturated specimens after 28-day cure and 101 freeze-thaw cycles.

Figure G.6 Unclogged, saturated specimens after 28-day cure and 121 freeze-thaw cycles.

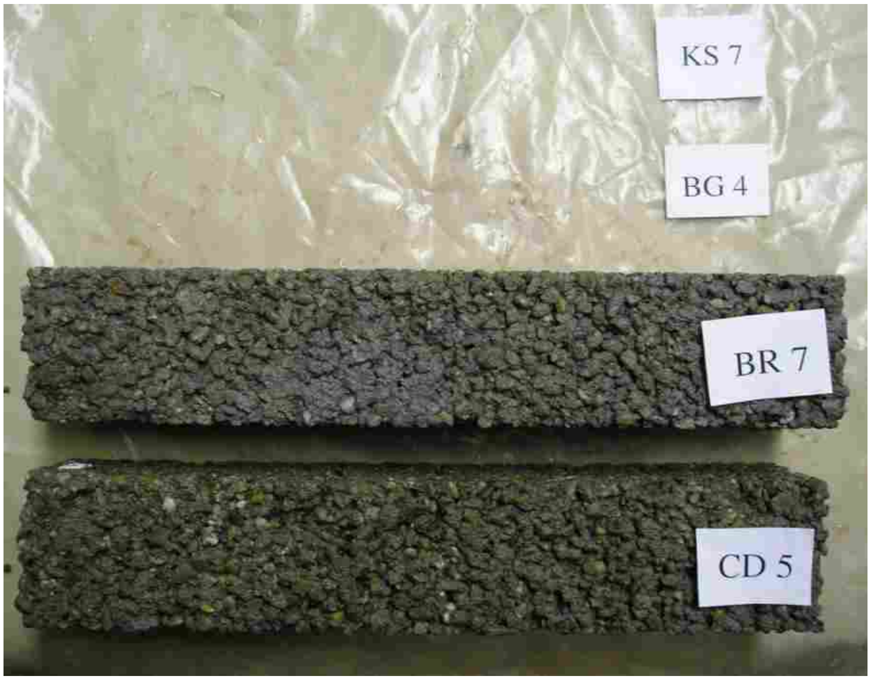

Figure G.7 Unclogged, saturated specimens after 28-day cure and 141 freeze-thaw cycles.

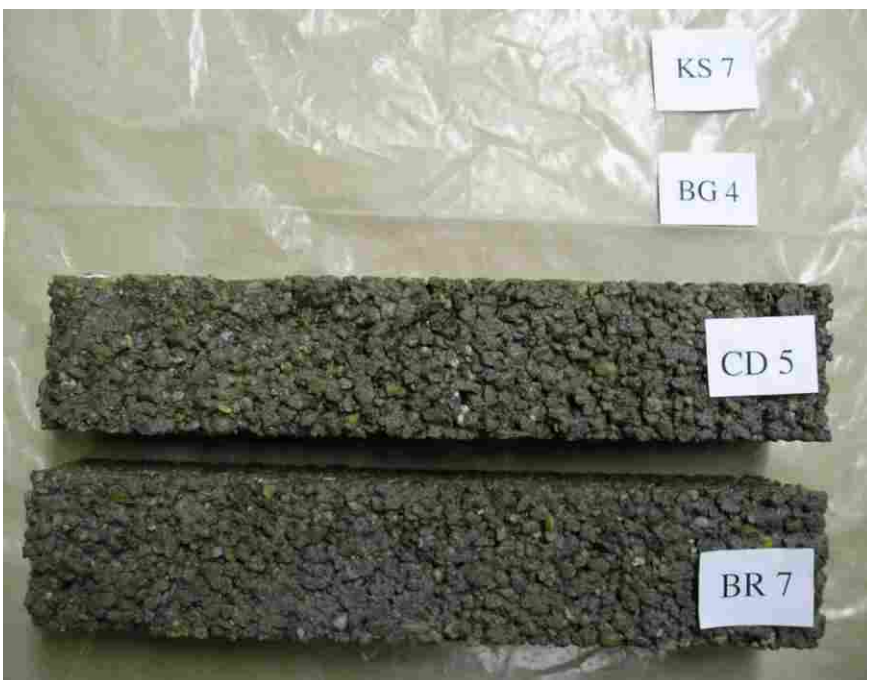

Figure G.8 Unclogged, saturated specimens after 28-day cure and 161 freeze-thaw cycles.

Figure G.9 Unclogged, saturated specimens after 28-day cure and 186 freeze-thaw cycles.

Figure G.10 Unclogged, saturated specimens after 28-day cure and 200 freeze-thaw cycles.

Figure G.11 Unclogged, saturated specimens after 28-day cure and 220 freeze-thaw cycles.

Figure G.12 Unclogged, saturated specimens after 28-day cure and 240 freeze-thaw cycles.

APPENDIX H:

PICTORAL RESULTS OF SPECIMENS

CURED FOR 28 DAYS AND TESTED

IN A UNCLOGGED,

UNSATURATED

CONDITION

Figure H.1 Unclogged, unsaturated specimens after 28-day cure and 20 freeze-thaw cycles.

Figure H.2 Unclogged, unsaturated specimens after 28-day cure and 40 freeze-thaw cycles.

Figure H.3 Unclogged, unsaturated specimens after 28-day cure and 60 freeze-thaw cycles.

Figure H.4 Unclogged, unsaturated specimens after 28-day cure and 81 freeze-thaw cycles.

Figure H.5 Unclogged, unsaturated specimens after 28-day cure and 101 freeze-thaw cycles.

Figure H.6 Unclogged, unsaturated specimens after 28-day cure and 121 freeze-thaw cycles.

Figure H.7 Unclogged, unsaturated specimens after 28-day cure and 141 freeze-thaw cycles.

Figure H.8 Unclogged, unsaturated specimens after 28-day cure and 161 freeze-thaw cycles.

Figure H.9 Unclogged, unsaturated specimens after 28-day cure and 186 freeze-thaw cycles.

Figure H.10 Unclogged, unsaturated specimens after 28-day cure and 200 freeze-thaw cycles.

Figure H.11 Unclogged, unsaturated specimens after 28-day cure and 220 freeze-thaw cycles.

Figure H.12 Unclogged, unsaturated specimens after 28-day cure and 240 freeze-thaw cycles.

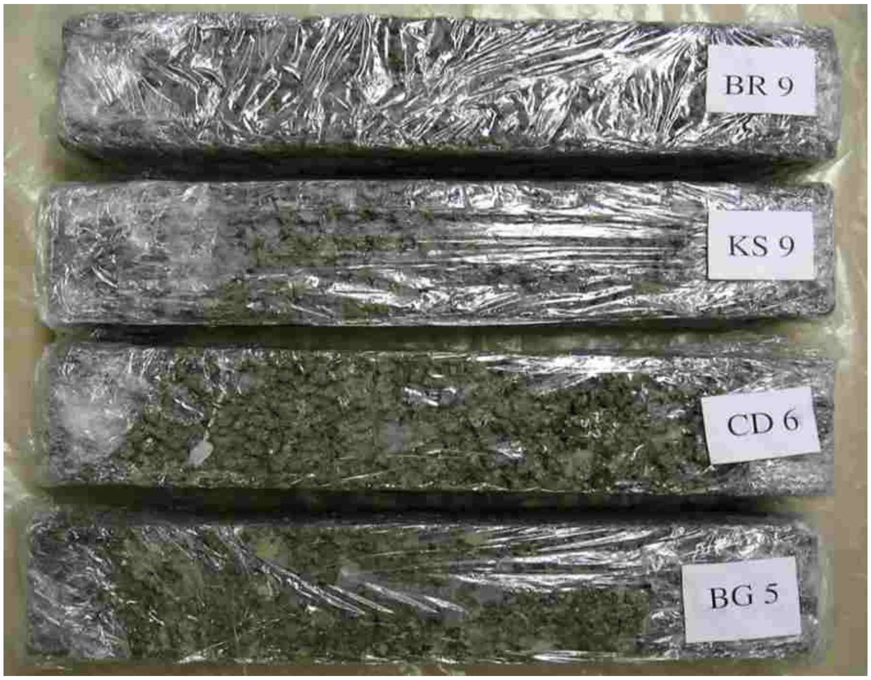

Figure H.13 Unclogged, unsaturated specimens after 28-day cure and 260 freeze-thaw cycles.

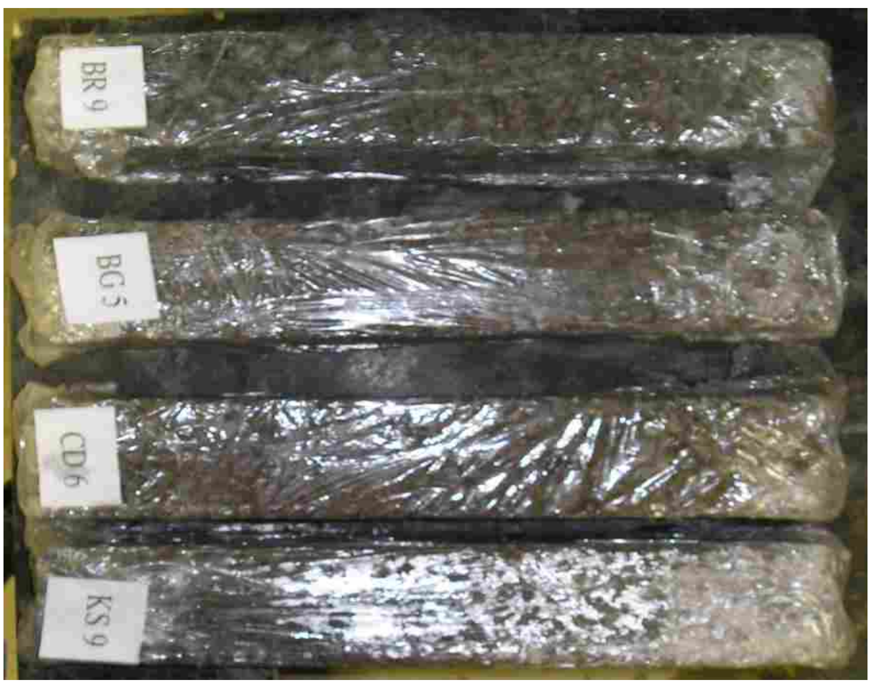

Figure H.14 Unclogged, unsaturated specimens after 28-day cure and 280 freeze-thaw cycles.

Figure H.15 Unclogged, unsaturated specimens after 28-day cure and 300 freeze-thaw cycles.

APPENDIX I:

PICTORAL RESULTS OF SPECIMENS CURED FOR 90 DAYS AND TESTED IN A CLOGGED, SATURATED CONDITION

Figure I.1 Clogged, saturated specimens after 90-day cure and 20 freeze-thaw cycles.

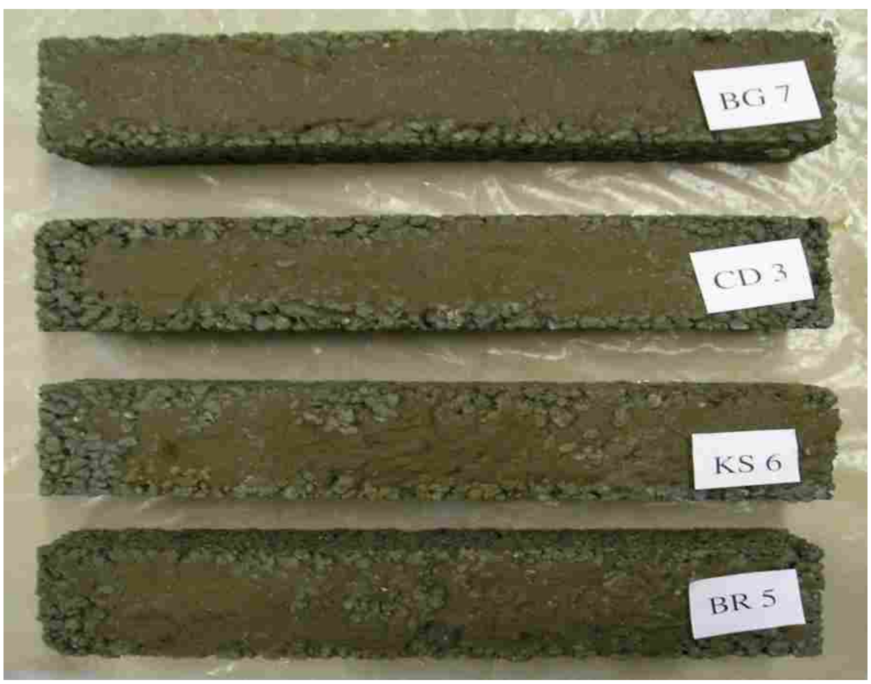

Figure I.2 Clogged, saturated specimens after 90-day cure and 40 freeze-thaw cycles.

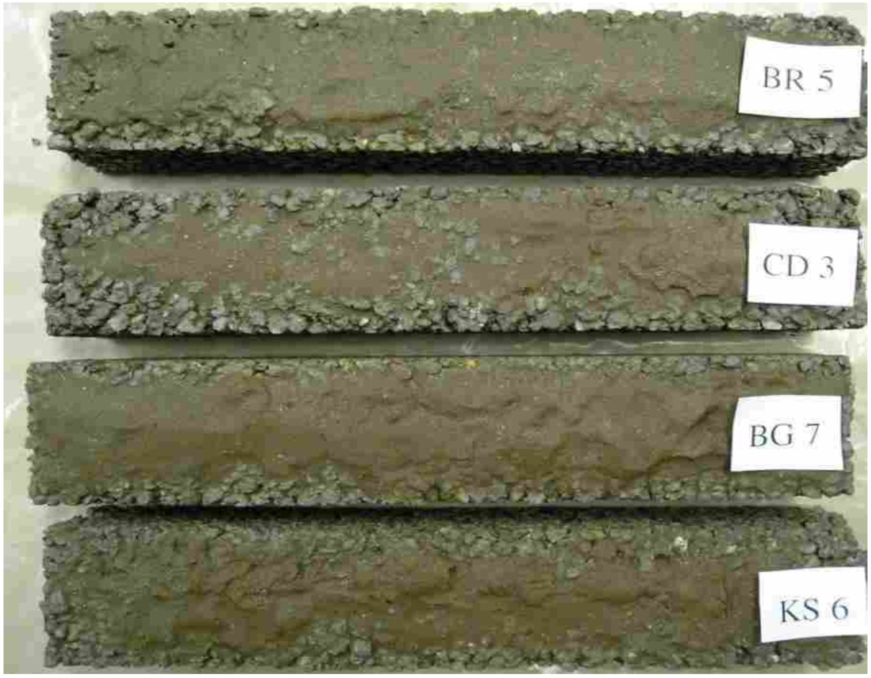

Figure I.3 Clogged, saturated specimens after 90-day cure and 60 freeze-thaw cycles.

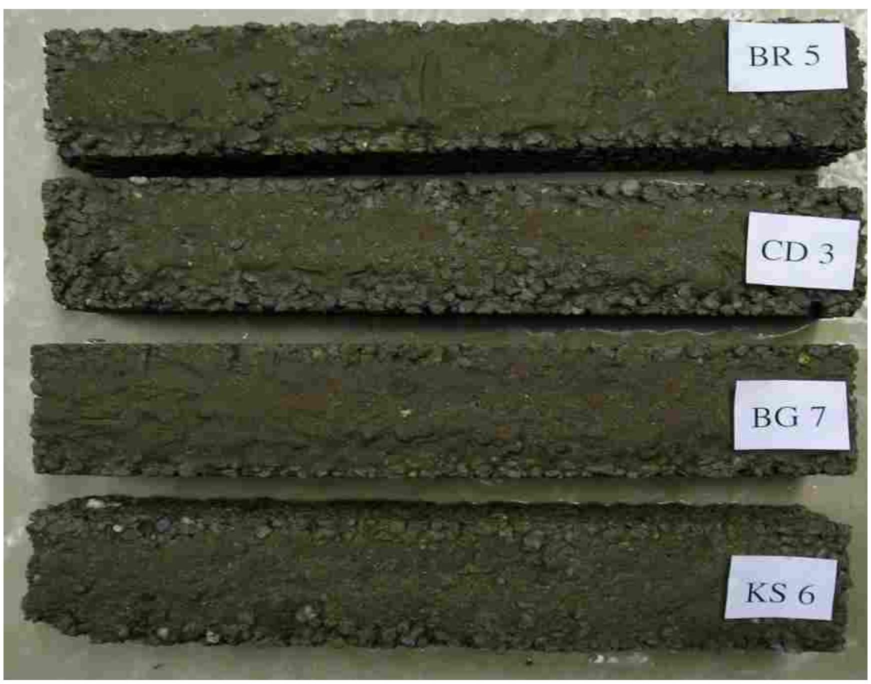

Figure I.4 Clogged, saturated specimens after 90-day cure and 80 freeze-thaw cycles.

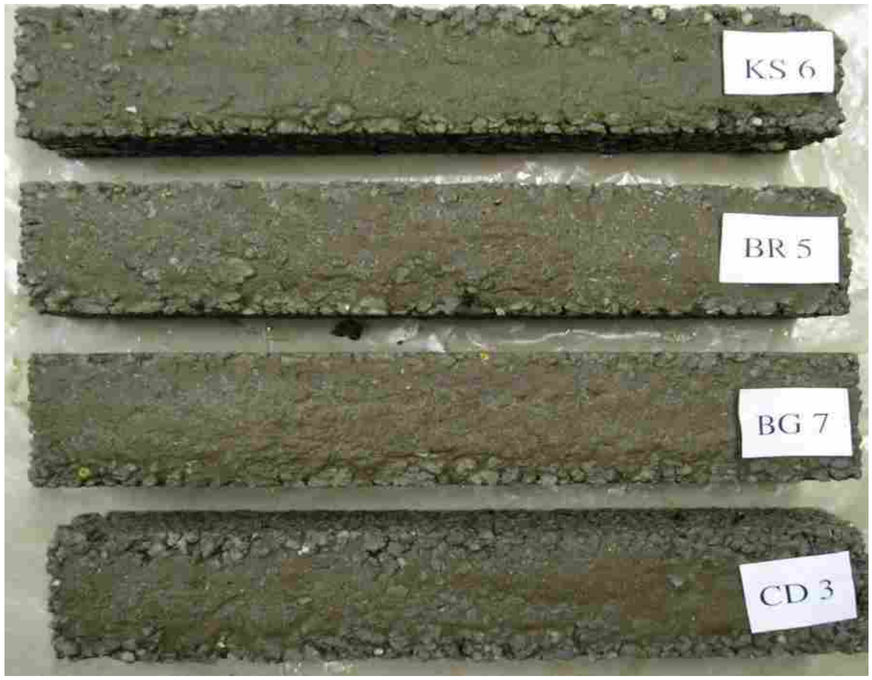

Figure I.5 Clogged, saturated specimens after 90-day cure and 100 freeze-thaw cycles.

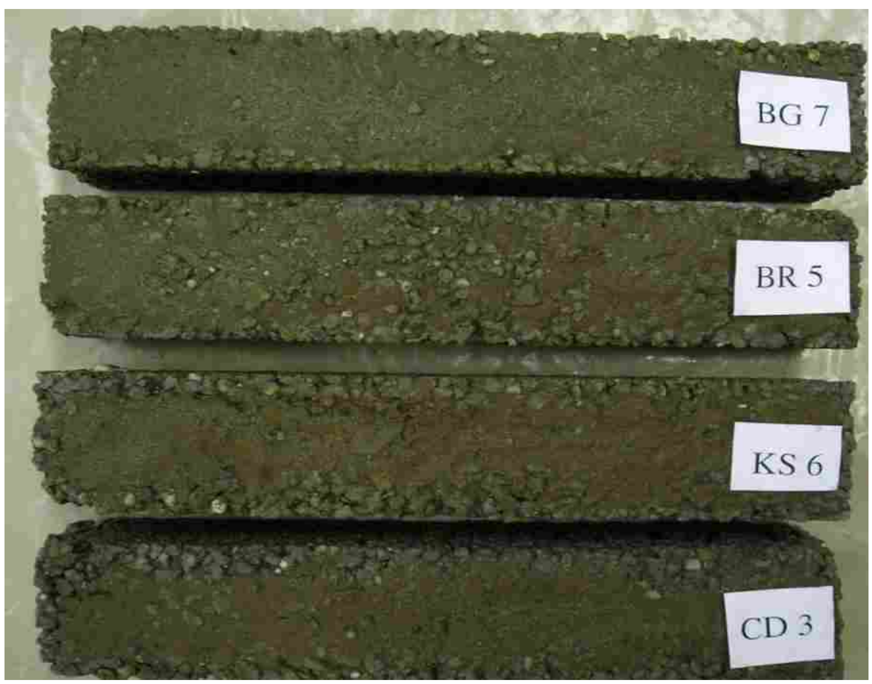

Figure I.6 Clogged, saturated specimens after 90-day cure and 120 freeze-thaw cycles.

Figure I.7 Clogged, saturated specimens after 90-day cure and 140 freeze-thaw cycles.

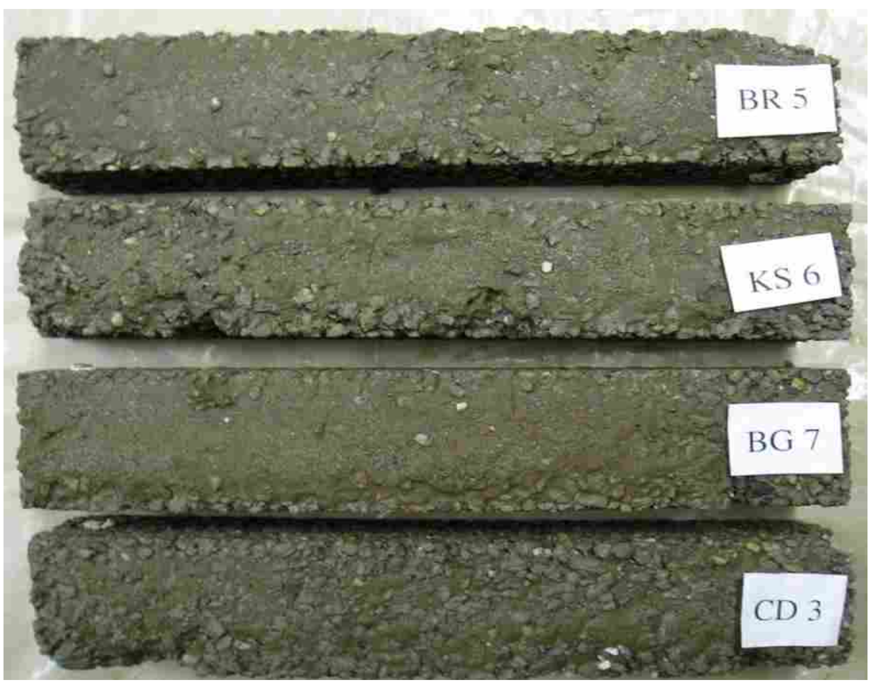

Figure I.8 Clogged, saturated specimens after 90-day cure and 160 freeze-thaw cycles.

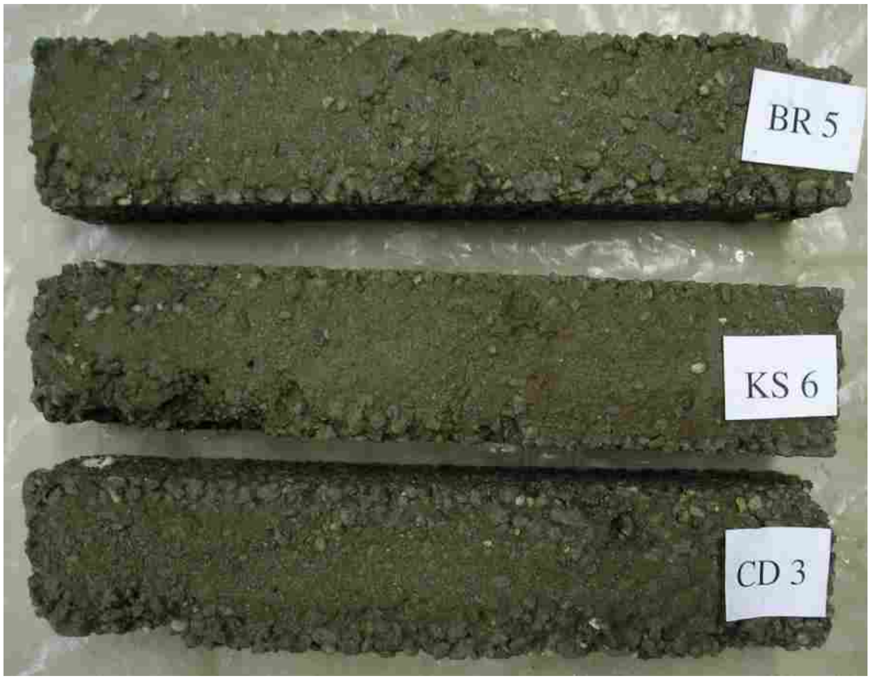

Figure I.9 Clogged, saturated specimens after 90-day cure and 180 freeze-thaw cycles.

Figure I.10 Clogged, saturated specimens after 90-day cure and 200 freeze-thaw cycles.

APPENDIX J:

PICTORAL RESULTS OF SPECIMENS CURED FOR 90 DAYS AND TESTED IN AN CLOGGED, UNSATURATED CONDITION

Figure J.1 Clogged, unsaturated specimens after 90-day cure and 20 freeze-thaw cycles.

Figure J.2 Clogged, unsaturated specimens after 90-day cure and 40 freeze-thaw cycles.

Figure J.3 Clogged, unsaturated specimens after 90-day cure and 60 freeze-thaw cycles.

Figure J.4 Clogged, unsaturated specimens after 90-day cure and 80 freeze-thaw cycles.

Figure J.5 Clogged, unsaturated specimens after 90-day cure and 100 freeze-thaw cycles.

Figure J.6 Clogged, unsaturated specimens after 90-day cure and 120 freeze-thaw cycles.

Figure J.7 Clogged, unsaturated specimens after 90-day cure and 140 freeze-thaw cycles.

Figure J.8 Clogged, unsaturated specimens after 90-day cure and 160 freeze-thaw cycles.

Figure J.9 Clogged, unsaturated specimens after 90-day cure and 180 freeze-thaw cycles.

Figure J.10 Clogged, unsaturated specimens after 90-day cure and 200 freeze-thaw cycles.

Figure J.11 Clogged, unsaturated specimens after 90-day cure and 220 freeze-thaw cycles.

Figure J.12 Clogged, unsaturated specimens after 90-day cure and 240 freeze-thaw cycles.

Figure J.13 Clogged, unsaturated specimens after 90-day cure and 260 freeze-thaw cycles.

Figure J.14 Clogged, unsaturated specimens after 90-day cure and 281 freeze-thaw cycles.

Figure J.15 Clogged, unsaturated specimens after 90-day cure and 306 freeze-thaw cycles.

APPENDIX K:

PICTORAL RESULTS OF SPECIMENS CURED FOR 90 DAYS AND TESTED IN A UNCLOGGED, SATURATED CONDITION

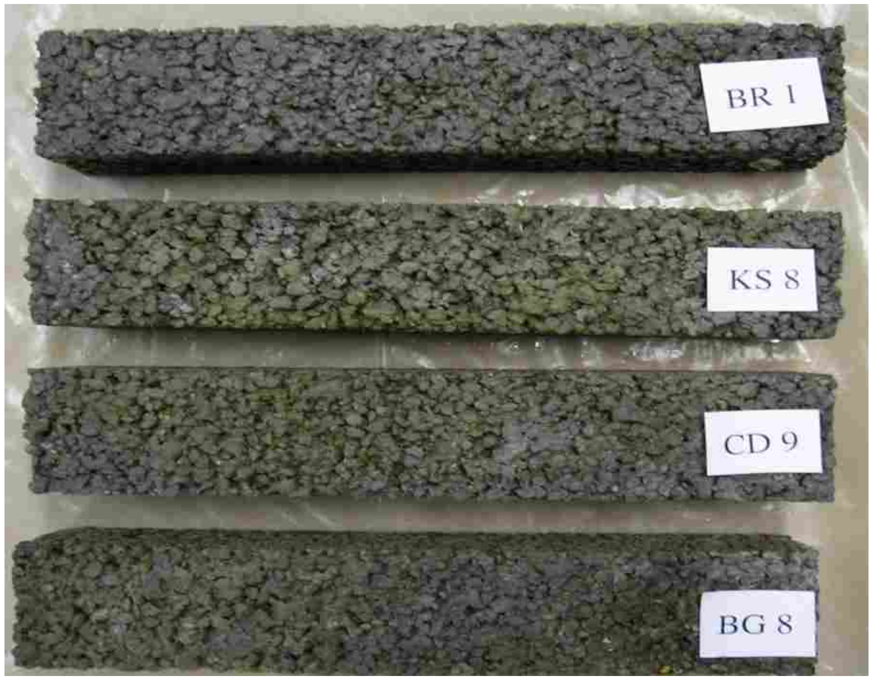

Figure K.1 Unclogged, saturated specimens after 90-day cure and 20 freeze-thaw cycles.

Figure K.2 Unclogged, saturated specimens after 90-day cure and 40 freeze-thaw cycles.

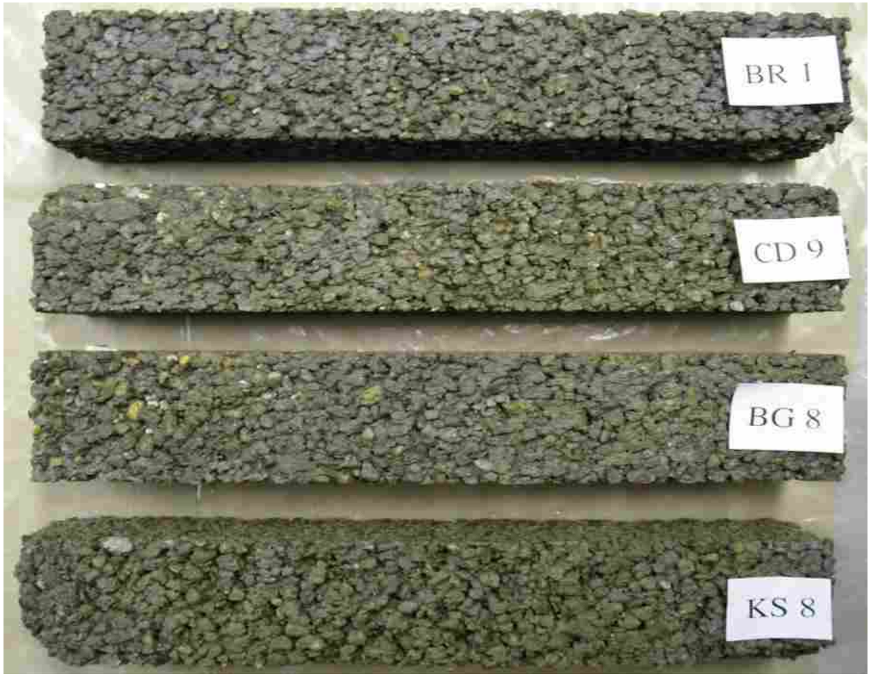

Figure K.3 Unclogged, saturated specimens after 90-day cure and 60 freeze-thaw cycles.

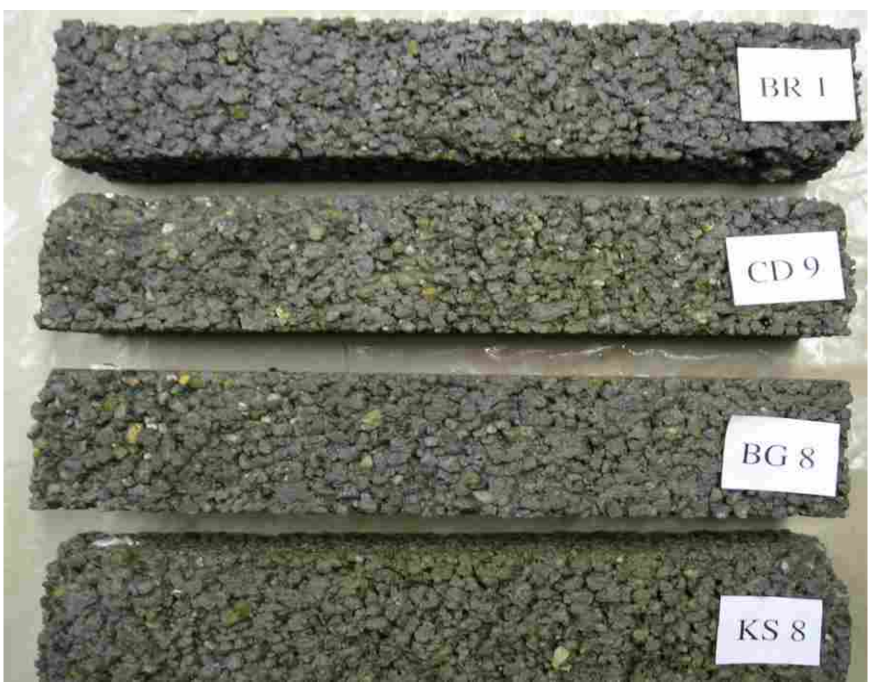

Figure K.4 Unclogged, saturated specimens after 90-day cure and 80 freeze-thaw cycles.

Figure K.5 Unclogged, saturated specimens after 90-day cure and 100 freeze-thaw cycles.

Figure K.6 Unclogged, saturated specimens after 90-day cure and 120 freeze-thaw cycles.

Figure K.7 Unclogged, saturated specimens after 90-day cure and 140 freeze-thaw cycles.

Figure K.8 Unclogged, saturated specimens after 90-day cure and 160 freeze-thaw cycles.

Figure K.9 Unclogged, saturated specimens after 90-day cure and 180 freeze-thaw cycles.

APPENDIX L:

PICTORAL RESULTS OF SPECIMENS CURED FOR 90 DAYS AND TESTED IN AN UNCLOGGED, UNSATURATED CONDITION

Figure L.1 Unclogged, unsaturated specimens after 90-day cure and 20 freeze-thaw cycles.

Figure L.2 Unclogged, unsaturated specimens after 90-day cure and 40 freeze-thaw cycles.

Figure L.3 Unclogged, unsaturated specimens after 90-day cure and 60 freeze-thaw cycles.

Figure L.4 Unclogged, unsaturated specimens after 90-day cure and 80 freeze-thaw cycles.

Figure L.5 Unclogged, unsaturated specimens after 90-day cure and 100 freeze-thaw cycles.

Figure L.6 Unclogged, unsaturated specimens after 90-day cure and 120 freeze-thaw cycles.

Figure L.7 Unclogged, unsaturated specimens after 90-day cure and 140 freeze-thaw cycles.

Figure L.8 Unclogged, unsaturated specimens after 90-day cure and 160 freeze-thaw cycles.

Figure L.9 Unclogged, unsaturated specimens after 90-day cure and 180 freeze-thaw cycles.

Figure L.10 Unclogged, unsaturated specimens after 90-day cure and 200 freeze-thaw cycles.

Figure L.11 Unclogged, unsaturated specimens after 90-day cure and 220 freeze-thaw cycles.

Figure L.12 Unclogged, unsaturated specimens after 90-day cure and 240 freeze-thaw cycles.

Figure L.13 Unclogged, unsaturated specimens after 90-day cure and 260 freeze-thaw cycles.

Figure L.14 Unclogged, unsaturated specimens after 90-day cure and 281 freeze-thaw cycles.

Figure L.15 Unclogged, unsaturated specimens after 90-day cure and 306 freeze-thaw cycles.