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Frost Susceptibility of Base Materials Treated with Asphalt Emulsion

Noelle Anderson

Brigham Young University - Provo

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Frost Susceptibility of Base Materials Treated with Asphalt Emulsion

Noelle Anderson

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

W. Spencer Guthrie, Chair
Grant G. Schultz
Kyle M. Rollins

Department of Civil and Environmental Engineering

Brigham Young University

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ABSTRACT

Frost Susceptibility of Base Materials Treated with Asphalt Emulsion

Noelle Anderson
Department of Civil and Environmental Engineering, BYU
Master of Science

The objective of this research was to investigate emulsion-treated base (ETB) frost susceptibility in terms of both freeze-thaw cycling and frost heave. The research performed in this study involved laboratory testing of ETB materials sampled from both the Redwood Road and 7800 South reconstruction projects in northern Utah. The effects of freeze-thaw cycling were evaluated by comparing the stiffness and strength of tested specimens to the same properties of control specimens not subjected to freeze-thaw cycling. Frost heave testing enabled evaluation of the effects of emulsion content and degree of curing on the volumetric stability of ETB materials during sustained freezing. Since permeability affects the frost susceptibility of a material, samples were also prepared to specifically evaluate the effect of curing condition on the permeability of the two base materials when treated with emulsion.

The results of freeze-thaw testing showed that both the Redwood Road and 7800 South specimens experienced decreases in modulus as a result of freeze-thaw damage. The results also showed that the Redwood Road specimens experienced substantial decreases in strength as a result of freeze-thaw damage. The specimens from 7800 South did not exhibit such strength loss; since those specimens initially had much lower modulus and unconfined compressive strength values than the Redwood Road specimens, they were less susceptible to stiffness and strength loss during the freeze-thaw test.

Results for the frost heave tests showed that the untreated base materials were not susceptible to frost heave and that the addition of emulsion, with or without curing, did not change the frost heave behavior in a practically important way. While susceptibility to frost heave is not expected to be a problem with these base materials, the laboratory results revealed a significant increase in the permeability of the ETB specimens after curing, which could facilitate greater freeze-thaw damage.

In consideration of these research results, engineers should ensure proper material sampling and laboratory testing to assess the efficacy of emulsion treatment for a given project. ETB to be constructed in cold regions should be subjected to freeze-thaw testing during the design phase, and designers should be aware that curing of the ETB may dramatically increase permeability and therefore increase frost susceptibility.

Key words: Emulsion-treated base, freeze-thaw testing, frost heave testing, frost susceptibility, full-depth reclamation, permeability

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1 INTRODUCTION

1.1 Problem Statement

Over time, pavement deterioration caused by traffic loading and environmental stresses necessitates the need for regular maintenance and/or rehabilitation (1). Full-depth reclamation (FDR) has been shown to be a cost-effective method for rehabilitating flexible pavements because it allows for in-place recycling and improvement of existing materials (2). The FDR process involves recycling of the existing pavement structure through pulverization of the in-place asphalt layer and mixing of the reclaimed asphalt pavement (RAP) into the upper portion of the existing base or subgrade to form a new base layer. While the presence of RAP in the mixture can lower the strength and stability of the material (3, 4), concerns about moisture and/or frost susceptibility may also warrant stabilization of the material (4). With many stabilizers available in the industry, engineers should use judgment in selecting a particular treatment option.

One type of treatment involves injection of asphalt emulsion into the reclaimed base layer. Treating the mixture of RAP and aggregate base with emulsion is intended to improve the mechanical properties of the recycled material and allow it to function as a new base layer (2). Selected research has been conducted on properties of emulsion-treated base (ETB) and combinations of emulsion with other stabilizers. For example, in China, cement-asphalt emulsion composites (CAEC) were compared to a control lean portland cement concrete. In that

study, the CAEC exhibited significantly lower compressive strength, flexural strength, and resilient modulus than the lean concrete, and values of all three of these properties of the CAEC decreased as the testing temperature increased, indicating that the CAEC had high temperature susceptibility (5). In a laboratory study in Texas, the curing temperature and curing time were found to significantly impact the strength of ETB. Specimens cured at a higher temperature and/or for a longer period of time exhibited higher strengths than specimens cured at a lower temperature and/or a shorter period of time (6). In a field study in Virginia, seasonal changes in the structural number of a pavement comprising an ETB layer were investigated; in particular, the pavement exhibited a significant reduction in effective structural number between the first winter and spring, a partial recovery during the summer and fall, and then a second reduction in stiffness between the second winter and spring (7).

In Utah, research on two roads that were reconstructed using FDR in conjunction with emulsion treatment documented slow rates of strength gain in the field, rutting susceptibility under early trafficking, and thaw weakening during spring (8, 9). These roads, Redwood Road (SR-68) just north of Saratoga Springs and 7800 South (SR-48) in West Jordan, showed similar trends in stiffness through the seasons as the field study performed in Virginia (7, 8, 9). Specifically, as shown in Figure 1-1 (8), the ETB modulus values on Redwood Road, which was reconstructed during the summer, were consistently low during the first 2 weeks after construction, increased dramatically by 4 months as winter commenced, and then decreased considerably by 1 year. The average ETB structural coefficient measured at 1 year, which included a winter with freezing temperatures, was only 47 percent of the design value. Additional data were collected 2 years after construction, which included an additional winter, and the ETB modulus, on average, was 42 percent lower than that measured 1 year after

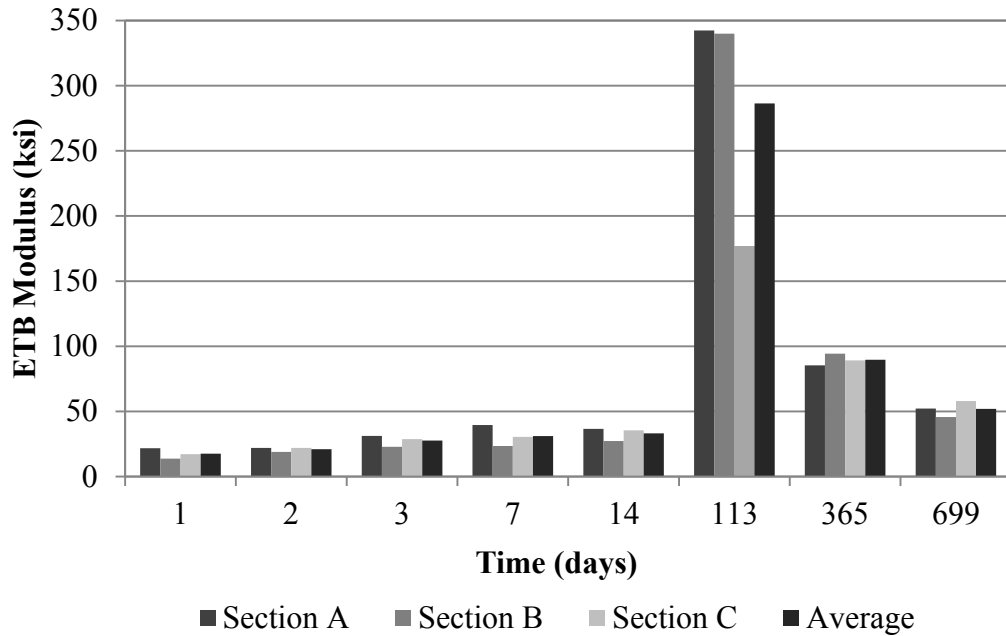


Figure 1-1: Field-measured modulus values for emulsion-treated base on Redwood Road.

construction. One possible explanation suggested for these results is the occurrence of freeze-thaw damage to the ETB layer during the winter. On 7800 South, after a few days following construction, the asphalt emulsion in the base layer was not curing sufficiently, and significant rutting, more than 4 in., was occurring under construction trafficking. The ETB layer was therefore removed except for one section that was retained for research purposes. Data collected from that section provided no evidence that the ETB layer experienced any sustained increase in strength as a result of emulsion curing; instead, the ETB modulus was shown to be greatly dependent on season, experiencing a reduction in modulus during the spring, consistent with Redwood Road (9). Although these studies suggest that ETB layers may experience frost damage during winter, no research specifically evaluating the effect of frost action on ETB was identified in the literature review performed for this research.

1.2 Research Objective and Scope

The objective of this research was to investigate ETB frost susceptibility in terms of both freeze-thaw cycling and frost heave. The research performed in this study involved laboratory freeze-thaw and frost heave testing of ETB materials sampled from both the Redwood Road and 7800 South reconstruction projects in northern Utah. At each location, three 800-ft by 24-ft test sections, each containing 10 individual test stations randomly located throughout the section, were established. Samples of base material were obtained from each station immediately before and after emulsion injection. Sufficient material was obtained at each sample location to prepare specimens for both laboratory freeze-thaw testing and frost heave testing. Neat emulsion was also obtained directly from the supplier.

The effects of freeze-thaw cycling were evaluated by comparing the stiffness and strength of tested specimens to the same properties of control specimens not subjected to freeze-thaw cycling. Frost heave testing enabled evaluation of the effects of emulsion content and degree of curing on the volumetric stability of ETB materials during sustained freezing. Since permeability affects the frost susceptibility of a material, samples were also prepared to specifically evaluate the effect of curing condition on the permeability of the two base materials when treated with emulsion.

1.3 Outline of Report

This report contains five chapters. Chapter 1 introduces the problem statement, explains the research objective and scope of work, and outlines the report. Chapter 2 gives detailed information about frost susceptibility, FDR, and asphalt emulsion. Chapter 3 describes the procedures involved in material sampling and laboratory testing, and Chapter 4 presents the

results of the freeze-thaw cycling, frost heave, and permeability experiments. Chapter 5 gives a summary of the research, highlights important findings, and offers recommendations.

2 BACKGROUND

2.1 Overview

The following sections provide background information obtained through a literature review on frost susceptibility, FDR, and asphalt emulsion treatment.

2.2 Frost Susceptibility

In cold regions, significant amounts of damage can occur to roads constructed of frost-susceptible materials. The frost susceptibility of a given soil or aggregate is largely dependent on the permeability, or hydraulic conductivity, of the compacted material (10, 11). Permeability to water is largely a function of void space, where a higher percentage and interconnectivity of voids allows higher flow rates (12, 13). The properties of the void space, especially the pore size distribution, also affect the capillarity of the soil or aggregate. Materials containing silts and silty sands, for which the combination of permeability and capillarity can facilitate significant water ingress and movement, therefore exhibit high levels of frost susceptibility (12). As frost penetrates soils and aggregates that have been moistened with water, damage from either freeze-thaw cycling or frost heave can occur as described in the following sections.

2.2.1 Freeze-Thaw Cycling

Freeze-thaw cycling is characterized by repeated freezing and thawing of pavement materials as ambient temperatures fall and subsequently rise above 32°F, respectively. As the

ambient air temperature is changing, the depth of frost in the ground varies as well (14). During freezing periods, affected aggregate base materials typically exhibit an increase in stiffness and strength as the particles are tightly bound together by the formation of ice (15). However, because ice is 9 percent larger in volume than an equivalent mass of liquid water, the formation of ice can also expand the aggregate matrix and therefore disrupt particle-to-particle contacts in the base layer; this problem is exacerbated when the material is saturated or nearly saturated (11, 16, 17). Furthermore, depending on the absorption and strength of the aggregates, freezing can cause fracture of the individual particles, thereby generating fines over time. In addition, for stabilized layers, chemical and/or mechanical bonds that may have formed between the aggregate particles can be broken. One mechanism by which freezing of asphalt-treated materials, in particular, causes damage is the loss of interfacial adhesion between the asphalt cement and aggregate particles (18).

As a frozen material begins to thaw, the fractured aggregates and/or broken bonds can result in reduced bearing capacity of the affected layer. Reductions in the stiffness and strength of both granular and fine-grained soils and aggregates have been documented in several studies (15, 19, 20, 21, 22, 23). Dependent on the type and percentage of stabilizer, reductions in the strength of a stabilized base material after freeze-thaw cycles have also been documented (24). Repeated freeze-thaw cycles over multiple seasons can therefore lead to fatigue cracking of bound pavement surface layers under trafficking (10, 16). Freeze-thaw cycling has also been shown to increase overall pavement roughness (25, 26).

2.2.2 *Frost Heave*

Frost heave within a pavement section can occur when a frost-susceptible material with an available source of water experiences sustained freezing temperatures. When a road is

exposed to cold weather, the surface of the pavement can freeze. If cold temperatures persist, the continuous removal of heat from the pavement causes a freezing “front” to slowly progress downward. The temperature difference between the colder front and the warmer underlying ground constitutes a thermal gradient within the pavement section (17, 27). Under such conditions, available moisture in frost-susceptible soils naturally rises through capillary action into the frozen soil, where it freezes and expands 9 percent in volume (16, 17). As this process continues, lenses of ice can be created that generate substantial upward force on the overlying pavement structure. When the uplift force exceeds the overburden weight of the pavement section, frost heave of the roadway surface occurs (13). Depending on the degree of spatial variability in soil properties and moisture availability within a given pavement section, differential frost heave can occur, which leads to surface cracking and roughness of the affected roadway during winter (11, 13, 27, 28).

During spring, as the pavement thaws from the ground surface downward, melt water can become trapped above the still-frozen underlying pavement layers, leading to conditions of super-saturation above the thawing front (11, 27). Under trafficking, high pore water pressures generated within the super-saturated material decrease the effective stress within the layer, which reduces its shear strength (11, 27). During this period of time, the surface layers may not be adequately supported, and accelerated damage in the form of cracking and/or rutting may occur (11, 20, 27, 29).

In laboratory frost heave testing, the rate at which a specimen heaves is an indication of the frost susceptibility of the soil. The U. S. Army Corps of Engineers has developed frost susceptibility classifications based on the rate of heave exhibited by a soil as shown in Table 2-1 (13).

Table 2-1: Frost Susceptibility Classifications of Soil

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

2.3 Full-Depth Reclamation

FDR is a common method of pavement reconstruction and can be performed in conjunction with various forms of stabilization. FDR has been recommended for pavements when resurfacing is not sufficient for rehabilitation because the existing distresses extend into the base or subgrade layers (30). Therefore, FDR should be used for pavements with deep rutting, load-associated cracks, non-load-associated thermal cracks, reflection cracks, and pavements where 15 to 20 percent of the surface area necessitates full-depth patching. It is particularly recommended for pavements having a problem with the base or subgrade (1, 30).

FDR allows for a portion of the asphalt surface layer to be recycled and combined with the existing base material. If the existing material has inadequate strength or durability, stabilization of the new base layer may be necessary to improve the mechanical properties of the layer (30). Several stabilizers are available, including portland cement, lime, fly ash, foamed asphalt, and asphalt emulsion (1); proper material sampling and laboratory testing are required to determine the appropriate type and amount of stabilizer for use on a given project.

When stabilization is warranted, the FDR process involves 1) removing excess asphalt pavement, 2) pulverizing the remaining asphalt and mixing it with the existing base material, 3) applying and mixing in the stabilizer, 4) compacting the stabilized RAP-base blend, 5) curing

the new base layer, and 6) applying the pavement surface (8). Figures 2-1 and 2-2 show an asphalt emulsion being added to a RAP-base blend, and Figures 2-3 and 2-4 show compaction of the treated material. The intended benefits of using FDR in road repair and reconstruction include an improvement of the pavement's structural integrity without altering the geometry; a more uniform pavement, leading to improved ride quality; a possible reduction in frost susceptibility; and a reduction in engineering cost, materials, and energy associated with removal and landfill storage of old asphalt and importing of new materials (4, 21, 31).



Figure 2-1: Asphalt emulsion injection at Redwood Road.



Figure 2-2: Asphalt emulsion injection at 7800 South.



Figure 2-3: Compaction of emulsion-treated base layer at Redwood Road.



Figure 2-4: Compaction of emulsion-treated base layer at 7800 South.

2.4 Asphalt Emulsion

Asphalt emulsion is typically considered to be an oil-in-water emulsion, meaning that it consists of asphalt particles that are suspended in water through the use of an emulsifier (32, 33). Emulsifiers create charges on the surface of the asphalt particles within the emulsion. Asphalt emulsions typically contain 25 to 60 percent water, 40 to 75 percent bitumen, and 0.1 to 2.5 percent emulsifier (34). Solvents are sometimes added to modify emulsion properties and behavior. The specific composition of an asphalt emulsion determines the emulsion characteristics, such as reactivity, viscosity, and stability.

The process of curing involves the gradual evaporation and/or expulsion of water from the emulsion. The curing of ETB begins when the emulsion starts to destabilize due to compaction (35). During compaction, the asphalt particles are forced together, causing them to overcome static repulsion and begin to coalesce into larger asphalt droplets. The asphalt droplets eventually become large enough to bind the aggregate particles together. The rate of curing depends on several factors, including chemistry and environmental factors such as wind speed,

humidity, and temperature (33, 35). Compaction or trafficking of the ETB can increase the rate of curing by forcing the asphalt particles closer together (34); however, depending on the material properties, higher densities resulting from compaction can actually restrict water evaporation and therefore decrease curing rates (36).

Curing to the design strength may require a few weeks to a couple of years, depending on the properties of the emulsion used (33, 34, 35). ETB exhibits low strengths immediately after construction due to the nature of uncured emulsion. In one study, researchers found that the stiffness of ETB after compaction was actually lower than the reclaimed material before the emulsion treatment (37); however, ETB layers have been found to exhibit large increases in resilient modulus during the first 28 days of curing (38, 39). Other researchers have measured a 300 percent increase in resilient modulus during the first 10 months (40). The Asphalt Institute suggests that ETB remains relatively weak during the first month following construction, stiffens dramatically for the next few months, and then levels out after approximately 6 months. The Asphalt Institute has also found that curing times longer than 6 months do not significantly increase ETB strength (41), although some reports indicate that ETB can take as long as 2 years to fully cure (33). These results show that, although the final strength of ETB can be high, the ETB layer remains fairly weak during the period of time immediately following construction while the emulsion is curing. Undesirable construction conditions, such as excessive ground water, precipitation, and/or high humidity, can prevent the ETB from drying as necessary before the surface course is placed. When the emulsion is not allowed to cure, low strengths have been recorded (9).

2.5 Summary

In cold regions, significant amounts of damage can occur to roads constructed of frost-susceptible materials. As frost penetrates soils and aggregates that have been moistened with water, damage from either freeze-thaw cycling or frost heave can occur. Freeze-thaw cycling is characterized by repeated freezing and thawing of pavement materials and leads to a reduction in the stiffness and strength of both granular and fine-grained soils and aggregates; dependent on the type and percentage of stabilizer, reductions in the strength of a stabilized base material after freeze-thaw cycles have also been documented. Frost heave occurs when lenses of ice are created in the pavement layers that generate substantial upward force on the overlying pavement structure. This process leads to surface cracking and roughness of the affected roadway during the winter and accelerated damage in the form of cracking and/or rutting during thawing in the spring.

For repair of such damage, FDR is a common method of pavement reconstruction that allows for a portion of the asphalt surface layer to be recycled and combined with the existing base material. If the existing material has inadequate strength or durability, stabilization of the new base layer may be necessary to improve the mechanical properties of the layer. One type of treatment involves injection of asphalt emulsion into the reclaimed base layer.

Asphalt emulsion is typically considered to be an oil-in-water emulsion, meaning that it consists of asphalt particles that are suspended in water through the use of an emulsifier. The process of curing involves the gradual evaporation and/or expulsion of water from the emulsion so that the asphalt droplets eventually become large enough to bind the aggregate particles together. Although the final strength of ETB can be high, the ETB layer remains fairly weak during the period of time immediately following construction while the emulsion is curing.

3 PROCEDURES

3.1 Overview

This research focused on two pavement reconstruction projects in northern Utah, including Redwood Road just north of Saratoga Springs and 7800 South in West Jordan. Each of the two sites was divided into three 800-ft by 24-ft sections, which were labeled A, B, and C, and 10 individual test stations were randomly located in each of the three sections. The standard layout used for each section at both projects is shown in Figure 3-1. At 7800 South, an adjustment was made to the two stations farthest from the edge of the road to avoid placing them immediately over a shallow utility pipe in the roadway. The following sections discuss the material sampling and laboratory testing performed in this research.

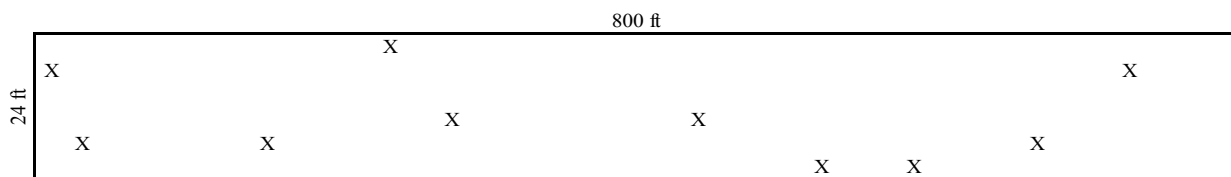


Figure 3-1: Test station layout for both Redwood Road and 7800 South.

3.2 Material Sampling

For laboratory freeze-thaw testing, samples of base material were taken from Redwood Road and 7800 South during the construction process. Immediately following emulsion

injection, samples representative of the full depth of the treated layer were collected with a scoop or shovel from each of the 10 individual test stations within each of the three sections. A sufficient amount of treated material was removed from each test station to permit preparation of five specimens, which were compacted on site using modified Proctor compaction in accordance with ASTM D1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³ (2,700 kN-m/m³))) Method B. As depicted in Figures 3-2 and 3-3, this method involved compaction of the ETB material in 4-in.-diameter molds in five lifts of 25 blows each. In total, with five specimens per test station, 10 test stations per section, and three sections per site, 150 specimens were prepared for each site and transported to the Brigham Young University (BYU) Highway Materials Laboratory for testing. Four of the



Figure 3-2: Compaction of emulsion-treated base specimen at Redwood Road.



Figure 3-3: Compaction of emulsion-treated base specimen at 7800 South.

specimens from each test station were used for unconfined compressive strength (UCS) testing at 7 days, 28 days, 3 months, and 1 year following construction, as reported in previous research (8, 9). The fifth specimen from each station was intended for freeze-thaw testing; however, due to the fragile nature of some of the specimens, not all stations had five intact specimens available for testing. Specifically, a fifth specimen was not available from stations A1, A4, A5, A7, A10, and B3 from Redwood Road.

For laboratory frost heave and permeability testing, a specified percentage of asphalt emulsion was to be added to the samples. Therefore, untreated samples of base material were collected from the individual test stations immediately before emulsion injection as shown in Figures 3-4 and 3-5. These loose samples were also transported to BYU for preparation and testing.



Figure 3-4: Sample collection at Redwood Road.



Figure 3-5: Sample collection at 7800 South.

3.3 Laboratory Testing

The laboratory evaluations performed in this research included freeze-thaw, frost heave, and permeability testing as described in the following sections.

3.3.1 *Freeze-Thaw Test*

Prior to freeze-thaw testing, the Redwood Road specimens were allowed to cure for 2 years in open air at room temperature within the BYU Highway Materials Laboratory. While the actual curing period in the field was limited to 2 weeks between compaction of the ETB layer and placement of the hot-mix asphalt (HMA) surface, the intent of the extended laboratory curing was to allow all evaporable water to leave the specimens so that the asphalt droplets could coalesce and bind the soil particles together to the extent possible. After drying during the extended curing period, the Redwood Road specimens were submerged in water for 24 hours immediately before testing to simulate the effects of precipitation and groundwater in the field, and the specimens were then sealed in plastic bags to prevent water evaporation during testing.

On the 7800 South project, excess water, cool temperatures, and high subgrade moisture contents prevented proper drying of the ETB before the road was surfaced with HMA. Consequently, the ETB material was not allowed to fully cure. To simulate these field conditions, the 7800 South specimens were sealed in plastic bags immediately following compaction to ensure that water could not evaporate, just as water could not evaporate from the ETB layer once it had been surfaced with HMA. The sealed specimens were stored at room temperature in the laboratory for 30 days to allow the moisture to equilibrate within each specimen.

For freeze-thaw testing, the Redwood Road and 7800 South specimens were tested in two separate groups. Freeze-thaw testing was able to proceed only 30 days after construction for the 7800 South specimens since no curing was allowed. Since the Redwood Road specimens were allowed to cure for 2 years, freeze-thaw testing of those specimens was performed 2 years after construction. Figures 3-6 and 3-7 show selected Redwood Road and 7800 South specimens,



Figure 3-6: Freeze-thaw specimens from Redwood Road.



Figure 3-7: Freeze-thaw specimens from 7800 South.

respectively, prepared for freeze-thaw testing. The group of Redwood Road specimens and the group of 7800 South specimens were subjected to the same testing procedures.

To establish a baseline condition for each specimen, the initial weight and height of each specimen was recorded. The specimen height was measured using a micrometer at four locations equally spaced around the specimen circumference, and the individual readings were then averaged. The specimens were then sealed in plastic bags and subjected to non-destructive stiffness testing performed using a free-free resonant column apparatus, in which the resonant frequency was used together with specimen length and density to compute Young's modulus for the material. In this test, a specimen was elevated on a stand, and an accelerometer mounted in a styrofoam disk was placed under the specimen; the disk acoustically isolated the specimen from the stand, and the weight of the specimen ensured good mechanical coupling between the accelerometer and specimen. A hammer equipped with a load cell was then used to lightly tap the top surface of the specimen as depicted in Figure 3-8. If a well-seated large aggregate was not exposed and available as a strike location at the specimen surface, a small metal disk was placed on the specimen surface to serve as a striking plate for the hammer. The amplitude and frequency of stress waves initiated by the hammer strike were measured by the accelerometer. A computer display of the measured wave response was used to determine the quality of a test run, and the average of nine measurements was used to compute Young's modulus for the specimen with Equation 3-1, which is derived from the fundamental relationship between modulus, density, and longitudinal compression wave velocity for specimens subject to resonant column testing (42):

$$E = \frac{\gamma}{32.2} \cdot (2 \cdot l \cdot f)^2 \tag{3-1}$$

where E = Young's modulus, psi

γ = density, pcf

l = length, ft

f = resonant frequency, Hz

Although the strain levels induced in the specimens through the resonant column testing were far below those that would occur in the field under typical traffic loading, this testing approach has been shown to be very effective for monitoring the development of freeze-thaw damage in laboratory specimens (23).

After the initial stiffness testing was completed, the specimens were placed in a freezer, as shown in Figure 3-9, which was maintained at a temperature not warmer than -10°F.

Following 24 hours of freezing, the specimens were allowed to thaw for 24 hours at room



Figure 3-8: Modulus testing of a freeze-thaw specimen.



Figure 3-9: Freezing of specimens.

temperature on the laboratory bench, and this process was repeated for a total of 12 freeze-thaw cycles. After each set of three freeze-thaw cycles was completed, the specimens were briefly removed from their bags so that specimen weights and heights could be measured; afterwards, they were returned to their bags, and stiffness testing was then performed.

Once the freeze-thaw testing was finished, the specimens were removed from their bags and subjected to UCS testing in general accordance with ASTM D1633 (Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders). After being capped with high-strength gypsum, as shown in Figure 3-10, the specimens were loaded at a strain rate of 0.05 in./minute in a testing frame as shown in Figure 3-11. The maximum load recorded during testing of a given specimen was divided by the initial cross-sectional area of the specimen to compute the compressive strength. The caps were then removed, and the specimens were weighed and placed in an oven at 140°F for drying to constant weight. The final weight of each specimen was then compared to the initial weight to obtain the moisture content.



Figure 3-10: Capping of a freeze-thaw specimen.



Figure 3-11: Unconfined compressive strength testing of a freeze-thaw specimen.

These UCS test results were compared directly with those obtained on companion specimens evaluated in previous research that did not involve freeze-thaw testing. For Redwood Road, the UCS test results obtained after freeze-thaw testing were compared to the UCS test results obtained in previous research at 1 year (8), while the UCS test results obtained after freeze-thaw testing of 7800 South specimens were compared with those obtained in previous research at 28 days (9). The same laboratory conditioning procedures applied to the specimens subjected to freeze-thaw testing in this research were applied to the specimens subjected to UCS testing in the previous research, with the Redwood Road specimens being cured in open air and the 7800 South specimens being sealed in plastic bags.

3.3.2 *Frost Heave Test*

For frost heave testing, all of the untreated samples of base material collected from the individual test stations on Redwood Road were combined, while all of the untreated samples of base material collected from the individual test stations on 7800 South were combined. Both combined samples were then oven-dried at 140°F and sieved in general accordance with ASTM D422 (Standard Test Method for Particle-Size Analysis of Soils) to determine the average particle-size distribution of each bulk material. All subsequent specimens were then prepared with gradations identical to that of the bulk material in each case.

Following sieving, the moisture-density relationship was investigated for each material to identify the optimum moisture content (OMC) and maximum dry density (MDD) of each material in the untreated condition and treated with 4 percent emulsion. Each sample was moistened with water and allowed to equilibrate for at least 24 hours before the addition of emulsion, as applicable, and subsequent compaction. Consistent with the freeze-thaw testing, the specimens were compacted following ASTM D1557 Method B. After compaction, the weight

and height of each specimen were measured, and then each specimen was dried at 140°F to constant weight in an oven to enable computation of moisture content and dry density. Plots of the moisture contents and dry densities measured for several specimens were used to graphically determine the OMC and MDD for each type of base material, and the results are shown in Table 3-1.

Additional samples were then prepared to specifically evaluate the effects of emulsion content and curing condition on the frost heave behavior of the two base materials. Emulsion contents of 0, 2, 4, and 6 percent were investigated, as well as conditions representing cured and not cured. For this testing, a total of 10 samples of each material were prepared. Two of the samples from each site were mixed with 2 percent emulsion, two of the samples were mixed with 4 percent emulsion, and two of the samples were mixed with 6 percent emulsion; after compaction, all of these specimens were cured. Two of the remaining four samples were mixed with 4 percent emulsion, while the other two were evaluated in the untreated condition; these specimens were not cured.

Prior to compaction, each of these samples was moistened with water and allowed to equilibrate for at least 24 hours. An appropriate amount of water was added to each sample treated with 2, 4, or 6 percent emulsion so that the total water content after the addition of the

Table 3-1: Target Moisture and Dry Density Values for Compaction of Frost Heave Specimens

Material	Emulsion Content (%)	Moisture Content (%)	Dry Density (pcf)
Redwood Road	0	7.2	123.0
Redwood Road	4	4.9	119.4
7800 South	0	5.6	136.8
7800 South	4	4.2	131.2

specified amount of emulsion would be equal to the OMC previously determined for the given base material at 4 percent emulsion. For the samples not treated with emulsion, the OMC previously determined for the given base material in the untreated condition was used.

After the appropriate amount of emulsion was thoroughly mixed into a sample, as required, compaction was performed in general accordance with ASTM D1557. This step involved compaction of the samples in 6-in.-diameter plastic molds in 10 lifts of 56 blows each to a target height of 9.2 in. Several 0.125-in.-diameter holes were pre-drilled into the bottom of the molds to facilitate water flow from the frost heave bath into the specimens during testing. In addition, several slits were cut into selected molds to enable placement of thermocouples through the mold walls into the specimens for monitoring of temperature profiles. The insides of the molds were oiled to minimize adfreezing, or adhesion of the specimen to the inside of the mold due to ice formation, during frost heave testing. The prepared plastic molds were then weighed and individually placed inside a steel mold for compaction of each specimen as shown in Figure 3-12. Afterwards, the steel mold was removed, and the weight and height of each compacted specimen, still in the plastic mold, were recorded. The specimen height was measured at four locations using a micrometer, and the individual readings were then averaged.

The specimens that required curing were then placed in an oven at 140°F for 2 weeks; weight monitoring indicated that approximately half of the water within the specimens evaporated during this period. The specimens were placed in the frost heave bath for testing after cooling to room temperature for a few hours following the curing period. The specimens that did not require curing were placed directly into the frost heave bath for testing generally within a few hours following compaction. The timing and sequence of specimen preparation



Figure 3-12: Compaction of a frost heave specimen.

was designed in such a way that all specimens to be tested in a given batch were ready for testing at the same time. Three separate frost heave batches were necessary in this research.

For frost heave testing, the weights and heights of the specimens were measured, and then the specimens that were prepared for temperature profile monitoring were instrumented with thermocouples. The specimens chosen to be instrumented with thermocouples in each batch were located in a corner, in the middle along one side, and in the center of the bath. The thermocouple tips were inserted approximately 1 in. into the sides of these specimens through small holes drilled through the slits in the mold, and electrical tape was then placed over the slits. All of the specimens were then wrapped laterally with insulation to minimize lateral heat flow during testing and placed into an insulated frost heave bath equipped with water pumps for circulation and computer-controlled heat tape to maintain a target water bath temperature of

35.6°F. A 10-lb overburden weight was placed on each specimen to simulate the presence of a pavement surface layer, and linear variable differential transformers (LVDTs) were then positioned over each specimen to monitor frost heave during testing. Figure 3-13 shows a complete setup ready for testing.

In this research, 10-day frost heave tests were performed. During the testing, the air temperature in the test chamber was set at 21.5°F. To supplement the computer-automated data collection, manual recordings of the LVDT data, in particular, were made daily. At the end of the testing, the specimens were removed from the bath; the overburden weights, insulation, and thermocouples, as applicable, were removed, and final weights and heights were measured and recorded. Frost heave was computed by subtracting the initial height from the final height in each case.



Figure 3-13: Frost heave test configuration.

3.3.3 *Permeability Test*

For permeability testing, Redwood Road and 7800 South specimens were prepared with gradations identical to that of the bulk material in each case, consistent with the frost heave testing. Samples were prepared to specifically evaluate the effect of curing condition on the permeability of the two base materials treated with 4 percent emulsion. For this testing, a total of four samples of each material were prepared at the previously determined OMC values and allowed to equilibrate in sealed plastic bags for approximately 24 hours; after compaction, two of these specimens were cured, while the other two were not cured.

After the emulsion was thoroughly mixed into a sample, compaction was performed in general accordance with ASTM D1557 Method B. This step involved compaction of the samples in 4-in.-diameter plastic molds in five lifts of 25 blows each to a target height of 4.6 in. The insides of the molds were coated with caulking, having a thickness generally between 0.0625 and 0.125 in., to minimize preferential water flow down the sides of the specimens. The specimens that required curing were then placed in an oven at 140°F for 2 weeks; these specimens were placed in the permeameter for testing after cooling to room temperature for a few hours following the curing period. The specimens that did not require curing were placed directly into the permeameter for testing generally within a few hours following compaction. Prior to permeability testing, the weight and height of each specimen were measured, with the latter being evaluated at four locations using a micrometer; these individual readings were averaged. The bottom of each specimen mold was then carefully removed with a rotary cutter to permit the passage of water through the specimen during testing.

As shown in Figure 3-14, the lower assembly of the permeameter was designed so that the lower surface of a specimen would be equal in elevation to the flow path in the raised pipe

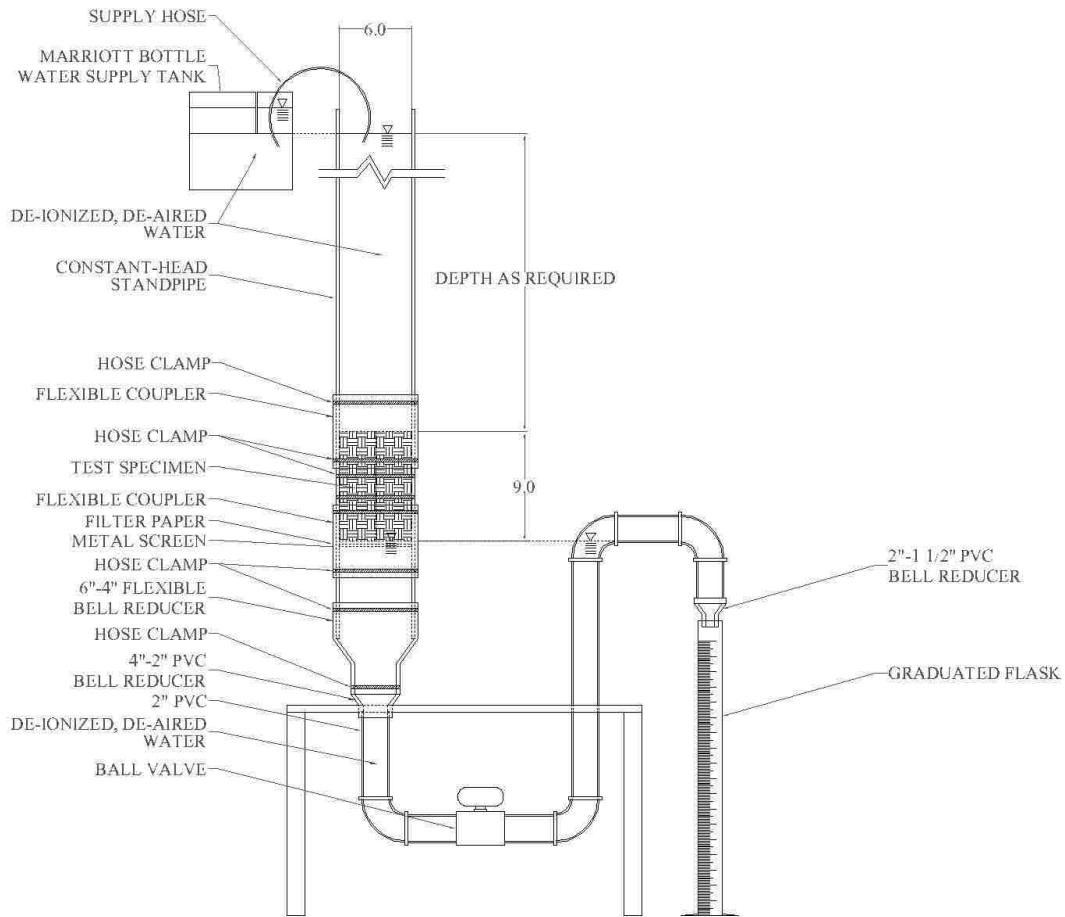


Figure 3-14: Schematic of permeameter.

section downstream of the valve. Water was poured into the pipe system to fill the lower part of the permeameter. The ball valve, located at the lowest point in the system, was then closed to prevent drainage of the water during the specimen soaking process.

As shown in Figure 3-15, the specimen to be tested was then placed inside a flexible coupler secured by a hose clamp on either end to the upper and lower parts of the permeameter. A metal screen and filter paper were situated immediately beneath the specimen to prevent fines from being washed out of the specimen during testing. The open 60-in. standpipe above the



Figure 3-15. Permeability test configuration.

specimen was then filled with water to saturate the specimen over a period of 24 hours. After the conditioning was complete, the pipe above the specimen was re-filled with water, an air-tight lid with an air hose fitting was installed on top of the pipe, an air hose regulated for each specimen at a value ranging from 0 to 10 psi was connected to the fitting to maintain a constant pressure head, the valve in the lower part of the permeameter was opened, and the rate of water flow was allowed to stabilize before several water flow rate measurements were obtained. For measurement of the water flow rate, a graduated cylinder was placed at the exit point of the permeameter, and a stopwatch was used to record the time required to collect a known volume of water in the cylinder. Figure 3-16 shows a test in progress. At least 10 measurements were taken for each specimen. The average permeability, or hydraulic conductivity, was then calculated using Equation 3-2 (43):

$$k = \frac{Q \cdot L}{A \cdot h \cdot t} \quad (3-2)$$

where k = hydraulic conductivity, in./s

Q = discharge volume, in.³

L = average length of the specimen, in.

A = cross-sectional area of the specimen, in.²

h = constant head, in.

t = time, seconds



Figure 3-16. Permeability testing of a specimen.

3.4 Summary

This research focused on two pavement reconstruction projects in northern Utah, including Redwood Road and 7800 South. Each of the two sites was divided into three 800-ft by 24-ft sections, which were labeled A, B, and C, and 10 individual test stations were randomly located in each of the three sections. For laboratory freeze-thaw testing, samples of base

material were collected from each of the individual test stations immediately following emulsion injection and were compacted on site. For laboratory frost heave and permeability testing, untreated samples of base material were collected from the individual test stations immediately before emulsion injection.

Prior to freeze-thaw testing, the Redwood Road specimens were allowed to cure for 2 years in open air at room temperature within the BYU Highway Materials Laboratory before being submerged in water for 24 hours and sealed in plastic bags immediately before testing. The 7800 South specimens were sealed in plastic bags immediately following compaction and stored at room temperature in the laboratory for 30 days. The intent of both procedures was to generally simulate field conditions at the respective sites. After initial stiffness testing was completed, the specimens were subjected to 12 freeze-thaw cycles involving 24 hours of freezing at a temperature not warmer than -10°F and 24 hours of thawing at room temperature on the laboratory bench. After each set of three freeze-thaw cycles was completed, specimen weights and heights were measured, and stiffness testing was performed. Once the freeze-thaw testing was finished, the specimens were subjected to UCS testing for direct comparison to UCS test results obtained on companion specimens evaluated in previous research that did not involve freeze-thaw testing.

For frost heave testing, specimens were prepared to specifically evaluate the effects of emulsion content and curing condition on the frost heave behavior of the two base materials. Emulsion contents of 0, 2, 4, and 6 percent were investigated, as well as conditions representing cured and not cured. For this testing, a total of 10 samples of each material were compacted in prepared plastic molds in the laboratory. The specimens that required curing were then placed in an oven at 140°F for 2 weeks, while the specimens that did not require curing were placed

directly into the frost heave bath for testing generally within a few hours following compaction. The specimens that were prepared for temperature profile monitoring were instrumented with thermocouples, all of the specimens were wrapped laterally with insulation to minimize lateral heat flow during testing, and LVDTs were then positioned over each specimen to monitor frost heave through a 10-day testing period. During the testing, the air temperature in the chamber was set at 21.5°F, while the temperature of the water in the frost heave bath was set at 35.6°F.

For permeability testing, samples were prepared to specifically evaluate the effect of curing condition on the permeability of the two base materials treated with 4 percent emulsion. Specimens were compacted in prepared plastic molds in the laboratory. The specimens that required curing were then placed in an oven at 140°F for 2 weeks, while the specimens that did not require curing were placed directly into the permeameter for testing. Before testing, each specimen was saturated over a period of 24 hours, and then several water flow rate measurements were obtained under a constant pressure head. A graduated cylinder was placed at the exit point of the permeameter, and a stopwatch was used to record the time required to collect a known volume of water in the cylinder. At least 10 measurements were taken for each specimen, and the average permeability, or hydraulic conductivity, was then calculated.

4 RESULTS

4.1 Overview

This chapter presents the results of this research, including the results of freeze-thaw, frost heave, and permeability testing as described in the following sections. The raw data corresponding to these tests are presented in Appendices A, B, and C, respectively, in which the presence of a hyphen in a table indicates that the data were not measured.

4.2 Freeze-Thaw Test

The results of freeze-thaw testing included both modulus and UCS measurements. The modulus measurements are presented in Figures 4-1 and 4-2 for Redwood Road and 7800 South, respectively. In each figure, the average modulus values measured both before and after freeze-thaw cycling are shown for each test section. For both roads, the specimens experienced decreases in modulus as a result of freeze-thaw damage that occurred during the 12 test cycles. The results show that the specimens representing sections A, B, and C at Redwood Road retained only 38.4, 36.8, and 43.8 percent, respectively, of the initial modulus value after testing, while the specimens representing sections A, B, and C at 7800 South retained 85.9, 31.8, and 79.5 percent, respectively. For each material, a paired *t*-test was performed with the null hypothesis that the initial and final modulus values were equal, the alternative hypothesis that the initial and final modulus values were not equal, and a significance level of 0.05. The paired *t*-test for the

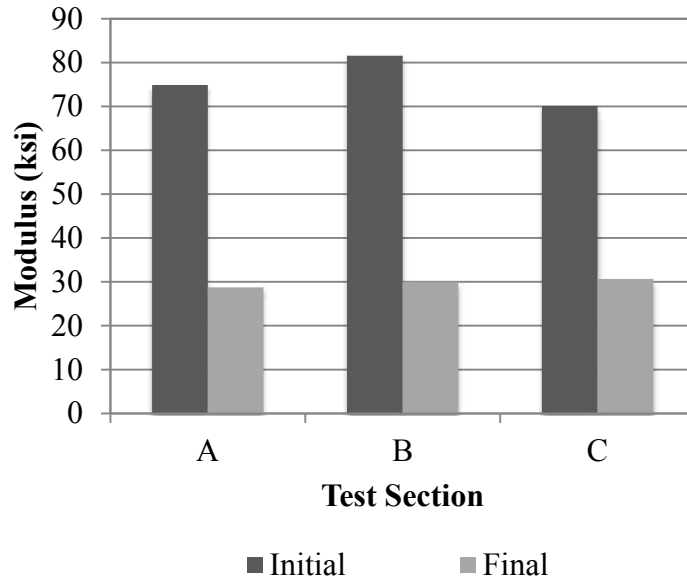


Figure 4-1: Modulus values for Redwood Road.

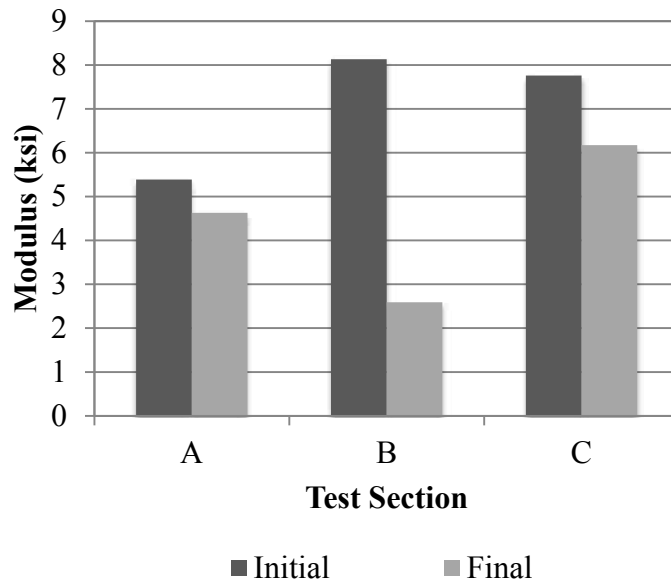


Figure 4-2: Modulus values for 7800 South.

Redwood Road specimens resulted in a p -value of less than 0.0001, with a 95 percent confidence interval of 40.2 to 50.6 ksi, leading to rejection of the null hypothesis. The results from the paired t -test for the 7800 South specimens resulted in a p -value of 0.0148, with a 95 percent confidence interval of 0.6 to 4.7 ksi, also leading to rejection of the null hypothesis.

The larger magnitude of modulus reduction on Redwood Road compared to the more varied modulus reduction on 7800 South may be explained by differences in initial modulus values between these two roads as a result of differences in curing. The average initial modulus values for Redwood Road ranged from 70.1 to 81.6 ksi after 2 years of curing in open air, while the corresponding values for 7800 South ranged from only 5.4 to 7.8 ksi, as these specimens were not allowed to cure prior to freeze-thaw testing. Since the 7800 South specimens initially had a much lower modulus value than the Redwood Road specimens, they were less susceptible to stiffness loss during the freeze-thaw test; mechanical bonds had not yet formed between the aggregate particles, as the asphalt droplets in the emulsion had not yet begun to coalesce. The reductions in stiffness of only the Redwood Road specimens are considered to be of practical importance.

The UCS results are presented in Figures 4-3 and 4-4 for Redwood Road and 7800 South, respectively. In each figure, the initial UCS values are the averages for the specimens that were not subjected to freeze-thaw cycling, while the final UCS values are the averages for the specimens that were subjected to 12 freeze-thaw cycles. The results show that the Redwood Road specimens experienced decreases in strength as a result of freeze-thaw damage. Specifically, the specimens representing sections A, B, and C at Redwood Road retained only 47.1, 54.7, and 59.3 percent, respectively, of the initial UCS values after testing. However, the 7800 South specimens did not exhibit such strength loss, retaining 99.6, 110.0, and 104.0 percent

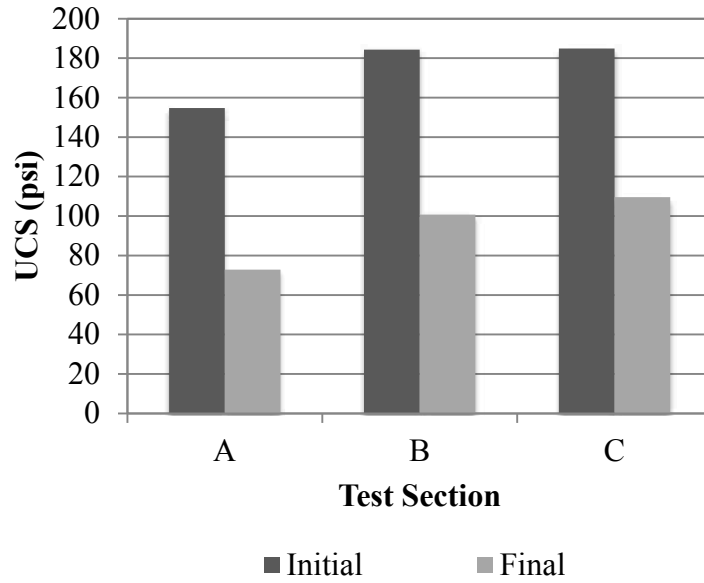


Figure 4-3: Unconfined compressive strength values for Redwood Road.

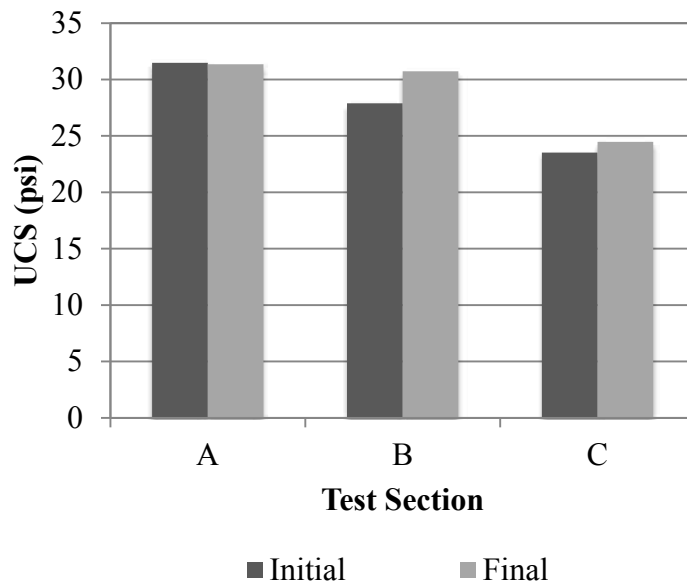


Figure 4-4: Unconfined compressive strength values for 7800 South.

of the initial UCS values in sections A, B, and C, respectively. For each material, a paired t -test was performed with the null hypothesis that the initial and final UCS values were equal, the alternative hypothesis that the initial and final UCS values were not equal, and a significance level of 0.05. The paired t -test for the Redwood Road specimens resulted in a p -value of less than 0.0001, with a 95 percent confidence interval of 65 to 94 psi, leading to rejection of the null hypothesis. The results from the paired t -test for the 7800 South specimens resulted in a p -value of 0.3029, with a 95 percent confidence interval of -4 to 1 psi, leading to failure to reject the null hypothesis.

As observed in the modulus testing, the differences in UCS results between the Redwood Road and 7800 South specimens may be explained by differences in initial UCS values between these two roads as a result of differences in curing. The average initial UCS values for Redwood Road ranged from 155 to 185 psi, while the corresponding values for 7800 South ranged from only 24 to 31 psi. Again, since the 7800 South specimens initially had a much lower strength than the Redwood Road specimens, they were less susceptible to strength loss during the freeze-thaw test. The reductions in strength of the Redwood Road specimens are considered to be of practical importance.

4.3 Frost Heave Test

The effects of emulsion content and curing condition on frost heave are presented in Figures 4-5 and 4-6, respectively. In both figures, the frost heave values shown for each test condition are the averages of two specimens and represent the total frost heave over the 10-day test. To statistically compare the results between different emulsion contents, an analysis of variance (ANOVA) was performed on the data. The ANOVA was performed with the null hypothesis that the total frost heave amounts were equal across all emulsion contents, the

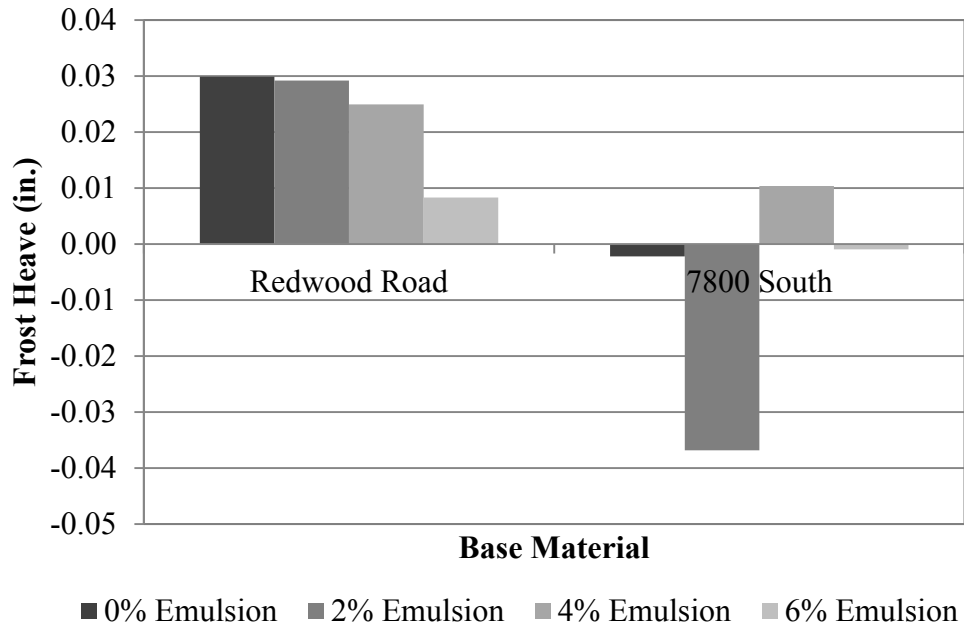


Figure 4-5: Effects of emulsion content on frost heave.

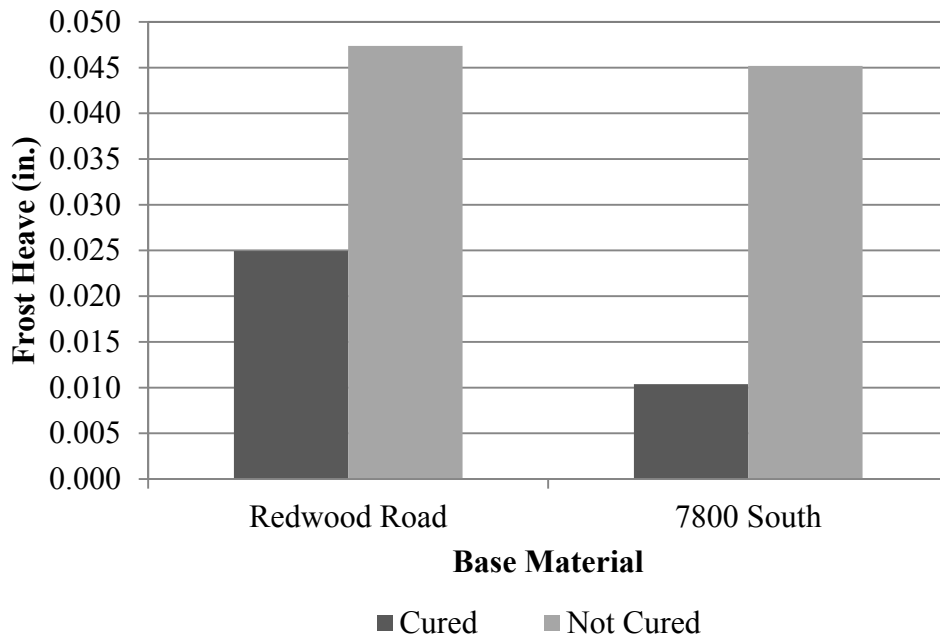


Figure 4-6: Effects of curing on frost heave.

alternative hypothesis that the total frost heave amounts were not equal across all emulsion contents, and a significance level of 0.05. The ANOVA for the Redwood Road specimens resulted in a p -value of 0.8103, leading to failure to reject the null hypothesis. The ANOVA for the 7800 South specimens resulted in a p -value of 0.0487, leading to rejection of the null hypothesis. However, for both roads, the data in Figure 4-5 show that the untreated base materials were not susceptible to frost heave, based on the criteria presented in Table 2-1, and that the addition of emulsion, with curing, did not change the frost heave behavior in a practically important way. Negative frost heave amounts, as measured for selected 7800 South specimens, indicate that the magnitude of thermal contraction that occurred upon freezing exceeded that of any subsequent increase in specimen height that may have occurred due to the ingress and freezing of water during testing.

To statistically compare the results between different curing conditions, a two-sample t -test was performed on the data. The two-sample t -test was performed with the null hypothesis that the total frost heave amounts were equal across both curing conditions, the alternative hypothesis that the total frost heave amounts were not equal across both curing conditions, and a significance level of 0.05. The two-sample t -test for the Redwood Road specimens resulted in a p -value of 0.8489, with a 95 percent confidence interval of -1.20 to 1.16 in., leading to failure to reject the null hypothesis. The two-sample t -test for the 7800 South specimens resulted in a p -value of 0.585, with a 95 percent confidence interval of -0.62 to 0.55 in., also leading to failure to reject the null hypothesis. Along with the lack of statistical evidence of difference in frost heave for 4 percent emulsion based on the curing conditions, again, the magnitudes of frost heave that occurred are not considered to be practically important.

4.4 Permeability Test

Results from the permeability test are shown in Figure 4-7 for Redwood Road and 7800 South. Each column in the figure represents the average of two specimens. The results reveal a significant difference in permeability between the specimens that were cured and those that were not cured. For Redwood Road and 7800 South, respectively, the permeability of the specimens that were cured was, on average, 60 and 29 times larger than the permeability of the specimens that were not cured; the increased permeability of the specimens that were cured compared to those that were not cured is attributable to the coalescing of the asphalt within the emulsion and its adhesion to the aggregate surfaces, thereby opening the middles of the pore spaces for water flow. The larger permeability of the Redwood Road specimens compared to the 7800 South specimens may be explained by differences in the fines contents of the two base materials.

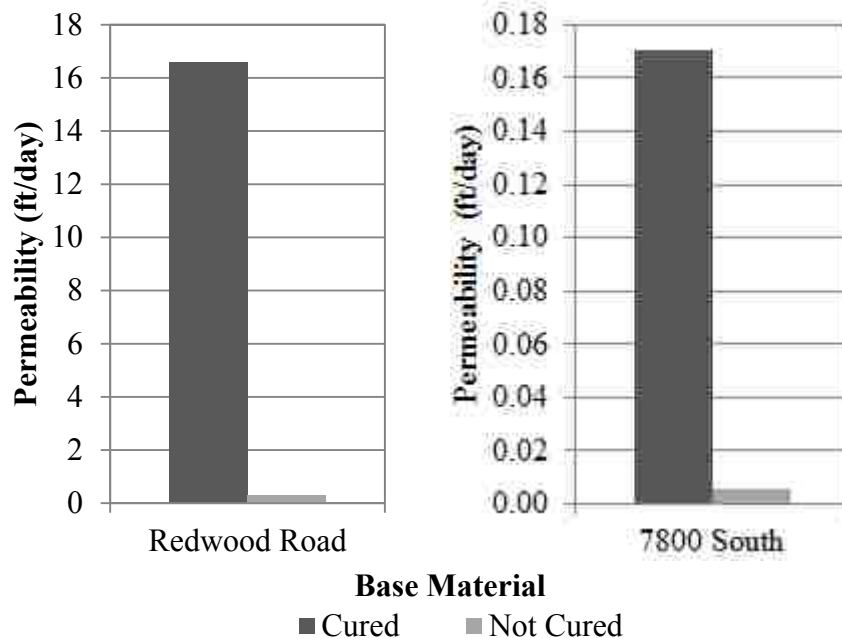


Figure 4-7: Effects of curing on permeability.

A paired *t*-test was performed on the two data sets with the null hypothesis that the permeability was equal across both curing conditions, the alternative hypothesis that the permeability was not equal across both curing conditions, and a significance level of 0.05. The paired *t*-test for the Redwood Road specimens resulted in a *p*-value of 0.1019, with a confidence interval of -17 to 50 ft/day, leading to failure to reject the null hypothesis. The paired *t*-test for the 7800 South specimens also resulted in failure to reject the null hypothesis, with a *p*-value of 0.0679 and a confidence interval of -0.06 to 0.39 ft/day. Although the small sample size for the *t*-tests led to the difference between cured and not cured samples not being statistically significant for either base material, the large difference is still practically important for this study.

4.5 Summary

The results of freeze-thaw testing included both modulus and UCS measurements. For both Redwood Road and 7800 South, the specimens experienced decreases in modulus as a result of freeze-thaw damage that occurred during the 12 test cycles. The results showed that the specimens representing sections A, B, and C at Redwood Road retained only 38.4, 36.8, and 43.8 percent, respectively, of the initial modulus value after testing and that those representing sections A, B, and C at 7800 South retained 85.9, 31.8, and 79.5 percent, respectively. The results also showed that the Redwood Road specimens experienced decreases in strength as a result of freeze-thaw damage. Specifically, the specimens representing sections A, B, and C at Redwood Road retained only 47.1, 54.7, and 59.3 percent, respectively, of the initial UCS values after testing. However, the 7800 South specimens did not exhibit such strength loss, retaining 99.6, 110.0, and 104.0 percent of the initial UCS values in sections A, B, and C, respectively,

after testing. Since the 7800 South specimens initially had much lower modulus and UCS values than the Redwood Road specimens, having not been allowed to cure, they were less susceptible to stiffness and strength loss during the freeze-thaw test.

Results for the frost heave tests showed that the untreated base materials were not susceptible to frost heave and that the addition of emulsion, with curing, did not change the frost heave behavior in a practically important way. Regarding the effects of curing, for 4 percent emulsion, the cured specimens exhibited less frost heave than those that were not cured, although, again, the magnitudes of frost heave that occurred are not considered to be practically important.

The permeability results revealed a significant difference in permeability between the specimens that were cured and those that were not cured. For Redwood Road and 7800 South, respectively, the permeability of the specimens that were cured was, on average, 60 and 29 times larger than the permeability of the specimens that were not cured.

These research findings suggest that frost damage due to freeze-thaw cycling was likely the cause of the modulus reductions measured in the field for Redwood Road, in particular (8). While susceptibility to frost heave is not expected to be a problem with the base materials on these two roads, the fact that the permeability increased substantially after curing of the emulsion could have facilitated greater freeze-thaw damage in the base layer.

5 CONCLUSION

5.1 Summary

The objective of this research was to investigate ETB frost susceptibility in terms of both freeze-thaw cycling and frost heave. The research performed in this study involved laboratory testing of ETB materials sampled from both the Redwood Road and 7800 South reconstruction projects in northern Utah. At each location, three 800-ft by 24-ft test sections, each containing 10 individual test stations randomly located throughout the section, were established. Samples of base material were obtained from each station immediately before and after emulsion injection. Sufficient material was obtained at each sample location to prepare specimens for both laboratory freeze-thaw testing and frost heave testing. Neat emulsion was also obtained directly from the supplier.

The effects of freeze-thaw cycling were evaluated by comparing the stiffness and strength of tested specimens to the same properties of control specimens not subjected to freeze-thaw cycling. Frost heave testing enabled evaluation of the effects of emulsion content and degree of curing on the volumetric stability of ETB materials during sustained freezing. Since permeability affects the frost susceptibility of a material, samples were also prepared to specifically evaluate the effect of curing condition on the permeability of the two base materials when treated with emulsion.

5.2 Findings

The results of freeze-thaw testing included both modulus and UCS measurements. For both Redwood Road and 7800 South, the specimens experienced decreases in modulus as a result of freeze-thaw damage. The results showed that the Redwood Road and 7800 South specimens retained 36.8 to 43.8 percent and 31.8 to 85.9 percent, respectively, of the initial modulus value after testing. The results also showed that the Redwood Road specimens experienced decreases in strength as a result of freeze-thaw damage, retaining only 47.1 to 59.3 percent of the initial UCS values after testing. The specimens from 7800 South did not exhibit such strength loss, retaining 99.6 to 110.0 percent of the initial UCS values after testing; since the 7800 South specimens initially had much lower modulus and UCS values than the Redwood Road specimens, having not been allowed to cure, they were less susceptible to stiffness and strength loss during the freeze-thaw test.

Results for the frost heave tests showed that the untreated base materials were not susceptible to frost heave and that the addition of emulsion, with curing, did not change the frost heave behavior in a practically important way. Regarding the effects of curing, for 4 percent emulsion, the cured specimens exhibited less frost heave than those that were not cured, although, again, the magnitudes of frost heave that occurred are not considered to be practically important.

The permeability results revealed a significant difference in permeability between the specimens that were cured and those that were not cured. For Redwood Road and 7800 South, respectively, the permeability of the specimens that were cured was, on average, 60 and 29 times larger than the permeability of the specimens that were not cured.

These research findings suggest that frost damage due to freeze-thaw cycling was likely the cause of the modulus reductions measured in the field for Redwood Road, in particular. While susceptibility to frost heave is not expected to be a problem with the base materials on these two roads, the fact that the permeability increased substantially after curing of the emulsion could have facilitated greater freeze-thaw damage in the base layer.

5.3 Recommendations

Several recommendations may be derived from this research. Proper material sampling and laboratory testing should be performed to assess the efficacy of emulsion treatment for a given project. ETB to be constructed in cold regions should be subjected to freeze-thaw testing during the design phase. Designers should be aware that curing of the ETB may dramatically increase permeability and therefore increase frost susceptibility. In situations when the addition of emulsion by itself does not provide a satisfactory level of freeze-thaw resistance, but the use of emulsion is still desirable, the addition of portland cement with the emulsion should be considered to increase the strength and durability of the material (44).

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APPENDIX A FREEZE-THAW TEST DATA

This appendix contains raw data for freeze-thaw tests. The presence of a hyphen in a table indicates that the given data were not measured.

Table A-1: Freeze-Thaw Test Data for Redwood Road Site A

Sample Location	Initial Wet Modulus (ksi)	Final Wet Modulus (ksi)	Retained Modulus (%)	Initial UCS (psi)	Final UCS (psi)	Retained UCS (%)	Moisture Content (%)	Dry Density (pcf)
A1	-	-	-	-	-	-	-	-
A2	90.3	27.0	29.9	156	75	48.3	2.1	119.2
A3	55.4	21.5	38.8	125	85	68.1	2.4	118.4
A4	-	-	-	-	-	-	-	-
A5	65.5	29.7	45.4	127	64	50.2	2.2	119.4
A6	82.6	35.5	42.9	246	107	43.6	1.5	124.0
A7	-	-	-	-	-	-	-	-
A8	67.7	28.6	42.2	146	47	32.4	3.0	120.2
A9	87.8	30.2	34.4	129	59	45.7	3.2	119.1
A10	-	-	-	-	-	-	-	-
Average	74.9	28.7	38.4	154.7	72.9	47.1	2.4	120.1
Std. Dev.	14.02	4.56	5.85	46.51	21.32	11.62	0.01	2.02
CV (%)	18.7	15.9	15.2	30.1	29.3	24.7	25.5	1.7

Table A-2: Freeze-Thaw Test Data for Redwood Road Site B

Sample Location	Initial Wet Modulus (ksi)	Final Wet Modulus (ksi)	Retained Modulus (%)	Initial UCS (psi)	Final UCS (psi)	Retained UCS (%)	Moisture Content (%)	Dry Density (pcf)
B1	98.5	27.2	27.6	250	75	29.9	2.1	126.2
B2	101.0	26.5	26.2	179	122	67.9	1.6	121.7
B3	-	-	-	-	-	-	-	-
B4	79.7	32.4	40.7	141	55	38.9	3.4	115.5
B5	76.7	29.7	38.7	189	124	65.7	1.3	123.4
B6	63.1	33.0	52.3	176	145	82.3	1.6	122.6
B7	92.3	28.3	30.6	219	110	50.1	2.0	126.5
B8	76.5	31.5	41.1	177	116	65.4	1.7	121.5
B9	76.3	29.5	38.7	177	69	38.9	2.8	120.1
B10	69.9	31.9	45.7	149	92	61.6	2.2	122.0
Average	81.6	30.0	36.8	184.3	100.8	54.7	2.0	122.7
Std. Dev.	12.91	2.37	8.54	33.31	29.81	17.14	0.01	2.17
CV (%)	15.8	7.9	23.2	18.1	29.6	31.3	27.2	1.8

Table A-3: Freeze-Thaw Test Data for Redwood Road Site C

Sample Location	Initial Wet Modulus (ksi)	Final Wet Modulus (ksi)	Retained Modulus (%)	Initial UCS (psi)	Final UCS (psi)	Retained UCS (%)	Moisture Content (%)	Dry Density (pcf)
C1	85.9	30.5	35.5	242	84	34.6	2.5	123.1
C2	66.3	32.3	48.7	164	95	57.8	2.3	124.3
C3	77.0	36.7	47.6	149	92	61.3	2.4	122.0
C4	77.1	36.5	47.3	231	172	74.6	1.4	132.9
C5	64.8	27.1	41.9	197	101	51.4	2.9	122.1
C6	64.3	30.3	47.2	183	115	62.9	2.4	122.7
C7	64.3	29.6	46.1	152	109	71.7	1.9	120.4
C8	59.4	27.0	45.5	188	144	76.5	1.7	113.0
C9	70.2	34.4	49.0	162	77	47.3	2.4	120.8
C10	72.0	22.4	31.2	180	107	59.4	1.9	124.1
Average	70.1	30.7	43.8	184.9	109.5	59.3	2.2	120.5
Std. Dev.	7.98	4.48	6.04	31.34	28.92	12.99	0.00	3.92
CV (%)	11.4	14.6	13.8	17.0	26.4	21.9	20.6	3.3

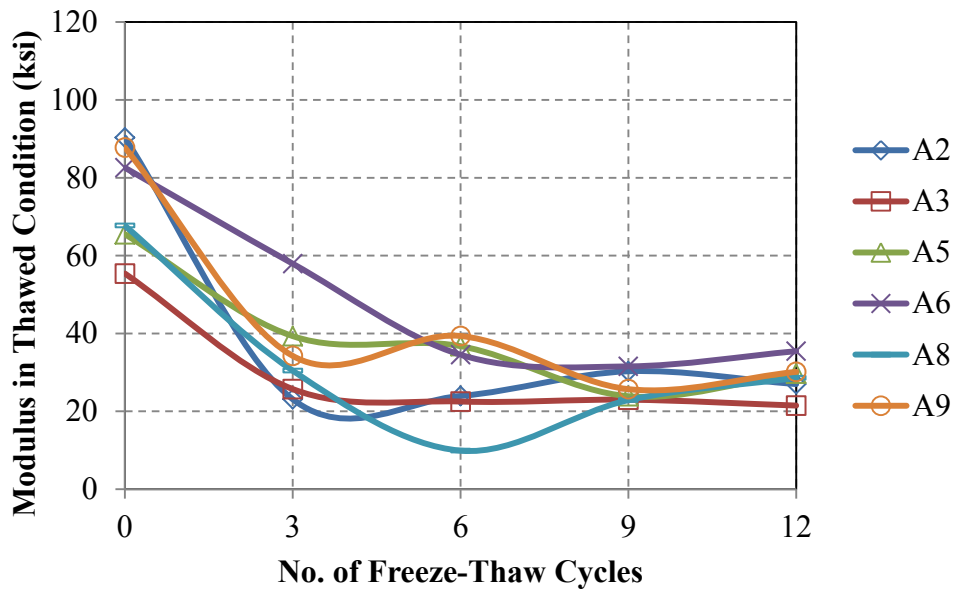


Figure A-1: Modulus values for Redwood Road site A.

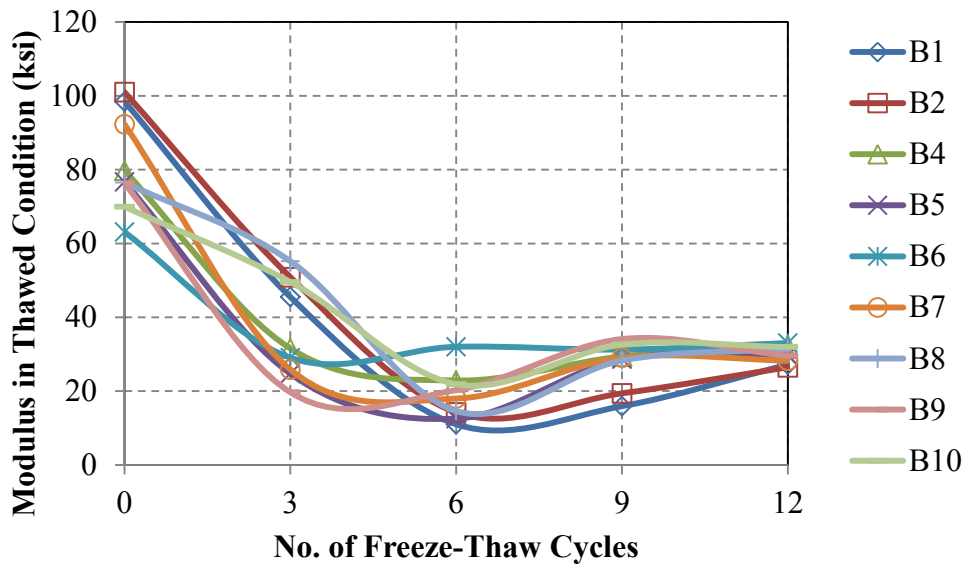


Figure A-2: Modulus values for Redwood Road site B.

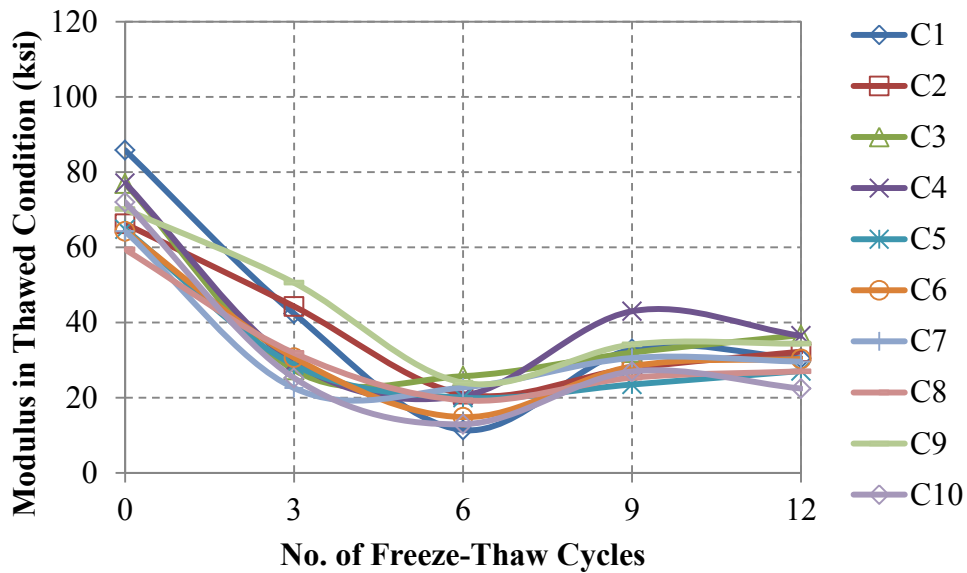


Figure A-3: Modulus values for Redwood Road site C.

Table A-4: Freeze-Thaw Test Data for 7800 South Site A

Sample Location	Initial Wet Modulus (ksi)	Final Wet Modulus (ksi)	Retained Modulus (%)	Initial UCS (psi)	Final UCS (psi)	Retained UCS (%)	Moisture Content (%)	Dry Density (pcf)
A1	2.43	9.12	375	40.6	41.8	103	5.7	123.7
A2	13.2	8.72	66.2	22.7	26.7	118	3.5	127.8
A3	4.19	2.58	61.5	29.4	33.0	112	6.5	129.4
A4	9.00	4.89	54.3	31.8	28.6	90.0	7.1	126.9
A5	5.06	2.32	45.9	28.6	39.4	138	6.4	130.7
A6	2.20	8.95	406	32.6	33.4	102	5.3	129.6
A7	5.23	1.01	19.3	28.6	26.7	93.1	8.4	127.0
A8	6.46	2.94	45.5	29.8	27.9	93.3	7.5	130.4
A9	3.40	2.86	84.2	39.0	27.9	71.4	7.0	127.1
A10	2.72	2.89	106	31.4	28.3	89.9	6.3	128.5
Average	5.39	4.63	86	31.5	31.4	99.6	6.8	128.1
Std. Dev.	3.44	3.11	141	5.18	5.44	18.2	1.06	2.09
CV (%)	63.8	67.3	165	16.4	17.3	18.3	15.6	1.6

Table A-5: Freeze-Thaw Test Data for 7800 South Site B

Sample Location	Initial Wet Modulus (ksi)	Final Wet Modulus (ksi)	Retained Modulus (%)	Initial UCS (psi)	Final UCS (psi)	Retained UCS (%)	Moisture Content (%)	Dry Density (pcf)
B1	5.41	1.62	29.9	23.9	27.5	115	7.1	128.8
B2	21.4	1.50	7.01	27.1	31.0	115	7.7	126.2
B3	14.2	2.50	17.6	40.2	28.3	70.3	6.6	129.2
B4	2.42	2.77	114	11.1	22.3	200	3.5	118.5
B5	6.14	6.78	110	22.3	36.6	164	4.8	124.7
B6	9.70	2.44	25.1	30.2	37.8	125	6.2	130.9
B7	4.86	0.91	18.7	35.0	25.9	73.9	8.5	125.5
B8	4.91	1.37	28.0	30.2	30.2	100	8.2	126.7
B9	9.74	4.06	41.7	25.9	29.8	115	5.8	127.0
B10	2.45	1.93	78.8	33.0	37.8	114	6.8	129.2
Average	8.13	2.59	31.8	27.9	30.7	110	6.7	126.7
Std. Dev.	5.93	1.72	39.5	7.97	5.24	38.7	1.42	3.46
CV (%)	72.9	66.5	124.0	28.6	17.1	35.1	21.2	2.7

Table A-6: Freeze-Thaw Test Data for 7800 South Site C

Sample Location	Initial Wet Modulus (ksi)	Final Wet Modulus (ksi)	Retained Modulus (%)	Initial UCS (psi)	Final UCS (psi)	Retained UCS (%)	Moisture Content (%)	Dry Density (pcf)
C1	9.24	7.64	82.6	30.2	26.7	88.2	5.6	128.5
C2	2.85	3.85	135	17.9	28.3	158	5.1	126.6
C3	3.44	3.64	106	27.9	21.5	77.1	6.1	126.9
C4	3.66	6.73	184	33.8	27.1	80.0	6.1	125.6
C5	2.56	1.00	39.2	21.9	23.9	109	7.7	125.5
C6	8.57	4.00	46.7	22.7	29.8	132	5.4	129.6
C7	8.38	13.7	163	21.1	22.7	108	3.9	127.3
C8	19.8	6.25	31.6	19.1	23.5	123	3.6	125.0
C9	10.8	6.11	56.5	24.7	23.9	96.8	4.6	125.3
C10	8.24	8.82	107	15.9	17.5	110	4.0	121.0
Average	7.76	6.17	80	23.5	24.5	104	4.9	126.1
Std. Dev.	5.21	3.48	53.2	5.67	3.60	24.8	1.52	2.33
CV (%)	67.2	56.4	66.8	24.1	14.7	23.8	31.2	1.8

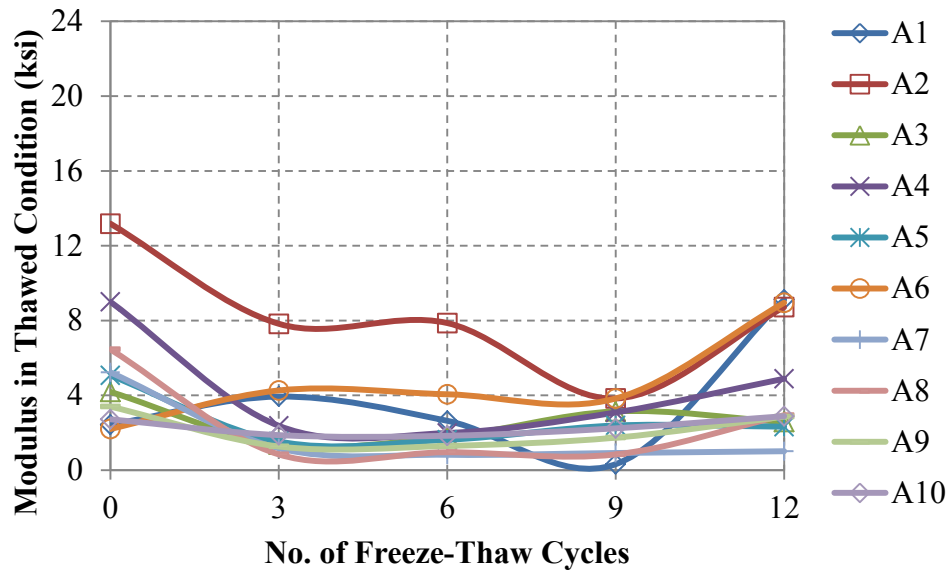


Figure A-4: Modulus values for 7800 South site A.

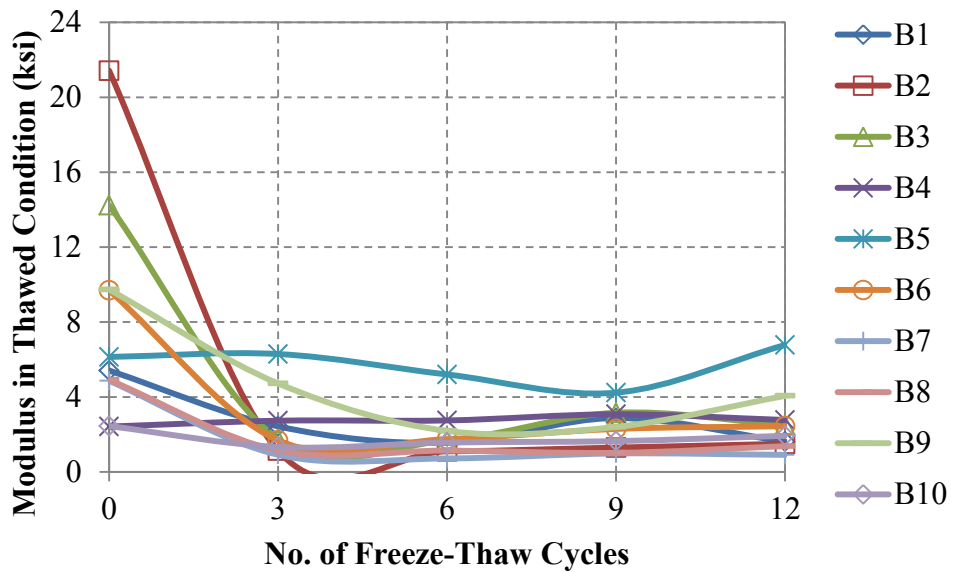


Figure A-5: Modulus values for 7800 South site B.

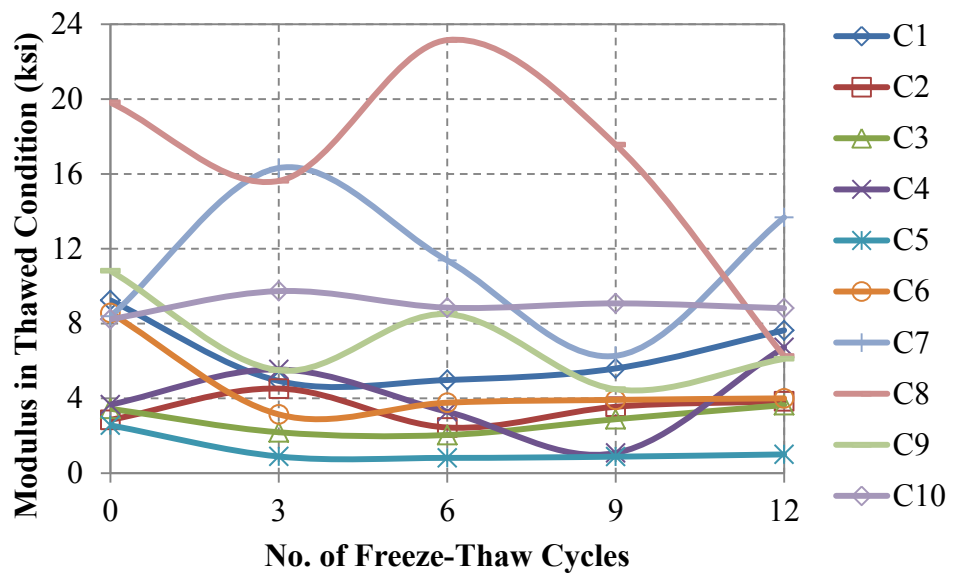


Figure A-6. Modulus values for 7800 South site C.

APPENDIX B FROST HEAVE TEST DATA

This appendix contains raw data for frost heave tests. The presence of a hyphen in a table indicates that the given data were not measured.

Table B-1: Frost Heave Test Data for Batch 1

Material	Emulsion Content (%)	Curing	Initial Height (in.)	Final Height (in.)	Height Change (in.)	Initial Weight (lb)	Final Weight (lb)	Weight Change (lb)
Redwood Road	6	Yes	9.1029	9.1415	0.0386	17.6365	17.6870	0.0505
Redwood Road	4	Yes	9.1693	9.1786	0.0094	18.0750	18.1080	0.0330
Redwood Road	2	Yes	8.9950	9.0344	0.0394	17.8410	17.8650	0.0240
Redwood Road	4	No	9.1228	9.2616	0.1389	18.3835	18.7690	0.3855
7800 South	6	Yes	9.1449	9.1525	0.0076	19.4000	19.4435	0.0435
7800 South	4	Yes	9.1250	9.1458	0.0207	19.6775	19.7810	0.1035
7800 South	2	Yes	8.9443	8.9139	-0.0304	19.2450	19.5195	0.2745
7800 South	0	No	8.9863	8.9789	-0.0074	20.9765	20.9160	-0.0605
7800 South	4	No	9.0949	9.1846	0.0898	19.9615	20.2530	0.2915

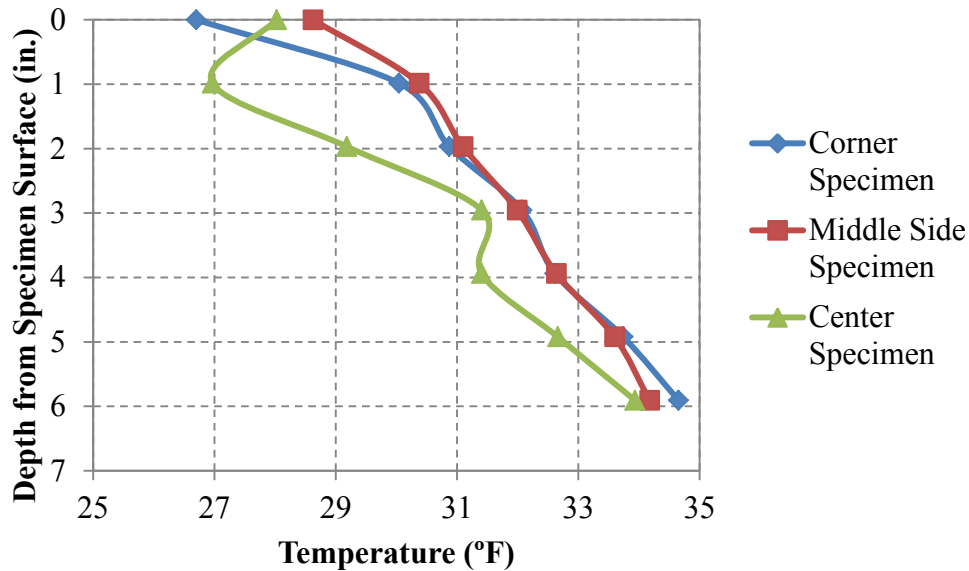


Figure B-1: Steady-state temperature profiles during frost heave testing of Batch 1.

Table B-2: Frost Heave Test Data for Batch 2

Material	Emulsion Content (%)	Curing	Initial Height (in.)	Final Height (in.)	Height Change (in.)	Initial Weight (lb)	Final Weight (lb)	Weight Change (lb)
Redwood Road	6	Yes	9.2891	9.2671	-0.0220	18.2195	18.2530	0.0335
Redwood Road	4	Yes	9.1533	9.1938	0.0405	18.0935	18.1330	0.0395
Redwood Road	2	Yes	8.8955	8.9145	0.0190	17.7815	17.8175	0.0360
Redwood Road	4	No	9.1494	9.1053	-0.0441	18.6750	18.9165	0.2415
7800 South	6	Yes	9.4621	9.4526	-0.0095	19.9775	20.0230	0.0455
7800 South	4	Yes	9.1383	9.1383	0.0000	19.6400	19.7255	0.0855
7800 South	2	Yes	9.0854	9.0421	-0.0433	19.6495	19.8890	0.2395
7800 South	0	No	9.0220	9.0250	0.0030	20.9465	20.9400	-0.0065
7800 South	4	No	9.2689	9.2695	0.0006	20.4335	20.5925	0.1590

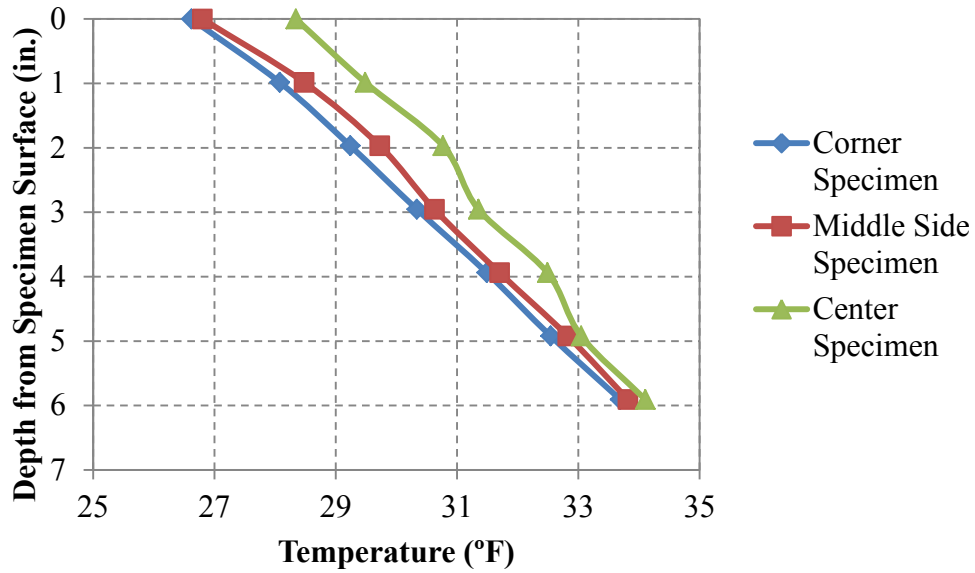


Figure B-2: Steady-state temperature profiles during frost heave testing of Batch 2.

Table B-3: Frost Heave Test Data for Batch 3

Material	Emulsion Content (%)	Curing	Initial Height (in.)	Final Height (in.)	Height Change (in.)	Initial Weight (lb)	Final Weight (lb)	Weight Change (lb)
Redwood Road	0	No	9.1435	9.1723	0.0288	20.3475	20.5655	0.2180
Redwood Road	0	No	8.9330	8.9640	0.0310	19.8940	20.1085	-0.2145

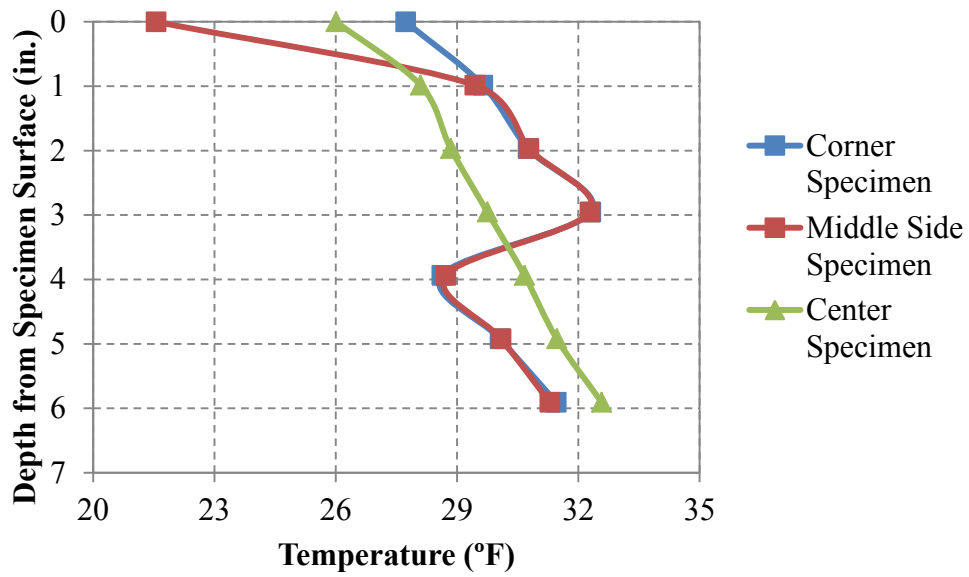


Figure B-3: Steady-state temperature profiles during frost heave testing of Batch 3.

APPENDIX C PERMEABILITY TEST DATA

This appendix contains raw data for permeability tests.

Table C-1: Permeability Test Data

Material	Emulsion Content (%)	Curing	Initial Height (in.)	Initial Weight (lb)	Permeability (ft/day)
Redwood Road	4	No	4.8140	4.2720	0.213
Redwood Road	4	No	4.6950	4.1415	0.341
Redwood Road	4	Yes	4.8870	4.0740	19.22
Redwood Road	4	Yes	4.8200	4.0970	13.95
7800 South	4	No	4.9640	4.6780	0.003
7800 South	4	No	4.9190	4.6680	0.008
7800 South	4	Yes	4.9030	4.5690	0.189
7800 South	4	Yes	5.0570	4.5975	0.152