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# Compositional and Structural Properties of Emulsion-Treated Base Material: 7800 South in West Jordan, Utah

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# Compositional and Structural Properties of Emulsion-Treated Base Material:

## 7800 South in West Jordan, Utah

Lisa R. Gurney

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

Master of Science

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# ABSTRACT

## Compositional and Structural Properties of Emulsion-Treated Base Material: 7800 South in West Jordan, Utah

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Master of Science

The objectives of this research were 1) to examine correlations between compositional and structural properties of emulsion-treated base (ETB) layers, determine which of these factors exhibit the greatest spatial variability, and determine if significant differences exist between different test sections on a given project and 2) to investigate temporal trends in the structural properties of base materials treated with asphalt emulsion and to assess the rate at which ETB design properties are achieved. The research conducted in this study focused on testing of the ETB layer constructed on 7800 South (SR-48) in West Jordan, Utah. The research conducted in this study involved field and laboratory evaluations of spatial and temporal variability in properties of ETB.

Regarding spatial results, the average modulus values of the ETB layer were unusually low for a typical stabilized base material and were in general even lower than the subgrade modulus values at this test site. All three sections had high moisture contents after compaction, with the moisture content of the ETB layer exceeding the specified optimum moisture content at many locations even before the emulsion was injected. One of the three test sections had higher percentages of reclaimed asphalt pavement and emulsion than the other two. The ETB compressive strength was very low throughout the entire year of testing, clearly demonstrating the consequences of inadequate emulsion curing associated with this project. The statistical analyses showed that higher pre-treatment moisture contents and higher amounts of binder added were associated with lower stiffness and strength, while higher wet densities were associated with higher stiffness and strength. The analyses also showed substantial variation in most response variables but comparatively low variation in predictor variables. Only four structural properties were significantly different between sections.

Temporal testing was performed to monitor the properties of the ETB layer and to compare the ETB section to an adjacent untreated base course (UTBC) section. The ETB moisture content did not change significantly during the 1-year monitoring period, showing that drying of the ETB layer did not occur following placement of the hot mix asphalt surface. Furthermore, the analyses 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, with higher ETB moisture contents and temperatures corresponding to lower ETB modulus values. Even during the winter when the ETB stiffness reached its peak, the modulus was still below the target value specified for this project. The statistical analyses indicated that the modulus values of the ETB and UTBC layers were not statistically different.

Key words: asphalt emulsion, emulsion-treated base, full-depth reclamation, modulus, reclaimed asphalt pavement, stabilization, stiffness, strength gain

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# 1 INTRODUCTION

## 1.1 Problem Statement

Full-depth reclamation (FDR) has become increasingly prevalent in the transportation industry during the last few decades as a means of rehabilitating and reconstructing flexible pavements (*1, 2*). The FDR process involves recycling of the existing pavement structure by pulverizing the in-place asphalt layer and mixing the reclaimed asphalt pavement (RAP) into the upper portion of the existing base to form a new base layer. FDR provides a feasible solution to problems such as pavement geometry restrictions, lack of quality aggregate, and the cost of asphalt disposal (*3*); however, the reclamation process can cause a reduction in the strength of the base layer because it disturbs the existing base material and because the introduction of RAP into the base material has been shown to decrease the bearing capacity of some base materials and possibly impede proper compaction of the base material (*4, 5*). For these reasons, stabilization is often needed to improve the structural properties of base materials constructed using FDR (*5*). One product that has been used in road stabilization since the early 1900s is asphalt emulsion (*6*). The application of asphalt emulsion is an easy method for adding asphalt binder to road base during the reclamation process. The resulting product, emulsion-treated base (ETB), may then be surfaced with a wearing course for trafficking.

Several studies have been performed to assess the long-term strength of ETB in the field. In pavement tests performed 6 months or more following pavement reconstruction, Illinois Department of Transportation personnel measured resilient modulus values as high as 200 ksi, and researchers at the Texas Transportation Institute measured resilient modulus values as high as 275 ksi (*1, 2*). Although these studies have determined that long-term ETB strengths are sufficient to support even heavy traffic loads, little research has been performed to determine the rate at which ETB develops strength in the period between construction and the time that ETB design properties are achieved. In particular, the ability of a pavement to withstand early trafficking depends on the strength developed in the pavement system immediately following construction. If the strength of the pavement system is not sufficiently high before traffic is reintroduced, early trafficking will cause permanent deformation of the treated layer, compromising long-term pavement performance. Furthermore, if the ETB does not reach design strengths for an extended period of time, continued trafficking may cause premature failure of the pavement system. For these reasons, an understanding of early strength development in ETB is vital for pavement engineers interested in utilizing FDR in conjunction with emulsion treatment.

In addition, many factors such as moisture content, aggregate gradation, and temperature have been shown to influence the mechanical properties of ETB (*1, 6, 7, 8*). Consequently, variability in these factors can cause variability in pavement structural capacity, ultimately reducing the reliability of the pavement system and leading to premature failure of some sections. Development of improved specifications governing construction of ETB layers requires an understanding of the factors that most directly influence ETB performance and identification of those that are most variable.

Therefore, the objectives of this research were 1) to examine correlations between compositional and structural properties of ETB layers, determine which of these factors exhibit the greatest spatial variability, and determine if significant differences exist between different test sections on a given project and 2) to investigate temporal trends in the structural properties of base materials treated with asphalt emulsion and to assess the rate at which ETB design properties are achieved.

## 1.2 Scope

The research conducted in this study involved field and laboratory evaluations of spatial and temporal variability in properties of ETB. Field testing was performed on a test site located on 7800 South (SR-48) in West Jordan, Utah. The experimental area, between 2700 West and 3200 West, was divided into three 800-ft by 24-ft test sections, each containing 10 individual test stations randomly located throughout the section. The field instruments utilized in this research included the portable falling-weight deflectometer (PFWD), dynamic cone penetrometer (DCP), heavy Clegg impact soil tester (CIST), soil stiffness gauge (SSG), and nuclear density gauge (NDG). All of the field tests were conducted at all stations immediately following construction, and continued testing using the PFWD was performed at one station every two weeks for 1 year. At this station, the moisture and temperature of the ETB were also measured using in-situ sensors installed at the time of construction.

Laboratory testing involved moisture content determinations, sieve analyses, and burn-off testing of untreated material samples and unconfined compressive strength (UCS) testing, moisture content determinations, and burn-off testing of treated material samples taken from each field test station. UCS tests were performed on one emulsion-treated sample from each test station at 7 days, 28 days, 6 months, and 1 year following emulsion treatment.

The current study builds upon previous work conducted in the first phase of this research, in which data were collected from Redwood Road (SR-68) just north of Saratoga Springs, Utah (*9*). The current study reports on a second construction project involving different materials, contractors, and site conditions.

## 1.3 Outline of Report

This report contains five chapters. Chapter 1 introduces the problem statement and scope of the research. Chapter 2 provides background information on ETB construction processes, ETB strength gain, and factors that affect ETB performance. Chapter 3 gives a description of site layouts, field and laboratory procedures, and statistical analyses for spatial and temporal testing. Chapter 4 presents the results of spatial and temporal testing and analysis, and Chapter 5 offers conclusions and recommendations.

# 2 BACKGROUND

## 2.1 Overview

The following sections provide background information obtained through a literature review on ETB construction processes, ETB strength gain, construction factors affecting ETB performance, environmental factors affecting ETB performance, and the effects of early trafficking on ETB.

## 2.2 Emulsion-Treated Base Construction Processes

The process of FDR with emulsion treatment begins with pulverization of the existing asphalt layer and mixing with a specified thickness of the underlying base material. Partial milling of the existing asphalt layer at some locations may be needed before reclamation to ensure uniform RAP contents within the reclaimed base layer (*8*). The reclaimed material is then graded and compacted to approximate final elevations before being treated with emulsion (*10*). Water can be added during the initial pulverization process to facilitate uniform distribution of the emulsion (*11*, *12*). Emulsion is then injected into the base material using a reclaimer, shown in Figure 2-1, and mixed to ensure uniform distribution.

Figure 2-2 shows the emulsion injection process. Additional water can be added during injection as needed to reach the optimum moisture content (OMC) of the ETB material. The treated base is compacted using sheep's foot rollers or vibratory breakdown rollers. Figure 2-3

Figure 2-1: Reclaimer.

Figure 2-2: Emulsion injection.

**Figure 2-3: Emulsion-treated base compaction.**

shows a compactor following directly behind the reclaimer. Following compaction, the ETB is graded and finish-rolled. Paving of the ETB is sometimes delayed as much as 2 weeks following construction to allow moisture to escape from the ETB during the early curing process (*7, 9*, *11, 12*); maximum allowable ETB moisture contents before paving are typically 2 to 3 percent (*12*); however, traffic is often reintroduced immediately following final compaction of the ETB layer, even before paving. If no visually apparent deflections are observed under a heavy truck, the ETB layer is usually judged to be ready for trafficking (*11, 12*).

## 2.3 Emulsion-Treated Base Strength Gain

Asphalt emulsion is typically considered an oil-in-water emulsion, meaning it consists of asphalt binder particles that are suspended in water through the use of an emulsifier (*6, 13*). Emulsifiers create charges on the surfaces of the asphalt particles that cause them to repel each other, stabilizing the particles within the emulsion. Asphalt emulsions typically contain between

25 to 60 percent water, 40 to 75 percent bitumen, and 0.1 to 2.5 percent emulsifier (*13*). Solvents are sometimes added to modify emulsion properties and behavior. The specific composition of an asphalt emulsion determines emulsion characteristics such as reactivity, viscosity, and stability.

The process of curing involves the gradual evaporation and expulsion of water from the emulsion. Curing of ETB begins when the emulsion begins to destabilize due to compaction and water evaporation (*7*). During compaction, the asphalt particles are forced together, causing them to overcome static repulsion and begin to coalesce into larger asphalt droplets. If curing continues, the asphalt droplets eventually become large enough to bind aggregate particles together. The rate of curing depends on several factors, including the reactivity of both the emulsion and the aggregate, emulsion chemistry, and environmental factors such as wind speed, humidity, and temperature (*7, 14*). Compaction or trafficking of the ETB can increase curing rates by forcing asphalt particles closer together (*13*); however, depending on the material properties, higher densities resulting from compaction can actually restrict water evaporation and therefore decrease curing rates (*15*).

Curing to the design strength may require from a few weeks to a couple of years depending on the properties of the emulsion used (*7, 13, 14*). ETB exhibits low strengths immediately following construction due to the lack of curing of the emulsion. In one study, researchers found that the stiffness of ETB after compaction was actually lower than the reclaimed material before emulsion treatment (*16*); however, ETB layers have been found to exhibit large increases in resilient modulus during the first 28 days of curing (*17, 18*). Other researchers have measured a 300 percent increase in resilient modulus during the first 10 months (*19*). The Asphalt Institute (AI) 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 AI has also found that curing times longer than 6 months do not significantly increase ETB strength (*20*), but some reports indicate that ETB can take as long as 2 years to fully cure (*14*). 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.

## 2.4 Construction Factors Affecting Emulsion-Treated Base Performance

Several construction factors can affect the performance of ETB materials. Some of these factors include gradation, subgrade strength, degree of ETB compaction, and total moisture content (TMC) of the ETB.

The gradation of the reclaimed base material before emulsion treatment can impact ETB strength (*8*). The fraction of material passing the No. 200 sieve should be less than 25 percent to avoid weakening the ETB (*6*). Therefore, the inclusion of portions of subgrade in the reclaiming process, which could introduce excessive fines into the reclaimed base, should generally be avoided (*1*).

The subgrade strength is especially important in the period of time immediately following construction (*2*). The treated base layer is fairly weak following pulverization and reclamation, so the ability of the subgrade to withstand construction and early traffic loads will greatly affect the support offered to the ETB. The strength of the subgrade will also affect the degree of compaction possible in the ETB (*8*).

The degree of ETB compaction affects ETB strength development. Compaction can aid in the initial destabilization of the asphalt emulsion but also affects the rate of curing within the ETB. The percentage of voids remaining after compaction should be low enough to minimize water ingress but sufficiently high to allow water to evaporate from the emulsion during the curing process (*15*).

TMC includes the in-situ moisture that exists before emulsion injection and the water added during the injection process, including the water contained in the emulsion. If the TMC is not within an acceptable percentage of the OMC for the ETB material, compaction of the ETB layer to the specified density may not be possible. If TMC approaches saturation, compaction of the ETB can be extremely difficult if not impossible. If in-situ moisture contents are such that the addition of emulsion will increase TMC to unacceptable values, the reclaimed material must be allowed to dry before emulsion can be added (*7*).

## 2.5 Environmental Factors Affecting Emulsion-Treated Base Performance

Environmental factors such as moisture content and temperature can also affect the performance of ETB materials. Several studies have found that, during the early stages of curing, excessive moisture contents due to rain or other water sources can cause pavement weakness and even failure (*2, 21*). After the emulsion has fully cured, the ability of moisture to affect the pavement system is reduced, but high moisture contents in the period immediately following construction can slow the curing process and lower the early strength of the ETB (*7*).

Because of the temperature susceptibility of asphalt binder, the structural properties of ETB are affected by ETB temperature (*6, 14, 22*). As pavement temperature increases, the strength of the ETB layer decreases due to the softening of the asphalt binder material (*2, 23*). Ambient air temperature and relative humidity also affect the rate at which the ETB can cure because these factors affect evaporation rates. Low temperature and high humidity typically reduce evaporation rates, thus preventing expelled water from being removed from the pavement system and slowing curing rates (*7*).

## 2.6 Effect of Early Trafficking on Emulsion-Treated Base Performance

The degree to which emulsion has cured has a large effect upon the stiffness and strength of the ETB during the first two years following construction (*14*). During this time, permanent deformation is the primary failure mechanism for the ETB layer because the curing process is not yet completed (*13*). Because of the nature of this failure mechanism, the stiffness of the ETB in large part governs its ability to support traffic loads (*22*). In current pavement design methods, the stiffness of a pavement layer is directly tied to pavement structural capacity. If the layer modulus is low, pavement structural capacity is significantly reduced.

One of the stated benefits of ETB is that the pavement can be opened to traffic within hours following construction (*1, 2, 7, 11, 12, 24*); however, some ETB projects have experienced severe rutting problems during early pavement life due to the adverse effects of traffic on weak pavement (*2, 24*). In one study, the life of a pavement comprised of an ETB layer was found to increase by more than 400 percent when traffic was withheld from the pavement for 48 hours following construction compared to allowing trafficking within 2 hours following construction (*24*).

## 2.7 Summary

The process of FDR with emulsion treatment involves pulverization of the existing asphalt layer and mixing with a specified thickness of the underlying base material. Emulsion is injected into the base material using a reclaimer, after which the treated base is compacted, graded, and finish-rolled. Paving of the ETB is delayed as much as 2 weeks following construction to allow moisture to escape from the ETB during the early curing process. The process of curing involves the gradual evaporation and expulsion of water from the emulsion, forcing the asphalt particles to coalesce and bind aggregate particles together. Curing to the design strength may require from a few weeks to a couple of years depending on the properties of the emulsion used. ETB exhibits low strengths immediately following construction due to the lack of curing of the emulsion. The performance of ETB materials can be affected by several construction factors, including aggregate gradation, subgrade strength, degree of ETB compaction, and TMC of the ETB. ETB performance can also be affected by environmental factors such as temperature, relative humidity, and moisture content. One of the stated benefits of ETB is that the pavement can be opened to traffic within hours following construction; however, some ETB projects have experienced severe rutting problems during early pavement life due to the adverse effects of traffic on weak pavement.

# 3 PROCEDURES

## 3.1 Overview

The procedures for this research involved both spatial and temporal testing of an ETB layer constructed using FDR. The following sections describe the site layout, procedures, and analyses performed during this research.

## 3.2 Spatial Testing

This section provides a description of the site layout, field and laboratory procedures, and statistical analyses associated with spatial testing.

### *3.2.1 Site Layout*

The test site chosen for this research comprised the eastbound lanes of 7800 South in West Jordan, Utah, between 2700 West and 3200 West. This section of 7800 South was part of a multi-phase reconstruction project. Figures 3-1 and 3-2 show 7800 South during the reconstruction process. The pavement design applied to the test section included the use of 1 in. of open-graded surface course (OGSC) on 5 in. of hot-mix asphalt (HMA) on 8 in. of ETB. Construction of the 7800 South test area occurred in October 2010. The experimental area was divided into three 800-ft by 24-ft test sections, labeled as sections A, B, and C. Ten individual test stations were established in each of the three sections. These stations were randomly located

Figure 3-1: Base material prepared for emulsion treatment.

Figure 3-2: Emulsion treatment of prepared base material.

throughout each test section as shown in Figure 3-3; however, an adjustment was made to the three stations farthest from the edge of the road. These three stations were moved 2 ft closer to

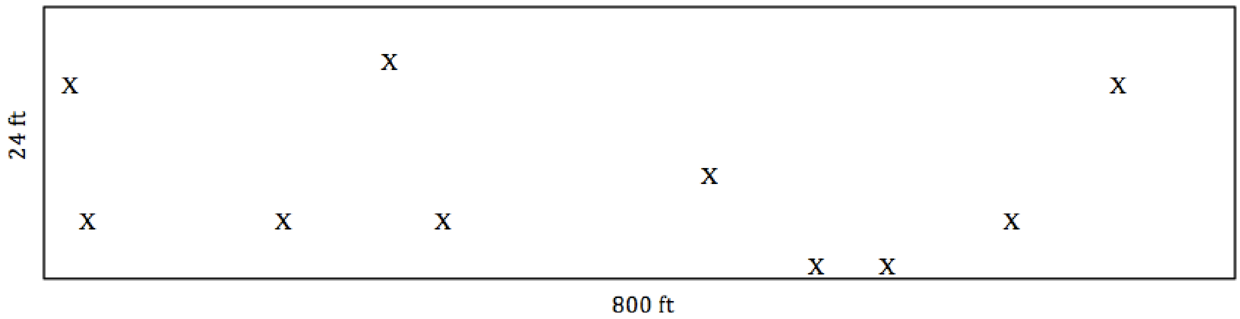

Figure 3-3: Test station layout.

the curb in order to avoid placing them immediately over a shallow utility pipe in the roadway. The same layout was used for all three sections.

### *3.2.2 Field Procedures*

Field testing was performed on the day of ETB construction and during the first few days following construction. This testing was performed to characterize the in-situ structural properties of the ETB layer. The field instruments utilized in this research include the PFWD, DCP, CIST, SSG, and NDG. All instruments were used on the day of compaction; however, due to limited access to the site, not all instruments were used during testing on the day following compaction or 4 days after compaction.

The PFWD shown in Figure 3-4 was utilized in general accordance with American Society for Testing and Materials (ASTM) E2583 (Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD)). The PFWD consists of a 44.1-lb weight that is dropped 30 in. onto a 7.87-in.-diameter load plate. Three sensors were used to measure surface deflection at radial distances of 0, 12, and 24 in. from the point of impact. A seating load was applied before actual measurements were taken to ensure that the load plate was

**Figure 3-4: Portable falling-weight deflectometer.**

properly situated on the ETB surface. Three PFWD tests were performed at each station on the day of ETB construction and on the following day, and the deflections were used to backcalculate the modulus of each layer of the pavement system in ksi in each case.

The DCP shown in Figure 3-5 was utilized in general accordance with ASTM D6951 (Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications). The DCP is used to measure bearing capacity and uniformity of compacted base, subbase, and subgrade layers. It consists of a standard metal cone at the end of a 0.47-in.-diameter metal rod. A 10-lb slide hammer is repeatedly dropped 22.5 in., and the penetration rate is recorded. Penetration rates from DCP testing are used to characterize the stiffness of the

Figure 3-5: Dynamic cone penetrometer.

pavement layers in terms of mm/blow. In this research, the DCP test was performed 1 day following ETB construction, prior to placement of the asphalt layer. Testing was continued to a target depth of 24 in., which allowed determination of average penetration rates for both the ETB and subgrade layers.

The CIST displayed in Figure 3-6 was utilized in general accordance with ASTM D5874 (Standard Test Method for Determination of the Impact Value of a Soil). The CIST is employed to evaluate the stiffness or strength of a base, subbase, or subgrade material used in pavement construction. A heavy Clegg hammer, consisting of a 44-lb weight that is dropped 12 in. through a guide tube, returns the highest deceleration value at each point as a Clegg impact value (CIV),

**Figure 3-6: Clegg impact soil tester.**

where 1 CIV is equivalent to 10 times the acceleration rate of gravity (*25*). In this research, the CIST was used to determine the CIV of the ETB layer. Three CIST measurements were taken at each station on the day of construction and after 1 and 4 days.

The SSG shown in Figure 3-7 was utilized in general accordance with ASTM D6758 (Standard Test Method for Measuring Stiffness and Apparent Modulus of Soil and Soil-Aggregate In-Place by Electro-Mechanical Method). The SSG is a compact cylinder weighing 22 lb that imparts very small displacements, using a harmonic oscillator, to the soil through a ring-shaped foot. Stiffness is then determined from the deflections of the soil caused by the induced vibrations. The SSG measures the stiffness of the underlying soil to an average depth of

**Figure 3-7: Soil stiffness gauge.**

9 to 12 in. from the surface. In this research, the SSG was used to determine the stiffness of the ETB layer in MN/m. Following standard procedures, a thin layer of moist sand was placed between the SSG and the ETB surface during testing to improve contact with the ground, and the SSG was removed and replaced between readings. Three SSG measurements were taken at each station on the day of ETB construction and again on the day after construction.

NDG tests were performed in general accordance with ASTM D6938 (Standard Test Method for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)). The NDG was used to measure in-situ wet density, moisture content, and percent moisture of the compacted ETB on the day of construction. It was used in direct transmission mode with a rod penetration of 6 in. One test was performed at each test station; tests were not repeated on later days. The NDG utilized on this project is shown in Figure 3-8.

On the day of construction, samples of the reclaimed base material were removed from each test station both before and after emulsion treatment. Sampling of the untreated material is shown in Figure 3-9. The samples of untreated material were bagged and transported to the Brigham Young University (BYU) Highway Materials Laboratory for sieve, moisture content, and burn-off analyses. The samples of treated material were compacted on site using the modified Proctor compaction protocol in general accordance with ASTM D1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft$^3$ (2,700 kN-m/m$^3$))) Method B. This method involved compaction of the ETB material in 4-in.-diameter molds in five lifts of 25 blows each. The modified Proctor compaction set-up is shown in Figure 3-10. Five specimens were prepared for each of the test stations. At the laboratory, these specimens were subjected to UCS, moisture content, and burn-off analyses.

**Figure 3-8: Nuclear density gauge.**

Figure 3-9: Pre-treatment material sampling.

Figure 3-10: Specimen compaction.

The test data obtained through field testing were analyzed to determine several structural properties of the ETB layer. Modulus values were determined from the PFWD test using BAKFAA backcalculation software (*26*). The original pavement design layer thicknesses were used during backcalculation; these thicknesses were also used in calculating separate penetration rates for the ETB layer and subgrade from the DCP tests. A Poisson's ratio of 0.35 and full interface bonding were assumed for all backcalculations. DCP penetration rates were used to determine ETB CBR and modulus values using Equations 3-1 and 3-2, respectively (*27*):

$$CBR = \frac{292}{PR^{1.12}} \tag{3-1}$$

where $CBR$ = California bearing ratio, %

$PR$ = penetration rate, mm/blow

$$M_R = 2550 \cdot CBR^{0.64} \tag{3-2}$$

where $M_R$ = resilient modulus, psi

$CBR$ = California bearing ratio, %

The impact values measured with the CIST were correlated to modulus values using Equation 3-3 (*28*), and soil stiffness values were converted to modulus values using Equation 3-4 (*29*). A Poisson's ratio of 0.35 was used to calculate modulus values from SSG readings.

$$M_R = 33.56 \cdot CIV^2 \tag{3-3}$$

where $M_R$ = resilient modulus, psi

$CIV$ = Clegg impact value

$$M_R = 0.2511 \cdot SS(1 - \nu^2) \tag{3-4}$$

where $M_R$ = resilient modulus, psi

$SS$ = soil stiffness, lbf/in.

$\nu$ = Poisson’s ratio

### *3.2.3 Laboratory Procedures*

At the BYU Highway Materials Laboratory, material characterization testing was conducted on field-sampled base material from each test station to determine average properties for each of the three test sections. A dry sieve analysis was performed on the untreated material from each station in general accordance with ASTM D422 (Standard Test Method for Particle-Size Analysis of Soils) to determine the variation between test sections. In addition, a washed sieve analysis was performed on a representative sample of untreated material in order to determine the soil classification. Atterberg limits were determined in general accordance with ASTM D4318 (Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils) in order to further classify the soil type. Untreated material collected from each station immediately before ETB construction was weighed before and after being placed in a 140°F oven to determine the moisture content before emulsion treatment.

A burn-off test was performed on both untreated and treated materials in general accordance with ASTM D6307 (Standard Test Method for Asphalt Content of Hot-Mix Asphalt by Ignition Method) using the burn-off oven shown in Figure 3-11. These tests were used to determine the asphalt content of the reclaimed base material at each test station both before and after ETB construction. The amount of emulsion injected at each station was then calculated as

**Figure 3-11: Burn-off testing.**

the measured difference in the asphalt content of the base material before and after emulsion treatment divided by the design asphalt content of 64 percent by weight of the emulsion.

UCS tests were performed as shown in Figure 3-12 in general accordance with ASTM D1633 (Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders) on one emulsion-treated sample from each test station at 7 days, 28 days, 6 months, and 1 year following construction of the test sections. Samples were stored at room temperature in sealed plastic bags until being tested to simulate the absence of water evaporation in the field after asphalt placement. They were then capped with gypsum and subjected to UCS testing at a strain

**Figure 3-12: Unconfined compressive strength testing.**

rate of 0.05 in./minute. UCS values were plotted to develop strength-gain curves for ETB under these laboratory curing conditions.

### *3.2.4 Statistical Analyses*

The spatial data were evaluated using several statistical analyses, including multivariate regression, coefficient of variation (CV) comparisons, analysis of variance (ANOVA), and Tukey's mean separation procedure to examine spatial variability and significant correlations between predictor and response variables. Statistical analysis software was used to perform the analyses as presented in the following sections.

#### 3.2.4.1 Multivariate Regression

In the stepwise multivariate regression analysis, the level of significance, or *p*-value, of each of the potential predictor variables in predicting a given response variable was determined. Once the *p*-value of each predictor variable was determined, a regression model was developed for each response variable. Regression models were used as a form of analysis to investigate correlations between predictor and response variables and, when a correlation existed, to determine whether the relationship was positive or negative. Consistent with previous research, regression models were developed using predictor variables having *p*-values less than or equal to 0.15, which is the default value utilized for variable selection in the computer software utilized for this purpose (*10*). The coefficient of determination, or $R^2$ value, for each regression model was then computed. The $R^2$ value is a measure of the percentage of variation in the response variable that can be explained by variation in the predictor variables used in the model (*30*).

Response variables evaluated in the multivariate regression analyses included ETB structural properties measured on the day of construction, the day after construction, and 4 days after construction. For the day of construction, the response variables included modulus as measured by the PFWD, CIV, and soil stiffness. For the day following construction, the response variables included the modulus as measured by the PFWD, penetration rate as measured by the DCP, CBR as backcalculated from DCP measurements, CIV, and soil stiffness. Finally, for 4 days following construction, the response variable included CIV. Also included in the response variables were the 7-day, 28-day, 6-month, and 1-year UCS values. The predictor variables included the percent passing each sieve size; binder content before treatment; percent change in binder; pre-treated moisture content; and wet density, dry density, moisture content, and percent moisture as measured by the NDG. In addition, for each UCS test, the corresponding wet density, dry density, and moisture content of the given specimen were considered as predictor variables.

### 3.2.4.2 Coefficient of Variation Comparisons

CV values were computed for each response and predictor variable to determine which parameters were the most variable. The CV for a given data set is the ratio of the standard deviation to the mean. CV values are useful for comparing the variability of dissimilar variables because the CV is scaled according to the mean value of the parameter (*31*).

### 3.2.4.3 Analysis of Variance and Tukey's Mean Separation Procedure

An ANOVA was performed to determine if significant differences existed between test sections for each of the response variables. The ANOVA method compares multiple population means while controlling the possibility of incorrectly claiming that significant differences exist (*32*). A *p*-value less than or equal to 0.05 indicated significant differences between the sections. Tukey's mean separation procedure was then used to determine which specific sections were significantly different from the others (*33*).

## 3.3 Temporal Testing

The intent of the temporal testing phase of this project was to monitor the ETB properties over a 1-year period. To that end, moisture and temperature sensors were installed in the ETB layer at three stations, one in each of the three test sections; however, during the first 3 days following construction, the asphalt emulsion in the base layer was not curing sufficiently. The base material had been too wet at the time of emulsion injection, and, following compaction, cool temperatures (45 to 65°F measured on the day of construction) and high subgrade moisture contents prevented drying of the layer. As a result of the excess water, proper compaction of the ETB layer was predictably difficult (*7*), and significant rutting was occurring under construction trafficking. As shown in Figure 3-13, the rutting was measured to be deeper than 4 in. in some locations. As winter was approaching, the engineer and the contractor both recognized that the environmental conditions were not likely to improve, and, after lengthy discussion, they decided to remove the ETB layer, remaining base, and subgrade to a depth of 31 in. and replace it with 8 in. of untreated base course (UTBC) underlain by 11 in. of granular borrow, 6 in. of excavated ETB material, and a geotextile; a 1-in. OGSC and a 5-in. HMA layer were specified as surface courses. Thus, the ETB layer was removed just 4 days after it had been constructed.

Although the research team was prepared to immediately remove the sensors from all three stations before the failed ETB layer was excavated, the UDOT engineer responsible for the project agreed to leave one of the instrumented stations in place to support the completion of this research; it was located immediately east of 3200 West in approximately the same position as

**Figure 3-13: Significant rutting occurring hours after emulsion-treated base construction.**

station A1. Thus, only one of the original three stations was available for monitoring in this research. A description of the site layout, field and laboratory procedures, and statistical analyses associated with temporal testing are provided in the following sections.

### *3.3.1 Site Layout*

At the single station preserved for monitoring, two dielectric-type moisture and temperature sensors had been installed according to the layout shown in Figure 3-14. These sensors were positioned in the middle of the ETB layer, at a depth of approximately 4 in. as shown in Figure 3-15. The sensor wires were protected in a foam wrapping, routed through a

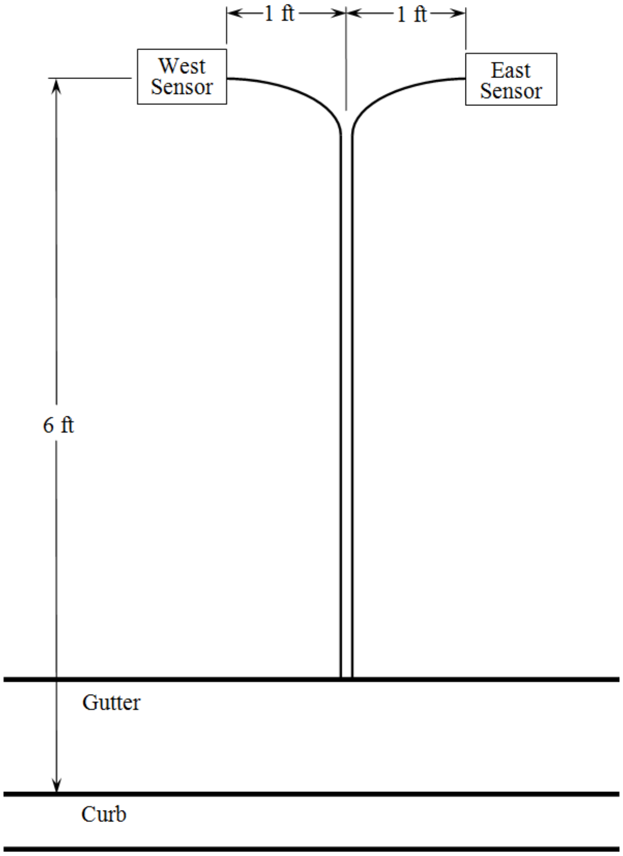

**Figure 3-14: Sensor site layout.**

**Figure 3-15: Sensor site just before installation of sensors.**

conduit that was installed beneath the curb and gutter along the edge of the road, and terminated in a sprinkler valve box for convenient future access. A sensor is shown in Figure 3-16.

### *3.3.2 Field Procedures*

After the HMA and OGSC layers were placed at the station to be monitored, survey nails were hammered into the pavement surface immediately over the sensors. Two nails, spaced the same distance apart and placed at the same distance from the lip of the gutter, were also placed in a corresponding section of the conventional pavement structure installed after the ETB failure, about 50 ft away, in order to provide a comparison between the ETB and granular base materials.

**Figure 3-16: Soil moisture and temperature sensor.**

Although comparing the two base materials was not part of the original scope of work, the close proximity of the two different pavement structures provided an opportunity for evaluating the performance of the ETB against a typical UTBC in the same conditions. Biweekly testing involved obtaining sensor readings from the ETB section, measuring ambient conditions, and obtaining PFWD measurements at both the ETB and UTBC sections.

The sensors used in this project measured the volumetric moisture content, which was converted into gravimetric moisture content, and soil temperature (*34*). Sensors were installed to enable investigation of potential correlations between the ETB modulus and the ETB moisture and temperature recorded by the sensors installed in the ETB section. To document the ambient conditions during each site visit, the average wind speed (approximated over about 1 minute of observation), pavement surface temperature, and air temperature were measured using handheld units and recorded. At each survey nail in the ETB and UTBC sections, PFWD tests were performed according to the same protocol previously described for spatial data collection, except that the testing was performed on top of the HMA layer.

### *3.3.3 Statistical Analyses*

Statistical analyses were performed on the temporal data in order to predict the modulus of the ETB layer and to compare the stiffness of the ETB and the UTBC, as described in the following sections.

#### 3.3.3.1 Regression

The response variable evaluated in the regression analyses was ETB modulus, as backcalculated from PFWD data, and the predictor variables were time since ETB construction (age), ETB moisture content, and ETB temperature. After data points that corresponded to freezing base layer temperatures were removed, being considered outliers for the purpose of these analyses, individual regression lines were fitted to the data. The form of the regression line was chosen to maximize the coefficient of determination, or $R^2$ value, in each analysis.

#### 3.3.3.2 Comparison of ETB and UTBC

Given that testing was performed on both the ETB and UTBC sections under equivalent environmental conditions and given that the sections were constructed within one week of each other, paved at the same time, and experienced the same trafficking, a direct comparison of the base layer modulus values was of interest on this project. Regression lines were fitted to the temporal data trends for visual evaluation, and a paired *t*-test was performed to compare the average base layer modulus values measured for each section through time. In the *t*-test, the null hypothesis was that the two sections had equal modulus values, and the alternative hypothesis was that the modulus values were different. As before, a *p*-value less than or equal to 0.05 indicated a significant difference between the sections.

## 3.4 Summary

The test site chosen for this research comprised the eastbound lanes of 7800 South in West Jordan, Utah, between 2700 West and 3200 West. The experimental area was divided into three 800-ft by 24-ft test sections, labeled as sections A, B, and C. Ten individual test stations were randomly located throughout each test section.

Spatial testing, comprising field testing and laboratory testing, was performed to characterize the in-situ structural properties of the ETB layer. Field testing was performed on the day of ETB construction and during the first few days following construction. The field instruments utilized in this research include the PFWD, DCP, CIST, SSG, and NDG. On the day of construction, samples of the reclaimed base material were removed from each test station both before and after emulsion treatment. The samples of untreated material were bagged and transported to the BYU Highway Materials Laboratory for sieve analyses, Atterberg limits determinations, moisture content determinations, and burn-off analyses. The samples of treated material were compacted on site; at the laboratory, these specimens were subjected to UCS testing. The spatial data were evaluated using several statistical analyses, including multivariate regression, CV comparisons, ANOVA, and Tukey’s mean separation procedure.

The intent of the temporal testing phase of this project was to monitor the ETB properties at three stations, one in each section, over a 1-year period. However, after a few days following construction, the asphalt emulsion in the base layer was not curing sufficiently, and significant rutting was occurring under construction trafficking. As winter was approaching, the engineer and the contractor both recognized that the environmental conditions were not likely to improve, and, after lengthy discussion, they decided to remove the ETB section and replace it with a UTBC section. However, the UDOT engineer responsible for the project agreed to leave one of the original three instrumented stations in place to support the completion of this research.

Although comparing the two base materials was not part of the original scope of work, construction of the new pavement structure immediately adjacent to the ETB monitoring station provided an opportunity for evaluating the performance of the ETB against a typical UTBC in the same conditions. Biweekly testing involved obtaining sensor readings from the ETB section, measuring ambient conditions, and obtaining PFWD measurements at both the ETB and UTBC sections. The temporal data were evaluated using regression and paired *t*-tests.

# 4 RESULTS

## 4.1 Overview

The following sections describe the results of both spatial and temporal testing, including field and laboratory testing and statistical analyses. Raw spatial and temporal data are provided in Appendix A and B, respectively, in which the presence of a hyphen in a table indicates that the given data were not measured. Because the results of this research are specific to the materials, construction processes, and environmental conditions on 7800 South, the research findings may not be applicable to other ETB projects.

## 4.2 Spatial Testing

This section includes field results, laboratory results, and statistical analyses of the spatial data.

### *4.2.1 Field Results*

Raw field data presented in Appendix A include measurements obtained using the PFWD on days 0 and 1; DCP on day 1; CIST on days 0, 1, and 4; SSG on days 0 and 1; and NDG on day 0.

Results for the ETB and subgrade layers from both the PFWD and DCP are shown in Table 4-1, while results for the ETB layer from the CIST and SSG are shown in Table 4-2. In

## Table 4-1: Portable Falling-Weight Deflectometer and Dynamic Cone Penetrometer Test Data

| Curing Time (days) | Section | PFWD | | DCP | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Modulus (ksi) | | Penetration Rate (mm/blow) | | CBR (%) | | Modulus (ksi) | |
| | | Average | Std. Dev. | Average | Std. Dev. | Average | Std. Dev. | Average | Std. Dev. |
| ETB | | | | | | | | | |
| 0 | A | 8.0 | 1.9 | - | - | - | - | - | - |
| | B | 13.0 | 11.5 | - | - | - | - | - | - |
| | C | 15.7 | 11.6 | - | - | - | - | - | - |
| | Average | 12.3 | 9.9 | - | - | - | - | - | - |
| 1 | A | 9.8 | 6.2 | 11.1 | 4.1 | 23.9 | 9.8 | 19.1 | 5.0 |
| | B | 9.8 | 8.5 | 11.2 | 5.0 | 24.0 | 9.1 | 19.2 | 4.9 |
| | C | 15.0 | 9.1 | 8.3 | 4.6 | 37.5 | 16.2 | 25.3 | 7.5 |
| | Average | 11.5 | 8.2 | 10.2 | 4.6 | 28.5 | 13.4 | 21.2 | 6.4 |
| Subgrade | | | | | | | | | |
| 0 | A | 12.5 | 9.9 | - | - | - | - | - | - |
| | B | 17.3 | 12.0 | - | - | - | - | - | - |
| | C | 11.3 | 7.7 | - | - | - | - | - | - |
| | Average | 13.7 | 10.0 | - | - | - | - | - | - |
| 1 | A | 11.7 | 7.8 | 25.0 | 10.7 | 14.4 | 9.4 | 13.3 | 6.3 |
| | B | 18.7 | 12.8 | 17.8 | 12.9 | 29.2 | 25.0 | 20.5 | 11.8 |
| | C | 10.0 | 7.2 | 25.5 | 20.5 | 19.2 | 13.6 | 15.9 | 8.0 |
| | Average | 13.5 | 10.0 | 22.8 | 15.2 | 21.0 | 17.8 | 16.5 | 9.2 |

## Table 4-2: Soil Stiffness Gauge and Clegg Impact Soil Tester Test Data

| Curing Time (days) | Section | CIST | | | | SSG | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | CIV | | Modulus (ksi) | | Stiffness (MN/m) | | Modulus (ksi) | |
| | | Average | Std. Dev. | Average | Std. Dev. | Average | Std. Dev. | Average | Std. Dev. |
| 0 | A | 8.8 | 3.6 | 3.0 | 2.5 | 10.4 | 2.4 | 13.1 | 3.0 |
| | B | 5.8 | 2.8 | 1.4 | 1.3 | 9.7 | 2.8 | 12.2 | 3.5 |
| | C | 4.1 | 5.9 | 1.6 | 3.9 | 11.2 | 3.0 | 14.1 | 3.8 |
| | Average | 6.2 | 4.6 | 2.0 | 2.8 | 10.5 | 2.7 | 13.2 | 3.4 |
| 1 | A | 7.8 | 5.4 | 2.9 | 4.3 | 13.3 | 2.9 | 16.8 | 3.7 |
| | B | 11.4 | 6.5 | 6.6 | 8.5 | 12.8 | 4.2 | 16.1 | 5.3 |
| | C | 4.1 | 3.9 | 6.2 | 3.3 | 15.7 | 4.8 | 19.7 | 6.1 |
| | Average | 10.8 | 5.6 | 5.1 | 5.4 | 14.0 | 4.1 | 17.6 | 5.2 |
| 4 | A | 9.9 | 6.7 | 4.6 | 4.8 | - | - | - | - |
| | B | 15.7 | 11.5 | 12.1 | 13.3 | - | - | - | - |
| | C | 13.8 | 4.6 | 7.0 | 5.0 | - | - | - | - |
| | Average | 12.9 | 8.1 | 7.6 | 8.6 | - | - | - | - |

both of these tables, the presence of a hyphen indicates data that were not measured. The average modulus values of the ETB layer within the first 4 days after construction were 11.9, 21.2, 4.8, and 15.4 ksi as estimated using the PFWD, DCP, CIST, and SSG, respectively. While some variability is evident among the different testing devices, all of these ETB modulus values are unusually low for a typical stabilized base material and were in general even lower than the subgrade modulus values as measured using the PFWD and DCP. While the SSG and CIST measurements suggested a slight increase in modulus as the ETB was allowed to cure during the limited time in which data were collected, the PFWD measurements did not indicate any strength gain.

Table 4-3 presents the results for NDG testing performed immediately following ETB compaction. The NDG testing suggested that all three sections had high moisture contents after compaction relative to the OMC; for reference, the OMC specified for this project was 7.5 percent for modified Proctor compaction, with a target dry density of 128.7 pcf (*35*); the average dry density measured in the field using the NDG was 118.0 pcf. (This estimation of dry density from the NDG data may be artificially low, however, to the degree that the presence of RAP and emulsion, both non-water hydrogen sources, caused artificially high water content measurements in the base material (*36*, *37*).

**Table 4-3: Nuclear Density Gauge Test Data**

| Curing Time (days) | Section | Wet Density (pcf) | | Moisture (pcf) | | Percent Moisture (%) | |
|---|---|---|---|---|---|---|---|
| | | Average | Std. Dev. | Average | Std. Dev. | Average | Std. Dev. |
| 0 | A | 131.5 | 4.1 | 12.6 | 1.6 | 10.6 | 1.4 |
| | B | 131.4 | 5.3 | 12.8 | 2.5 | 10.8 | 1.9 |
| | C | 129.7 | 3.7 | 13.0 | 1.3 | 11.2 | 1.4 |
| | Average | 130.8 | 4.4 | 12.8 | 1.8 | 10.9 | 1.6 |

### *4.2.2 Laboratory Results*

Raw data for laboratory tests conducted on samples taken from each of the 30 stations are shown in Appendix A. These tests include sieve analyses, Atterberg limits determinations, pre-treatment moisture determination, burn-off analyses, and UCS testing.

The results of the dry sieve analyses, shown in Figure 4-1, indicate minimal variation in average gradations among the three test sections. From the results of the washed sieve analysis and Atterberg limits testing, the soil can be classified as an A-1-a and GW-GM (well-graded gravel with silt and sand) using the American Association of State Highway and Transportation Officials (AASHTO) and Unified Soil Classification System (USCS) methods, respectively.

The pre-treatment moisture contents are shown in Table 4-4. These data show that the moisture content of the reclaimed base material exceeded the OMC at many locations even before the emulsion was injected. The results of the burn-off tests are shown in Table 4-5.

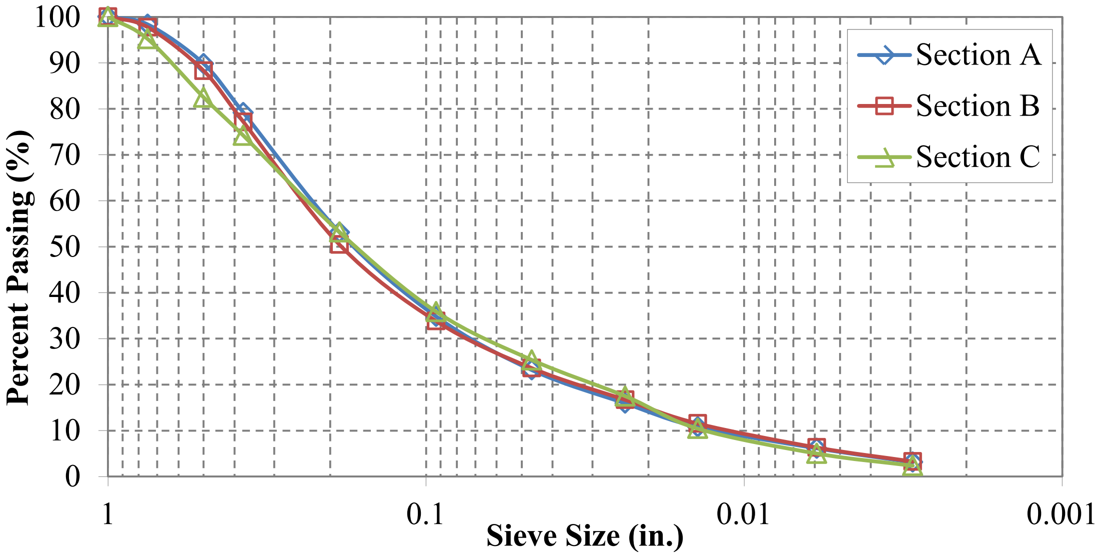

**Figure 4-1: Average gradations.**

**Table 4-4: Pre-Treatment Moisture Content Data**

| Section | Pre-treatment Moisture Content (%) | |
|---|---|---|
| | Average | Std. Dev. |
| A | 6.6 | 2.1 |
| B | 7.1 | 2.3 |
| C | 5.2 | 1.9 |
| Average | 6.3 | 2.2 |

**Table 4-5: Burn-off Test Data**

| Section | Asphalt Content before Treatment (%) | | Emulsion Added during Treatment (%) | |
|---|---|---|---|---|
| | Average | Std. Dev. | Average | Std. Dev. |
| A | 2.43 | 1.14 | 3.57 | 0.56 |
| B | 2.12 | 1.03 | 3.78 | 0.76 |
| C | 3.09 | 0.96 | 4.96 | 1.05 |
| Average | 2.55 | 1.09 | 4.10 | 1.00 |

The asphalt content before emulsion treatment, indicative of the percentage of RAP that was mixed into the base material, was fairly consistent between sections A and B but was higher in section C. The design percentage of emulsion added was 4.0 percent. Although the average of the three sections met this requirement, the percentage of emulsion added in sections A and B was too low, while the percentage of emulsion in section C was too high.

The results for UCS testing are shown in Table 4-6 and Figure 4-2. The average UCS values over all three test sections after 7 days, 28 days, 6 months and 1 year were 30, 28, 37, and 42 psi, respectively, and the percentages of 1-year strength developed after 7 days, 28 days, and 6 months were 71, 66, and 89 percent, respectively. The ETB compressive strength was very low throughout the entire year of testing, clearly demonstrating the consequences of inadequate emulsion curing. The moisture content of the UCS specimens was fairly constant throughout the

**Table 4-6: Unconfined Compressive Strength Test Data**

| Curing Time (days) | Section | UCS (psi) | | Moisture Content (%) | | Wet Density (%) | | Dry Density (%) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Average | Std. Dev. | Average | Std. Dev. | Average | Std. Dev. | Average | Std. Dev. |
| 7 | A | 32.4 | 3.5 | 7.1 | 1.1 | 135.1 | 2.0 | 126.1 | 2.2 |
| | B | 30.3 | 3.8 | 7.2 | 1.4 | 134.9 | 2.6 | 125.8 | 2.4 |
| | C | 26.2 | 5.9 | 5.3 | 1.5 | 129.9 | 4.0 | 123.3 | 2.6 |
| | Average | 29.6 | 5.1 | 6.5 | 1.6 | 133.2 | 3.8 | 125.1 | 2.6 |
| 28 | A | 31.5 | 5.2 | 6.7 | 1.6 | 135.3 | 3.2 | 126.8 | 2.3 |
| | B | 27.9 | 8.0 | 6.9 | 1.7 | 134.0 | 5.0 | 125.3 | 3.4 |
| | C | 23.5 | 5.7 | 5.3 | 1.5 | 132.5 | 3.0 | 125.8 | 1.8 |
| | Average | 27.6 | 7.0 | 6.3 | 1.7 | 133.9 | 3.9 | 126.0 | 2.6 |
| 181 | A | 40.7 | 4.8 | 6.6 | 1.6 | 134.5 | 4.8 | 126.2 | 3.7 |
| | B | 37.8 | 8.1 | 7.3 | 1.3 | 134.5 | 2.6 | 125.4 | 2.8 |
| | C | 33.4 | 7.8 | 5.4 | 1.4 | 131.1 | 3.9 | 124.3 | 2.8 |
| | Average | 37.3 | 7.4 | 6.4 | 1.6 | 133.3 | 4.1 | 125.3 | 3.1 |
| 365 | A | 42.2 | 7.8 | 6.4 | 1.6 | 133.7 | 3.9 | 125.7 | 2.9 |
| | B | 46.2 | 8.1 | 6.9 | 1.2 | 136.4 | 3.2 | 127.6 | 3.3 |
| | C | 37.2 | 7.4 | 5.2 | 1.4 | 132.0 | 3.7 | 125.4 | 2.5 |
| | Average | 41.7 | 8.4 | 6.2 | 1.5 | 134.0 | 4.0 | 126.2 | 2.9 |

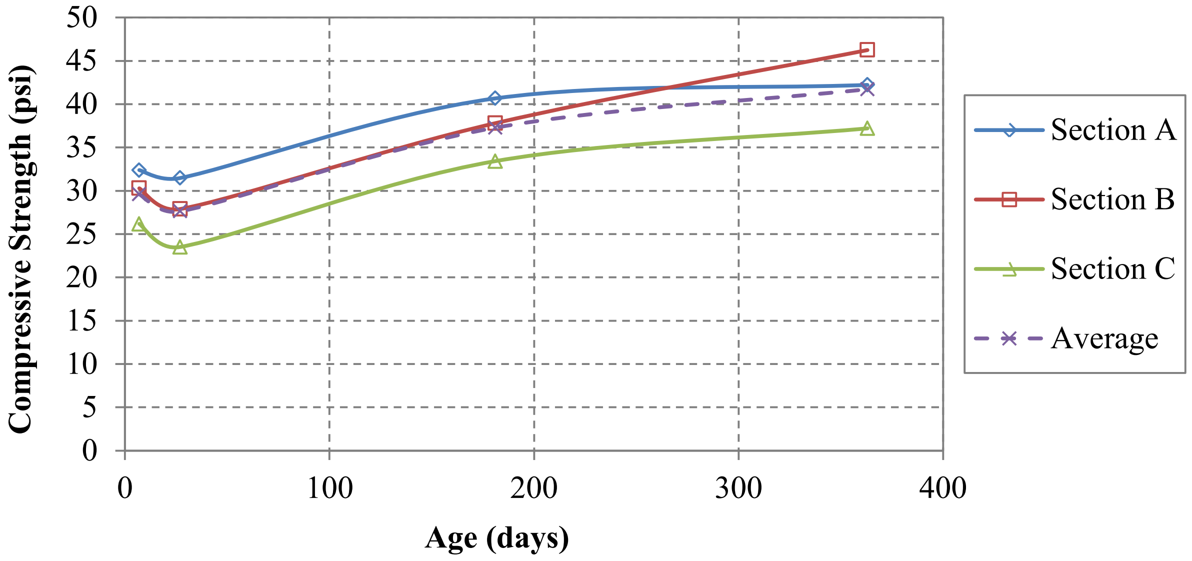

**Figure 4-2: Average unconfined compressive strength.**

year of testing as deliberately intended to simulate field conditions. The average dry densities of the specimens manually compacted for each section were consistently closer to the target value of 128.7 pcf than the average densities measured in the field using the NDG and reported in Table 4-3; the difference may be partially attributable to the poor subgrade condition in the field. Figure 4-3 shows a specimen before and after UCS testing.

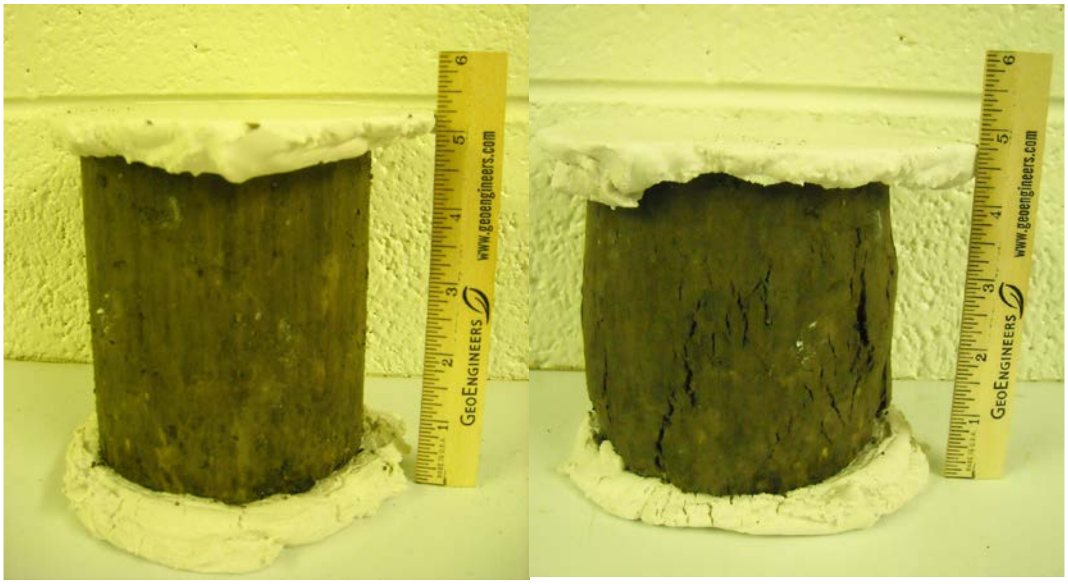

**Figure 4-3: Specimen before and after unconfined compressive strength test.**

### *4.2.3 Statistical Analyses*

The results of multivariate regression, CV comparisons, ANOVA, and Tukey's mean separation procedure performed on the spatial data are presented in the following sections.

#### 4.2.3.1 Multivariate Regression

Table 4-7 presents the *p*-values associated with the selected predictor variables and the $R^2$ values from each regression model developed in this research. Predictor variables with *p*-values less than or equal to 0.15 were included in the models. The hyphens in this table are all associated with properties of the laboratory specimens used in UCS testing; hyphens indicate

## Table 4-7: Results of Multivariate Regression

| Response Variable | Predictor Variable $p$-Values | | | | | | | | | | | | | | | | | | | | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Percent Passing the 3/4 in. Sieve | Percent Passing the 1/2 in. Sieve | Percent Passing the 3/8 in. Sieve | Percent Passing the No. 4 Sieve | Percent Passing the No. 8 Sieve | Percent Passing the No. 16 Sieve | Percent Passing the No. 30 Sieve | Percent Passing the No. 50 Sieve | Percent Passing the No. 100 Sieve | Percent Passing the No. 200 Sieve | Pre-treatment Moisture Content | NDG Wet Density | NDG Moisture Content | NDG Percent Moisture | RAP Binder Content | Change in Binder Content | 7-Day Dry Density | 28-Day Wet Density | 181-Day Moisture Content | 365-Day Dry Density | |
| 0-Day Modulus ($MOD_0$) | | | | | | | | 0.0009 | <0.0001 | 0.0021 | | 0.0895 | | | | | - | - | - | - | 0.64 |
| 1-Day Modulus ($MOD_1$) | | | | | | | | | | | <0.0001 | | | | | | - | - | - | - | 0.59 |
| 1-Day PR ($PR_1$) | | | | | | 0.0003 | | | <0.0001 | | | | | | | | - | - | - | - | 0.66 |
| 1-Day CBR ($CBR_1$) | 0.0043 | | | 0.0410 | 0.0006 | | | | | | 0.0002 | | 0.0337 | | | | - | - | - | - | 0.73 |
| 0-Day CIV ($CIV_0$) | | | 0.0861 | | | | | | | | | | | | | 0.0408 | - | - | - | - | 0.24 |
| 1-Day CIV ($CIV_0$) | 0.0823 | | | | | | | | <0.0001 | | | | | 0.0095 | | | - | - | - | - | 0.69 |
| 4-Day CIV ($CIV_4$) | | | | | | | | | | | 0.0086 | | | | | | - | - | - | - | 0.29 |
| 0-Day Stiffness ($SS_0$) | | | | | | | | | | 0.1164 | | 0.0227 | | | 0.1013 | | - | - | - | - | 0.44 |
| 1-Day Stiffness ($SS_1$) | | | | | | | 0.1466 | | | 0.0377 | | 0.0024 | | | 0.0421 | | - | - | - | - | 0.59 |
| 7-Day UCS ($UCS_7$) | | | | | | | | 0.0349 | | | | | 0.1356 | | | 0.0100 | 0.0980 | - | - | - | 0.53 |
| 28-Day UCS ($UCS_{28}$) | | | | | | | | | | | 0.1353 | 0.1172 | | | | 0.0004 | - | 0.0012 | - | - | 0.70 |
| 6-Month UCS ($UCS_{181}$) | | | | | | | | | | | 0.0777 | 0.0067 | | 0.0502 | | 0.0002 | - | - | 0.0173 | - | 0.59 |
| 1-Year UCS ($UCS_{365}$) | | <0.0001 | | | <0.0001 | <0.0001 | | 0.0163 | | | 0.0063 | | | | | 0.0022 | - | - | - | 0.0560 | 0.83 |

predictor variables that were not considered in the development of models for the various response variables, all of which are measures of the structural quality of the ETB layer. As shown in Table 4-7, pre-treatment moisture content was the most common predictor variable, appearing in six of the regression models created. The NDG wet density and change in binder content were the next most common predictor variables, appearing in five of the regression models. The change in binder content appeared in all four UCS regression models. The $R^2$ values indicate that the percentage of variation in the response variable that can be explained by variation in the predictor variables varied from 24 to 83 percent.

The regression analyses resulted in the following Equations 4-1 through 4-13:

$$MOD_0 = -53.021 + 4.9036 \cdot P_{No.50} - 17.779 \cdot P_{No.100} + 13.735 \cdot P_{No.200} + 0.57850 \cdot NDG_{WD} \qquad (R^2 = 0.64) \tag{4-1}$$

where $MOD_0$ = 0-day modulus measured using the PFWD, ksi

$P_{No.50}$ = percent passing the No. 50 sieve, %

$P_{No.100}$ = percent passing the No. 100 sieve, %

$P_{No.200}$ = percent passing the No. 200 sieve, %

$NDG_{WD}$ = wet density measured using the NDG, pcf

$$MOD_1 = 29.639 - 2.8611 \cdot MC_{pre} \qquad (R^2 = 0.59) \tag{4-2}$$

where $MOD_1$ = 1-day modulus measured using the PFWD, ksi

$MC_{pre}$ = moisture content before emulsion treatment, %

$$PR_1 = 56.785 - 0.63536 \cdot P_{No.16} + 2.2245 \cdot P_{No.100} - 0.33837 \cdot NDG_{WD} \quad (4\text{-}3)$$

$(\mathrm{R}^2 = 0.66)$

where $PR_1$ = 1-day DCP penetration rate, mm/blow

$P_{No.16}$ = percent passing the No. 16 sieve, %

$P_{No.100}$ = percent passing the No. 100 sieve, %

$NDG_{WD}$ = wet density measured using the NDG, pcf

$$CBR_1 = 243.87 - 2.4522 \cdot P_{3/4} - 1.2129 \cdot P_{No.\ 4} + 2.3297 \cdot P_{No.\ 8} \quad (4\text{-}4)$$

$$-3.1229 \cdot MC_{pre} + 1.9300 \cdot NDG_M \qquad (\mathrm{R}^2 = 0.73)$$

where $CBR_1$ = 1-day California bearing ratio, %

$P_{3/4}$ = percent passing the ¾” sieve, %

$P_{No.4}$ = percent passing the No. 4 sieve, %

$P_{No.8}$ = percent passing the No. 8 sieve, %

$MC_{pre}$ = moisture content before emulsion treatment, %

$NDG_M$ = moisture content measured using the NDG, pcf

$$CIV_0 = -11.299 - 1.6660 \cdot B_{change} + 0.31707 \cdot P_{3/8''} \qquad (\mathrm{R}^2 = 0.24) \quad (4\text{-}5)$$

where $CIV_0$ = 0-day CIV

$B_{change}$ = change in asphalt binder content during emulsion treatment, %

$P_{3/8''}$ = percent passing the 3/8” sieve, %

$$CIV_1 = 95.014 - 0.59417 \cdot P_{3/4''} - 2.4384 \cdot P_{No.100} - 1.1407 \cdot NDG_{M\%} \quad (4\text{-}6)$$

$(\mathrm{R}^2 = 0.69)$

where $CIV_1$ = 1-day CIV

$P_{3/4"}$ = percent passing the 3/4" sieve, %

$P_{No.100}$ = percent passing the No. 100 sieve, %

$NDG_{M\%}$ = percent moisture measured using the NDG, %

$$CIV_4 = 25.800 - 2.0883 \cdot MC_{pre} \qquad (\mathrm{R}^2 = 0.29) \qquad (4\text{-}7)$$

where $CIV_4$ = 4-day CIV

$MC_{pre}$ = moisture content before emulsion treatment, %

$$SS_0 = -23.246 + 1.0523 \cdot B_{RAP} - 0.87961 \cdot P_{No.200} + 0.25679 \cdot NDG_{WD} \qquad (4\text{-}8)$$

$(\mathrm{R}^2 = 0.44)$

where $SS_0$ = 0-day soil stiffness, MN/m

$B_{RAP}$ = asphalt binder present in the untreated material, %

$P_{No.200}$ = percent passing the No. 200 sieve, %

$NDG_{WD}$ = wet density measured using the NDG, pcf

$$SS_1 = -53.345 + 1.7622 \cdot B_{RAP} + 0.28519 \cdot P_{No.30} - 1.5996 \cdot P_{No.200} \qquad (4\text{-}9)$$

$$+0.47926 \cdot NDG_{WD} \qquad (\mathrm{R}^2 = 0.59)$$

where $SS_1$ = 1-day soil stiffness, MN/m

$B_{RAP}$ = asphalt binder present in the untreated material, %

$P_{No.30}$ = percent passing the No. 30 sieve, %

$P_{No.200}$ = percent passing the No. 200 sieve, %

$NDG_{WD}$ = wet density measured using the NDG, pcf

$$UCS_7 = -27.677 - 2.2705 \cdot B_{change} + 0.75361 \cdot P_{No.50} \tag{4-10}$$
$$-0.66684 \cdot NDG_M + 0.53617 \cdot DD_7 \qquad (\mathrm{R}^2 = 0.53)$$

where $UCS_7$ = 7-day unconfined compressive strength, psi

$B_{change}$ = change in asphalt binder content during emulsion treatment, %

$P_{No.50}$ = percent passing the No. 50 sieve, %

$NDG_M$ = moisture content measured using the NDG, pcf

$DD_7$ = 7-day specimen dry density, pcf

$$UCS_{28} = -152.28 - 3.2159 \cdot B_{change} - 0.76044 \cdot MC_{pre} \tag{4-11}$$
$$+0.33696 \cdot NDG_{WD} + 1.1485 \cdot WD_{28} \qquad (\mathrm{R}^2 = 0.70)$$

where $UCS_{28}$ = 28-day unconfined compressive strength, psi

$B_{change}$ = change in asphalt binder content during emulsion treatment, %

$MC_{pre}$ = moisture content before emulsion treatment, %

$NDG_{WD}$ = wet density measured using the NDG, pcf

$WD_{28}$ = 28-day specimen wet density, pcf

$$UCS_{181} = -20.180 - 4.6857 \cdot B_{change} + 1.6707 \cdot MC_{pre} \tag{4-12}$$
$$+0.77867 \cdot NDG_{WD} - 1.4744 \cdot NDG_{M\%} - 3.1240 \cdot MC_{181} \qquad (\mathrm{R}^2 = 0.59)$$

where $UCS_{181}$ = 181-day (6-month) unconfined compressive strength, psi

$B_{change}$ = change in asphalt binder content during emulsion treatment, %

$MC_{pre}$ = moisture content before emulsion treatment, %

$NDG_{WD}$ = wet density measured using the NDG, pcf

$NDG_{M\%}$ = percent moisture measured using the NDG, %

$MC_{181}$ = 181-day (6-month) specimen moisture content, %

$$UCS_{365} = -136.41 - 3.0946 \cdot B_{change} + 1.8965 \cdot P_{1/2"} \\ -5.0704 \cdot P_{No.8} + 6.6538 \cdot P_{No.16} - 2.5494 \cdot P_{No.50} \\ -1.8429 \cdot MC_{pre} + 0.65150 \cdot DD_{365} \qquad (R^2 = 0.83) \tag{4-13}$$

where $UCS_{365}$ = 365-day (1-year) unconfined compressive strength, psi

$B_{change}$ = change in asphalt binder content during emulsion treatment, %

$P_{1/2"}$ = percent passing the 1/2” sieve, %

$P_{No.8}$ = percent passing the No. 8 sieve, %

$P_{No.16}$ = percent passing the No. 16 sieve, %

$P_{No.50}$ = percent passing the No. 50 sieve, %

$MC_{pre}$ = moisture content before emulsion treatment, %

$DD_{1-year}$ = 365-day (1-year) specimen dry density, pcf

The regression equations quantify several relationships between compositional and structural characteristics of the stations and specimens tested. The three most common predictor variables are pre-treatment moisture content, wet density measured using the NDG, and change in asphalt binder content during emulsion treatment. In Equations 4-2, 4-4, 4-7, 4-11, and 4-13, the coefficient for pre-treatment moisture content is negative. Thus, a higher pre-treatment moisture content results in lower 1-day CBR, 1-day modulus as measured by the PFWD, 4-day CIV, 28-day UCS, and 1-year UCS. In Equations 4-1, 4-8, 4-9, 4-11, and 4-12, the coefficient for wet density is positive, indicating that a higher wet density indicates higher 0-day modulus as measured by the PFWD, 0-day soil stiffness, 1-day soil stiffness, 28-day UCS, and 6-month

UCS. Finally, in Equations 4-5, 4-10, 4-11, 4-12, and 4-13, the coefficient for binder content change is negative, indicating that a higher amount of binder added will result in a lower 0-day CIV and a lower UCS. Because the emulsion contains a high percentage of water, early strength can be compromised until sufficient evaporation has occurred for the asphalt in the emulsion to bind the aggregate particles together. These findings particularly demonstrate the importance of allowing the road bed to properly dry prior to emulsion injection, achieving good compaction, and then allowing the emulsion to cure prior to placement of a surface course.

#### 4.2.3.2 Coefficient of Variation Comparisons

Table 4-8 shows the average CV values for each response variable by test section. Consistent with previous research, variables with CV values greater than 40 are considered to have substantial variation (*9*, *10*). The results show that substantial variation occurred in all response variables except stiffness as measured by the SSG and UCS.

**Table 4-8: Coefficients of Variation for Response Variables**

| Variable | CV(%) | | |
|---|---|---|---|
| | Section A | Section B | Section C |
| 0-Day Modulus | 24 | 89 | 74 |
| 1-Day Modulus | 63 | 87 | 61 |
| 1-Day PR | 37 | 45 | 55 |
| 1-Day CBR | 41 | 38 | 43 |
| 0-Day CIV | 41 | 48 | 146 |
| 1-Day CIV | 70 | 57 | 30 |
| 4-Day CIV | 68 | 73 | 33 |
| 0-Day Stiffness | 23 | 28 | 27 |
| 1-Day Stiffness | 22 | 33 | 31 |
| 7-Day UCS | 11 | 12 | 23 |
| 28-Day UCS | 16 | 29 | 24 |
| 6-Month UCS | 12 | 22 | 23 |
| 1-Year UCS | 19 | 17 | 20 |

Table 4-9 displays the CVs of the predictor variables used in this research. The CV values were comparatively low among the predictor variables except for the percent passing the No. 200 sieve and the RAP content.

**Table 4-9: Coefficients of Variation for Predictor Variables**

| Variable | CV(%) | | |
|---|---|---|---|
| | Section A | Section B | Section C |
| Percent Passing the 3/4 in. Sieve | 1 | 1 | 2 |
| Percent Passing the 1/2 in. Sieve | 2 | 3 | 5 |
| Percent Passing the 3/8 in. Sieve | 5 | 4 | 6 |
| Percent Passing the No. 4 Sieve | 9 | 8 | 10 |
| Percent Passing the No. 8 Sieve | 11 | 12 | 15 |
| Percent Passing the No. 16 Sieve | 16 | 15 | 15 |
| Percent Passing the No. 30 Sieve | 19 | 17 | 16 |
| Percent Passing the No. 50 Sieve | 21 | 20 | 19 |
| Percent Passing the No. 100 Sieve | 26 | 28 | 34 |
| Percent Passing the No. 200 Sieve | 32 | 23 | 62 |
| Pretreatment Moisture Content | 32 | 32 | 36 |
| NDG Wet Density | 3 | 4 | 3 |
| NDG Moisture Content | 13 | 19 | 10 |
| NDG Percent Moisture | 14 | 18 | 12 |
| RAP Binder Content | 47 | 48 | 31 |
| Change in Binder Content | 16 | 20 | 21 |
| 7-Day Moisture Content | 15 | 19 | 29 |
| 28-Day Moisture Content | 24 | 24 | 28 |
| 6-Month Moisture Content | 25 | 18 | 26 |
| 1-Year Moisture Content | 25 | 17 | 26 |
| 7-Day Wet Density | 1 | 2 | 3 |
| 28-Day Wet Density | 2 | 4 | 2 |
| 6-Month Wet Density | 4 | 2 | 3 |
| 1-Year Wet Density | 3 | 2 | 3 |
| 7-Day Dry Density | 2 | 2 | 2 |
| 28-Day Dry Density | 2 | 3 | 1 |
| 6-Month Dry Density | 3 | 2 | 2 |
| 1-Year Dry Density | 2 | 3 | 2 |

#### 4.2.3.3 Analysis of Variance and Tukey's Mean Separation Procedure

The results of the ANOVA and Tukey's mean separation procedure are given in Table 4-10. These analyses show that only 1-day CBR, 7-day UCS, 28-day UCS, and 1-year UCS results exhibit statistically significant differences between test sections. In all UCS results except for those with a curing time of 6 months, section A is statistically different from section C. In the ANOVA, the between-sample variability is effectively compared to the within-sample variability, and a higher ratio of the former to the latter increases the probability that significant differences will be identified. Thus, as documented in Table 4-8, high within-sample variability for nearly all of the response variables evaluated in this project resulted in relatively few significant differences between sections.

**Table 4-10: Results of Analysis of Variance and Tukey's Mean Separation Procedure**

| Variable | ANOVA | Tukey's | | | |
|---|---|---|---|---|---|
| | *p*-values | Significant Difference Between Sections | | | |
| | | AB | BC | AC | None |
| 1-Day PR | 0.302 | | | | x |
| 1-Day CBR | 0.027 | | x | x | |
| 0-Day Modulus | 0.234 | | | | x |
| 1-Day Modulus | 0.258 | | | | x |
| 0-Day CIV | 0.059 | | | | x |
| 1-Day CIV | 0.096 | | | | x |
| 4-Day CIV | 0.344 | | | | x |
| 0-Day Stiffness | 0.495 | | | | x |
| 1-Day Stiffness | 0.259 | | | | x |
| 7-Day UCS | 0.017 | | | x | |
| 28-Day UCS | 0.033 | | | x | |
| 6-Month UCS | 0.087 | | | | x |
| 1-Year UCS | 0.056 | | | x | |

## 4.3 Temporal Testing

This section includes field results and statistical analyses of the temporal data.

### *4.3.1 Field Results*

The data presented in this section include subsurface and surface properties measured during each biweekly visit. As shown in Figure 4-4, the ETB moisture content appears to decrease slightly during the winter months and then rise again during the summer. One reason for the apparent decrease is that the dielectric-type moisture sensors installed in the ETB layer only measure liquid water and could therefore not account for the formation of ice during the winter. The lowest actual moisture contents observed were at the time of asphalt placement, and, overall, the moisture content did not change significantly during the 1-year monitoring period, showing that drying of the ETB layer did not occur following placement of the HMA surface. The average relative humidity and wind speed recorded during each site visit were 44.0 percent and 2.5 mph, respectively.

Figure 4-5 shows the air, pavement, and ETB temperatures measured during testing. ETB temperatures below 32°F were observed only twice, at 87 and 115 days after emulsion treatment; at these times, the ETB layer was assumed to contain ice. As expected, the temperature of the ETB layer did not fluctuate as much as the air and pavement temperatures.

Figure 4-6 shows the modulus values of the ETB and UTBC layers as backcalculated from PFWD data. Modulus values for the asphalt and other subsurface layers are given in Appendix B. For backcalculation of modulus values for the UTBC section, the subbase and subgrade were treated as a single layer in BAKFAA and are thus presented together in Appendix B. ETB temperatures in Figure 4-5 that indicate freezing conditions correspond to uncharacteristically high ETB and UTBC modulus values in Figure 4-6. In these cases, the high

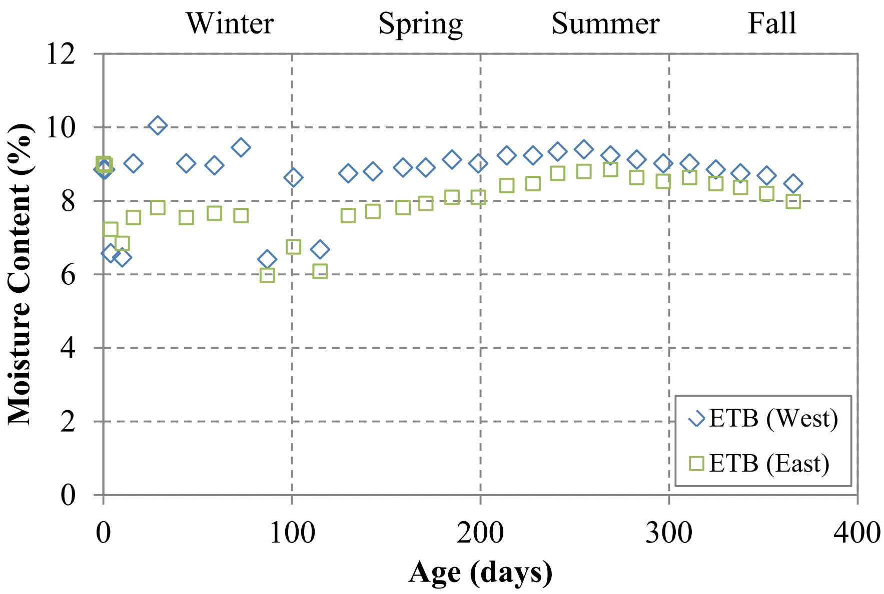

**Figure 4-4: Moisture content histories for the emulsion-treated base layer.**

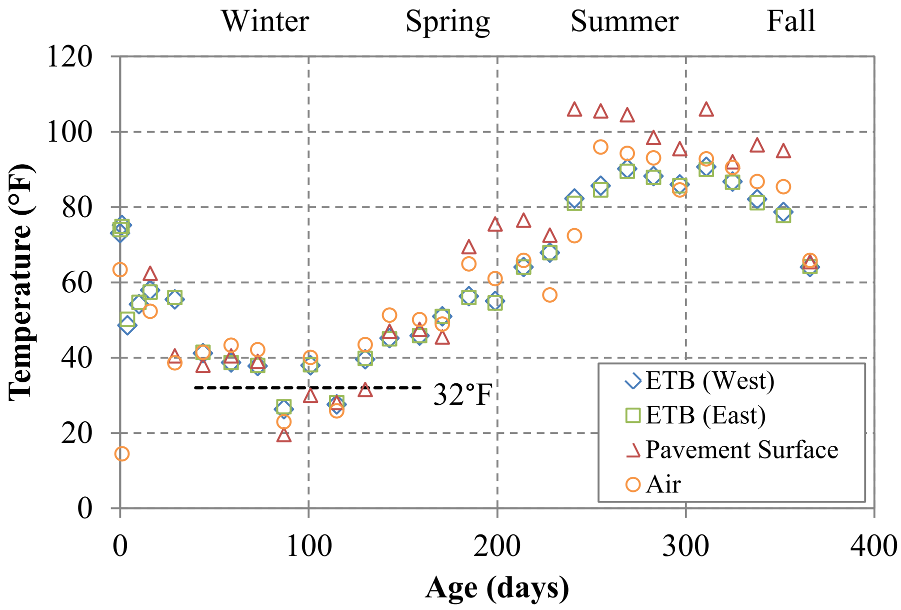

**Figure 4-5: Temperature histories.**

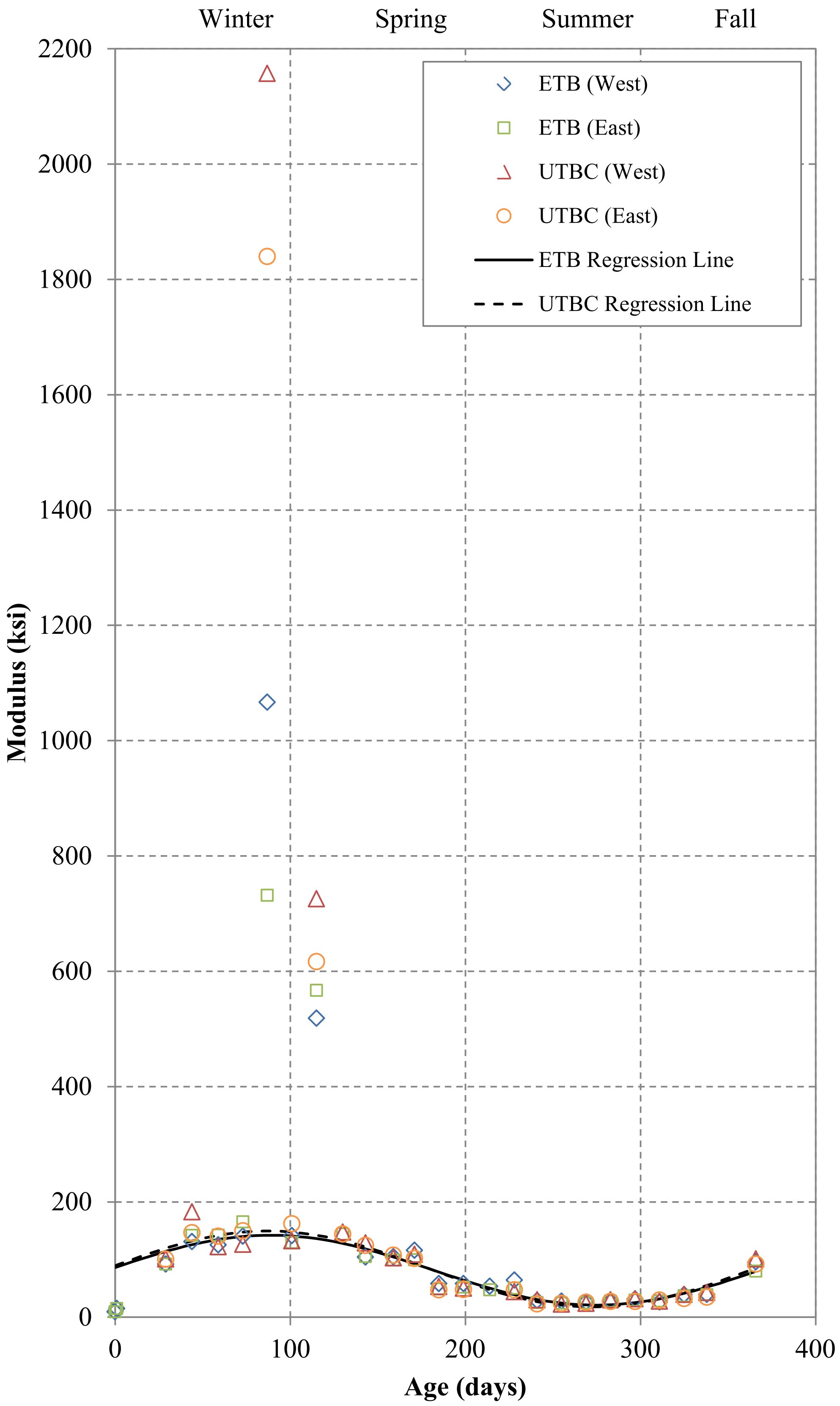

Figure 4-6: Modulus histories.

stiffness is attributable to the presence of ice binding the particles together. Excluding the frozen base layer modulus values, the data are sinusoidal, with high and low modulus values corresponding to winter and summer months, respectively.

### *4.3.2 Statistical Analyses*

The temporal data were analyzed to investigate correlations between specific ETB properties. Regression analyses and a paired *t*-test are described in the following sections.

#### 4.3.2.1 Regression

All of the regression equations developed to quantify the effects of time, moisture content, and temperature on the modulus of the ETB layer were created after the removal of data associated with testing times when the ETB temperature was below 32°F; for the purpose of the analyses performed in this research, these values were considered outliers in all cases.

In the previous section, Figure 4-6 presented the backcalculated ETB modulus values during the year following ETB construction. The equation for the ETB regression line shown in this figure is given as Equation 4-14:

$$MOD_{ETB} = 80.875 + 59.664 \cdot \sin(0.016909 \cdot Age + 6.3507) \quad (\mathrm{R}^2 = 0.92) \qquad (4\text{-}14)$$

where $MOD_{ETB}$ = ETB modulus as measured using the PFWD, ksi

$Age$ = time since ETB construction, days

Data collected on the day of ETB construction and on the following day were excluded from this analysis since the HMA layer was not yet in place and the UTBC section was not yet constructed. Figure 4-6 does not provide any evidence that the ETB layer experienced any sustained increase in strength as a result of emulsion curing; instead, the figure clearly demonstrates the significant dependency of the ETB modulus on season. Specifically, according to Equation 4-14, the modulus of the ETB can be expected to increase by approximately 60 ksi during winter and decrease by the same amount during summer, relative to a baseline of nearly 81 ksi. Therefore, even during the winter when the ETB stiffness reaches its peak, the modulus is still below the target value of 185 ksi that was specified for this project (*35*).

Figure 4-7 shows the relationship between ETB modulus and gravimetric moisture content. These data best follow a linear regression line, although not with a very strong correlation, as shown in Equation 4-15:

$$MOD_{ETB} = 350.22 - 32.730 \cdot w \qquad (\mathrm{R}^2 = 0.20) \tag{4-15}$$

where $MOD_{ETB}$ = ETB modulus as measured using the PFWD, ksi

$w$ = gravimetric moisture content, %

The negative slope of this line indicates that higher moisture contents correspond to lower ETB modulus values.

Figure 4-8 shows the relationship between ETB modulus and temperature. These data best follow a parabolic regression line as shown in Equation 4-16:

$$MOD_{ETB} = 0.04926 \cdot {T_{ETB}}^2 - 8.5195 \cdot T_{ETB} + 396.13 \qquad (\mathrm{R}^2 = 0.89) \tag{4-16}$$

where $MOD_{ETB}$ = ETB modulus as measured by the PFWD, ksi

$T_{ETB}$ = temperature of the ETB, °F

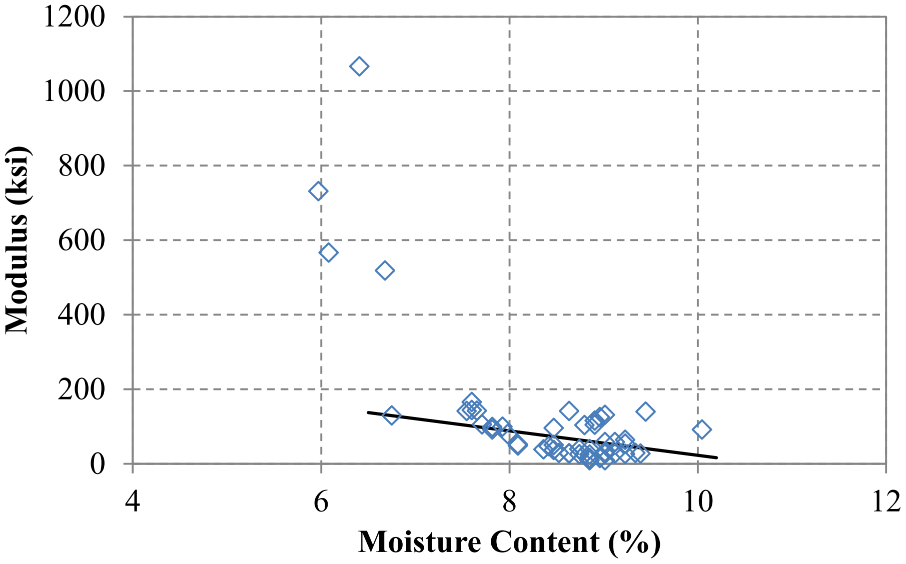

**Figure 4-7: Relationship between modulus and moisture content for the emulsion-treated base layer.**

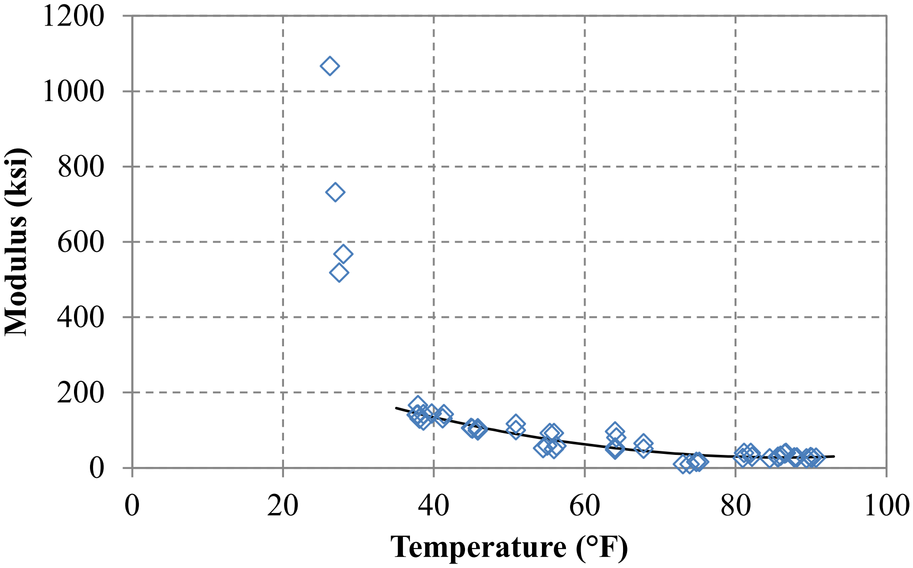

**Figure 4-8: Relationship between modulus and temperature for the emulsion-treated base layer.**

Although this equation was developed using ETB temperatures as high as 91°F, its use should be limited to ETB temperatures below 86.5°F, which is the value of the equation corresponding to the minimum possible modulus value. The equation is not applicable to ETB temperatures below 32°F. The negative slope of the line in this range indicates that higher ETB temperatures correspond to lower ETB modulus values.

### 4.3.2.2 Comparison of ETB and UTBC

Portrayed previously in Figure 4-6, the ETB and UTBC modulus values appear to be very similar through the 1-year monitoring period except during times of freezing, when the UTBC layer becomes much stiffer than the ETB layer. The equation for the UTBC regression line shown in Figure 4-6 is given as Equation 4-17:

$$MOD_{UTBC} = 87.710 + 65.734 \cdot \sin(0.017002 \cdot Age + 6.3706) \tag{4-17}$$

$(R^2 = 0.91)$

where $MOD_{UTBC}$ = UTBC modulus as measured using the PFWD, ksi

$Age$ = time since ETB construction, days

A comparison of Equation 4-17 to Equation 4-14 previously given for the ETB layer suggests that the ETB modulus is slightly lower than the UTBC modulus during fall and winter. Indeed, the average yearly modulus values for the ETB and UTBC layers were 119.9 ksi and 187.5 ksi, respectively; however, excluding data obtained on dates when the base layer was frozen, the average yearly modulus values were only 68.6 ksi and 78.2 ksi for the ETB and UTBC, respectively. The results of a paired *t*-test indicate that the modulus values of the ETB and UTBC layers were not statistically different when compared across the year during which data were collected; the *p*-value computed in the *t*-test was 0.464. The levels of support provided to the base layers by the subgrade or subbase/subgrade were practically identical in both the ETB and UTBC sections; the average modulus values were 17.4 and 19.2 ksi for the subgrade beneath the ETB and the subbase/subgrade beneath the UTBC, respectively.

## 4.4 Summary

For spatial results, the average modulus values of the ETB layer within the first 4 days after construction were 11.9, 21.2, 4.8, and 15.4 ksi as estimated using the PFWD, DCP, CIST, and SSG, respectively. These ETB modulus values were unusually low for a typical stabilized base material and were in general even lower than the subgrade modulus values at this test site. The NDG testing suggested that all three sections had high moisture contents after compaction.

The results of the dry sieve analyses indicate minimal variation in average gradations among the three sections. From the results of the washed sieve analyses and Atterberg limits testing, the soil can be classified as an A-1-a and GW-GM (well-graded gravel with silt and sand), using the AASHTO and USCS methods, respectively. The moisture content of the ETB layer exceeded the specified OMC at many locations even before the emulsion was injected. Burn-off tests showed higher percentages of RAP and emulsion in section C than in sections A and B. The average UCS values over all three sections after 7 days, 28 days, 6 months and 1 year were 30, 28, 37, and 42 psi, respectively. The ETB compressive strength was very low throughout the entire year of testing, clearly demonstrating the consequences of inadequate emulsion curing associated with this project.

The results of multivariate regression showed that a higher pre-treatment moisture content results in lower 1-day CBR, 1-day modulus as measured by the PFWD, 4-day CIV, 28-day UCS, and 1-year UCS; that a higher NDG wet density indicates higher 0-day modulus as measured by the PFWD, 0-day soil stiffness, 1-day soil stiffness, 28-day UCS, and 6-month UCS; and that a higher amount of binder added results in a lower 0-day CIV and a lower UCS.

CV comparisons showed substantial variation in most response variables but comparatively low variation in predictor variables. ANOVA and Tukey's mean separation procedure showed that 1-day CBR, 7-day UCS, 28-day UCS, and 1-year UCS results exhibit statistically significant differences between sections.

Regarding temporal results, the ETB moisture content did not change significantly during the 1-year monitoring period, showing that drying of the ETB layer did not occur following placement of the HMA surface. ETB temperatures below 32°F were observed only twice; at these times, the ETB layer was assumed to contain ice. At these low temperatures, both the ETB and UTBC layers compared in this research exhibited uncharacteristically high modulus values.

All of the regression equations developed to quantify the effects of time, moisture content, and temperature on the modulus of the ETB layer were created after the removal of data associated with testing times when the ETB temperature was below 32°F. The analyses 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, with higher ETB moisture contents and temperatures corresponding to lower ETB modulus values. The average yearly modulus values for the ETB and UTBC layers were 119.9 ksi and 187.5 ksi, respectively; however, excluding data obtained on dates where the base layer was frozen, the average yearly modulus values are only 68.6 ksi and 78.2 ksi for the ETB and UTBC, respectively. Even during the winter when the ETB stiffness reached its peak, the modulus was still below the target value of 185 ksi that was specified for this project. The results of a paired *t*-test indicate that the modulus values of the ETB and UTBC layers were not statistically different.

# 5 CONCLUSION

## 5.1 Summary

The objectives of this research were 1) to examine correlations between compositional and structural properties of ETB layers, determine which of these factors exhibit the greatest spatial variability, and determine if significant differences exist between different test sections on a given project and 2) to investigate temporal trends in the structural properties of base materials treated with asphalt emulsion and to assess the rate at which ETB design properties are achieved. The research conducted in this study involved field and laboratory evaluations of spatial and temporal variability in properties of ETB. The test site chosen for this research comprised the eastbound lanes of 7800 South in West Jordan, Utah, between 2700 West and 3200 West. The experimental area was divided into three test sections for evaluation.

Spatial testing was performed to characterize the in-situ structural properties of the ETB layer. The field instruments utilized in this research include the PFWD, DCP, CIST, SSG, and NDG. Laboratory testing included sieve analyses, Atterberg limits determinations, moisture content determinations, burn-off analyses, and UCS testing. These data were evaluated using several statistical analyses.

Temporal testing was performed to monitor the properties of the ETB layer and to compare the ETB section to an adjacent UTBC section. Although comparing the two base materials was not part of the original scope of work, construction of the new pavement structure immediately adjacent to the ETB monitoring station was required when the ETB layer experienced significant rutting under construction trafficking. Biweekly testing involved obtaining sensor readings from the ETB section, measuring ambient conditions, and obtaining PFWD measurements at both the ETB and UTBC sections. The temporal data were also evaluated using statistics.

## 5.2 Findings

Regarding spatial results, the average modulus values of the ETB layer were unusually low for a typical stabilized base material and were in general even lower than the subgrade modulus values at this test site. All three test sections had high moisture contents after compaction.

In the laboratory, the soil was classified as an A-1-a and GW-GM (well-graded gravel with silt and sand), using the AASHTO and USCS methods, respectively. The moisture content of the ETB layer exceeded the specified OMC at many locations even before the emulsion was injected, and one of the three test sections had higher percentages of RAP and emulsion than the other two. The ETB compressive strength was very low throughout the entire year of testing, clearly demonstrating the consequences of inadequate emulsion curing associated with this project.

The statistical analyses showed that higher pre-treatment moisture contents and higher amounts of binder added were associated with lower stiffness and strength, while higher wet densities were associated with higher stiffness and strength. The analyses also showed substantial variation in most response variables but comparatively low variation in predictor variables. Only four structural properties were significantly different between test sections.

Regarding temporal results, the ETB moisture content did not change significantly during the 1-year monitoring period, showing that drying of the ETB layer did not occur following placement of the HMA surface. Furthermore, the analyses 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, with higher ETB moisture contents and temperatures corresponding to lower ETB modulus values. Even during the winter when the ETB stiffness reached its peak, the modulus was still below the target value specified for this project. The statistical analyses indicated that the modulus values of the ETB and UTBC layers were not statistically different at this test site.

## 5.3 Recommendations

Several recommendations may be derived from this research. Construction of an ETB layer should not be scheduled when in-situ moisture contents are high, precipitation is expected, water evaporation rates are low, or insufficient time is available for ETB curing. Proper material sampling and laboratory testing should be performed to assess the efficacy of the emulsion for the given project. Before treatment, the material should be allowed to dry well below OMC to ensure that emulsion injection does not cause excessive moisture contents in the layer, which can lead to compaction difficulty and slower curing of the emulsion. Early trafficking of the ETB layer should be restricted to prevent rutting during the curing period, and the surface layer should not be placed until after the emulsion has satisfactorily cured. For sites similar to that studied in this research, an ETB layer should not be expected to continue curing following placement of the surface course.

High spatial variability in the structural properties of the ETB layer should be expected on FDR projects similar to the one investigated in this research, and such variability should therefore be accounted for in design when possible. In addition, seasonal variability in ETB modulus, including stiffening during winter and weakening during spring in cold regions, should also be accounted for in design.

In situations when high water contents or cold weather during construction of a given project cannot be avoided, but the use of emulsion is still desirable, the addition of portland cement with the emulsion should be considered to increase both the strength and the rate of strength gain. As the cement hydrates, it consumes part of the water present in the emulsion, enabling improved curing of the emulsion. Small percentages of cement have been used in conjunction with emulsion treatment on many projects (*38*, *39*).

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# APPENDIX A SPATIAL DATA

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

**Table A-1: Portable Falling-Weight Deflectometer Results for the Emulsion-Treated Base Layer**

| Curing Time (days) | Test | ETB Modulus (ksi) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Station | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Section A | | | | | | | | | | | |
| 0 | 1 | 8.5 | - | 6.7 | 9.0 | 7.2 | 10.8 | 5.2 | 6.0 | 7.0 | 7.2 |
| | 2 | 9.5 | - | 6.6 | 9.7 | 6.7 | 12.0 | 5.6 | 6.9 | 7.8 | 8.0 |
| | 3 | 10.2 | - | 7.0 | 10.0 | 6.4 | 12.4 | 5.7 | 7.3 | 6.9 | 8.5 |
| | Average | 9.4 | | 6.8 | 9.5 | 6.8 | 11.7 | 5.5 | 6.7 | 7.2 | 7.9 |
| 1 | 1 | 14.5 | 22.0 | 6.6 | 9.2 | 5.2 | 12.5 | 1.4 | 6.8 | 6.9 | 7.9 |
| | 2 | 15.3 | 23.7 | 6.7 | 9.5 | 5.3 | 13.4 | 1.5 | 7.2 | 7.1 | 8.5 |
| | 3 | 15.9 | 24.5 | 6.7 | 9.9 | 5.8 | 14.1 | 1.6 | 7.4 | 7.0 | 8.5 |
| | Average | 15.2 | 23.4 | 6.7 | 9.5 | 5.4 | 13.3 | 1.5 | 7.1 | 7.0 | 8.3 |
| Section B | | | | | | | | | | | |
| 0 | 1 | 8.4 | 4.3 | 11.3 | 35.8 | 29.3 | 12.9 | 4.8 | 8.6 | 7.4 | 2.2 |
| | 2 | 8.6 | 4.5 | 10.7 | 37.6 | 30.0 | 14.3 | 5.0 | 9.6 | 8.0 | 2.3 |
| | 3 | 8.8 | 4.6 | 11.7 | 40.2 | 28.6 | 14.7 | 5.2 | 10.1 | 8.0 | 2.4 |
| | Average | 8.6 | 4.5 | 11.2 | 37.9 | 29.3 | 14.0 | 5.0 | 9.4 | 7.8 | 2.3 |
| 1 | 1 | 7.8 | 4.8 | 8.5 | 27.2 | 19.8 | 4.7 | 3.3 | 2.9 | 8.0 | 6.2 |
| | 2 | 8.2 | 5.1 | 9.2 | 29.8 | 20.9 | 4.9 | 3.4 | 3.0 | 8.2 | 6.7 |
| | 3 | 8.4 | 5.2 | 9.2 | 31.0 | 21.3 | 4.6 | 3.4 | 3.2 | 9.1 | 6.6 |
| | Average | 8.1 | 5.1 | 8.9 | 29.3 | 20.7 | 4.8 | 3.4 | 3.0 | 8.4 | 6.5 |
| Section C | | | | | | | | | | | |
| 0 | 1 | 13.1 | 20.2 | 16.9 | 8.9 | 4.1 | 5.2 | 15.0 | 10.2 | 10.8 | 39.9 |
| | 2 | 13.7 | 24.0 | 18.8 | 9.6 | 4.1 | 6.0 | 15.2 | 10.4 | 10.5 | 45.2 |
| | 3 | 14.5 | 26.1 | 19.8 | 9.4 | 5.3 | 6.4 | 16.8 | 9.9 | 12.3 | 48.0 |
| | Average | 13.8 | 23.4 | 18.5 | 9.3 | 4.5 | 5.8 | 15.7 | 10.1 | 11.2 | 44.4 |
| 1 | 1 | 21.2 | 9.9 | 15.0 | 8.5 | 5.6 | 9.6 | 32.3 | 6.2 | 11.7 | 23.8 |
| | 2 | 22.1 | 11.3 | 16.2 | 8.9 | 4.9 | 10.0 | 33.8 | 6.4 | 12.4 | 25.8 |
| | 3 | 22.1 | 11.8 | 16.5 | 9.3 | 5.6 | 10.5 | 34.2 | 6.5 | 12.4 | 26.9 |
| | Average | 21.8 | 11.0 | 15.9 | 8.9 | 5.4 | 10.0 | 33.5 | 6.4 | 12.2 | 25.5 |

## Table A-2: Portable Falling-Weight Deflectometer Results for the Subgrade Layer

| Curing Time (days) | Test | Subgrade Modulus (ksi) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Station | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Section A | | | | | | | | | | | |
| 0 | 1 | 10.9 | - | 4.1 | 17.5 | 3.9 | 12.1 | 7.3 | 7.2 | 14.9 | 39.8 |
| | 2 | 10.4 | - | 4.0 | 17.1 | 3.8 | 11.6 | 6.9 | 7.2 | 14.3 | 35.3 |
| | 3 | 10.4 | - | 3.9 | 17.0 | 3.8 | 11.3 | 6.8 | 7.2 | 14.6 | 33.0 |
| | Average | 10.6 | - | 4.0 | 17.2 | 3.8 | 11.6 | 7.0 | 7.2 | 14.6 | 36.0 |
| 1 | 1 | 10.6 | 17.4 | 4.6 | 16.1 | 2.8 | 11.8 | 4.9 | 7.3 | 14.1 | 29.4 |
| | 2 | 10.3 | 17.5 | 4.5 | 16.0 | 2.8 | 11.5 | 4.7 | 7.2 | 14.0 | 28.4 |
| | 3 | 10.3 | 17.1 | 4.5 | 16.1 | 2.8 | 11.5 | 4.5 | 7.1 | 13.9 | 28.1 |
| | Average | 10.4 | 17.3 | 4.5 | 16.1 | 2.8 | 11.6 | 4.7 | 7.2 | 14.0 | 28.7 |
| Section B | | | | | | | | | | | |
| 0 | 1 | 10.5 | 12.5 | 43.3 | 32.9 | 23.2 | 23.4 | 13.3 | 6.0 | 7.8 | 5.7 |
| | 2 | 10.5 | 12.0 | 38.8 | 32.2 | 23.2 | 22.3 | 12.9 | 5.9 | 7.7 | 6.1 |
| | 3 | 10.4 | 12.0 | 40.9 | 32.2 | 22.0 | 21.5 | 11.6 | 5.8 | 7.4 | 6.0 |
| | Average | 10.5 | 12.2 | 41.0 | 32.5 | 22.8 | 22.4 | 12.6 | 5.9 | 7.6 | 5.9 |
| 1 | 1 | 11.4 | 13.2 | 28.6 | 31.2 | 26.5 | 4.4 | 9.4 | 12.5 | 8.4 | 42.0 |
| | 2 | 11.2 | 12.6 | 28.3 | 30.6 | 26.0 | 4.5 | 9.0 | 13.2 | 8.0 | 43.3 |
| | 3 | 11.2 | 12.3 | 28.0 | 29.3 | 25.3 | 4.5 | 8.7 | 12.4 | 8.1 | 47.2 |
| | Average | 11.3 | 12.7 | 28.3 | 30.4 | 26.0 | 4.5 | 9.0 | 12.7 | 8.1 | 44.2 |
| Section C | | | | | | | | | | | |
| 0 | 1 | 28.8 | 10.7 | 12.0 | 19.1 | 2.5 | 7.4 | 9.4 | 4.1 | 5.5 | 15.3 |
| | 2 | 28.0 | 10.6 | 12.0 | 18.7 | 2.4 | 7.6 | 9.2 | 4.0 | 5.4 | 14.9 |
| | 3 | 27.0 | 10.6 | 12.2 | 18.8 | 2.5 | 7.4 | 9.1 | 3.9 | 5.4 | 15.1 |
| | Average | 27.9 | 10.6 | 12.1 | 18.9 | 2.4 | 7.5 | 9.2 | 4.0 | 5.4 | 15.1 |
| 1 | 1 | 24.6 | 7.6 | 12.2 | 17.1 | 1.0 | 8.0 | 6.5 | 3.3 | 5.2 | 15.0 |
| | 2 | 24.5 | 7.6 | 12.2 | 17.3 | 0.9 | 7.9 | 6.4 | 3.2 | 5.1 | 14.7 |
| | 3 | 24.0 | 7.4 | 11.9 | 17.3 | 0.9 | 7.8 | 6.4 | 3.2 | 5.0 | 14.4 |
| | Average | 24.4 | 7.5 | 12.1 | 17.2 | 0.9 | 7.9 | 6.4 | 3.2 | 5.1 | 14.7 |

## Table A-3: Dynamic Cone Penetrometer Results for the Emulsion-Treated Base Layer

| Curing Time (days) | Section | Station | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Penetration Rate (mm/blow) | | | | | | | | | | | |
| 1 | A | 10.1 | 7.7 | 6.8 | 15.7 | 10.6 | 8.3 | 19.8 | 13.3 | 8.6 | 9.7 |
| | B | 10.2 | 19.4 | 7.8 | 6.4 | 7.0 | 9.3 | 14.8 | 19.9 | 8.1 | 8.8 |
| | C | 4.9 | 7.3 | 6.3 | 11.0 | 20.3 | 6.9 | 4.4 | 6.6 | 8.8 | 6.7 |
| CBR (%) | | | | | | | | | | | |
| 1 | A | 22.5 | 30.5 | 45.4 | 14.1 | 21.9 | 24.4 | 10.7 | 17.2 | 29.6 | 23.2 |
| | B | 21.7 | 12.0 | 30.2 | 36.6 | 34.8 | 24.4 | 15.2 | 10.6 | 28.3 | 25.7 |
| | C | 58.2 | 33.4 | 37.8 | 16.9 | 11.2 | 43.6 | 61.8 | 47.5 | 28.9 | 35.3 |

## Table A-4: Dynamic Cone Penetrometer Results for the Subgrade Layer

| Curing Time (days) | Section | Station | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Penetration Rate (mm/blow) | | | | | | | | | | | |
| 1 | A | 26.8 | 9.2 | 24.4 | 20.3 | 46.3 | 22.7 | 33.7 | 31.0 | 24.3 | 11.7 |
| | B | 12.1 | 30.1 | 3.9 | 7.2 | 5.4 | 29.3 | 17.3 | 23.6 | 41.6 | 6.9 |
| | C | 6.4 | 19.7 | 15.3 | 9.1 | 62.6 | 17.8 | 19.6 | 57.9 | 38.8 | 7.8 |
| CBR (%) | | | | | | | | | | | |
| 1 | A | 12.8 | 30.3 | 26.0 | 11.3 | 11.8 | 9.8 | 0.4 | 6.9 | 10.0 | 24.6 |
| | B | 19.5 | 7.8 | 77.9 | 46.1 | 54.7 | 8.5 | 14.2 | 12.3 | 5.9 | 45.6 |
| | C | 43.1 | 20.7 | 15.7 | 30.0 | 3.3 | 18.0 | 18.3 | 3.1 | 5.0 | 35.3 |

# Table A-5: Clegg Impact Soil Tester Results

| Curing Time (days) | Section | Test | Clegg Impact Value | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Station | | | | | | | | | |
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 0 | A | 1 | 12.6 | 12.8 | 8.6 | 5.4 | 7.7 | 10.8 | 3.6 | 4.6 | 4.9 | 7.8 |
| | | 2 | 11.7 | 14.4 | 13.5 | 6.5 | 14.3 | 7.8 | 4.8 | 6.3 | 6.3 | 4.1 |
| | | 3 | 16.7 | 20.4 | 8.1 | 10.1 | 7.3 | 6.8 | 12.1 | 6.1 | 5.0 | 3.8 |
| | | Average | 13.7 | 15.9 | 10.1 | 7.3 | 9.8 | 8.5 | 6.8 | 5.7 | 5.4 | 5.2 |
| | B | 1 | 6.7 | 1.9 | 10.8 | 12.7 | 8.6 | 4.8 | 5.1 | 4.2 | 5.1 | 2.5 |
| | | 2 | 6.1 | 2.1 | 9.5 | 4.7 | 8.8 | 4.7 | 3.1 | 4.1 | 4.7 | 4.1 |
| | | 3 | 6.2 | 4.6 | 15.1 | 7.2 | 4.9 | 8.9 | 4.9 | 3.7 | 2.3 | 1.8 |
| | | Average | 6.3 | 2.9 | 11.8 | 8.2 | 7.4 | 6.1 | 4.4 | 4.0 | 4.0 | 2.8 |
| | C | 1 | 7.0 | 5.5 | 21.3 | 0.3 | 0.4 | 2.0 | 4.7 | 6.8 | 0.1 | 0.1 |
| | | 2 | 5.2 | 5.7 | 18.6 | 0.3 | 1.5 | 0.4 | 0.1 | 7.1 | 0.2 | 0.1 |
| | | 3 | 6.9 | 5.4 | 18.6 | 0.9 | 0.1 | 0.0 | 0.8 | 0.2 | 1.1 | 0.1 |
| | | Average | 6.4 | 5.5 | 19.5 | 0.5 | 0.7 | 0.8 | 1.9 | 4.7 | 0.5 | 0.1 |
| 1 | A | 1 | 15.1 | 20.5 | 7.7 | 3.6 | 5.7 | 7.6 | 2.8 | 6.6 | 4.3 | 6.4 |
| | | 2 | 14.4 | 19.5 | 5.4 | 2.9 | 7.4 | 6.5 | 5.8 | 4.2 | 2.8 | 5.1 |
| | | 3 | 13.4 | 21.3 | 10.6 | 4.5 | 3.4 | 7.5 | 5.7 | 4.2 | 2.6 | 6.1 |
| | | Average | 14.3 | 20.4 | 7.9 | 3.7 | 5.5 | 7.2 | 4.8 | 5.0 | 3.2 | 5.9 |
| | B | 1 | - | 7.5 | 6.7 | 25.6 | 10.6 | 12.7 | 7.5 | 7.0 | 13.7 | 12.6 |
| | | 2 | 6.4 | 6.9 | 4.3 | 34.6 | 13.1 | 15.4 | 7.5 | 5.2 | 13.2 | 8.1 |
| | | 3 | 10.5 | 3.1 | 5.6 | 22.0 | 19.5 | 9.1 | 10.5 | 8.6 | 14.9 | 9.8 |
| | | Average | 8.5 | 5.8 | 5.5 | 27.4 | 14.4 | 12.4 | 8.5 | 6.9 | 13.9 | 10.2 |
| | C | 1 | 19.7 | 17.7 | 14.8 | 18.7 | 6.5 | 9.4 | 11.1 | 17.7 | 10.0 | 9.4 |
| | | 2 | 13.8 | 17.6 | 8.8 | 17.4 | 4.0 | 7.8 | 11.6 | 10.8 | 12.9 | 8.9 |
| | | 3 | 20.7 | 19.9 | 18.7 | 11.4 | 11.0 | 6.5 | 17.0 | 10.8 | 17.9 | 10.8 |
| | | Average | 18.1 | 18.4 | 14.1 | 15.8 | 7.2 | 7.9 | 13.2 | 13.1 | 13.6 | 9.7 |
| 4 | A | 1 | - | 9.4 | 7.7 | 6.0 | 17.7 | 24.6 | 10.4 | 3.9 | 2.8 | 2.3 |
| | | 2 | - | 19.7 | 12.6 | 11.0 | 12.3 | 18.5 | 8.1 | 1.6 | 2.5 | 1.8 |
| | | 3 | - | 20.4 | 10.2 | 15.4 | 16.8 | 18.0 | 6.8 | 1.1 | 1.3 | 3.7 |
| | | Average | - | 16.5 | 10.2 | 10.8 | 15.6 | 20.4 | 8.4 | 2.2 | 2.2 | 2.6 |
| | B | 1 | 8.8 | 2.7 | 16.3 | 30.9 | 32.7 | - | - | - | 16.9 | 4.4 |
| | | 2 | 5.8 | 1.8 | 28.5 | 27.0 | 29.9 | - | - | - | 13.1 | 5.1 |
| | | 3 | 2.2 | 2.5 | 21.6 | 29.7 | 29.1 | - | - | - | 8.2 | 13.5 |
| | | Average | 5.6 | 2.3 | 22.1 | 29.2 | 30.6 | - | - | - | 12.7 | 7.7 |
| | C | 1 | 11.3 | 6.4 | 24.2 | 16.3 | - | - | - | 15.5 | 17.4 | 12.9 |
| | | 2 | 10.9 | 11.0 | 19.6 | 10.0 | - | - | - | 10.0 | 14.8 | 11.1 |
| | | 3 | 11.4 | 11.1 | 24.6 | 10.9 | - | - | - | 4.9 | 13.3 | 22.4 |
| | | Average | 11.2 | 9.5 | 22.8 | 12.4 | - | - | - | 10.1 | 15.2 | 15.5 |

# Table A-6: Soil Stiffness Gauge Results

| Curing Time (days) | Section | Test | Soil Stiffness (MN/m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Station | | | | | | | | | |
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 0 | A | 1 | 13.9 | 14.5 | 8.5 | 11.5 | 8.3 | 12.3 | 6.0 | 7.4 | 9.4 | 12.9 |
| | | 2 | 14.1 | 8.1 | 8.4 | 12.1 | 9.3 | 13.3 | 6.1 | 8.0 | 10.3 | 12.4 |
| | | 3 | 8.5 | 14.5 | 9.4 | 12.9 | 9.8 | 13.4 | 6.3 | 8.0 | 10.5 | 12.8 |
| | | Average | 12.2 | 12.4 | 8.8 | 12.2 | 9.1 | 13.0 | 6.1 | 7.8 | 10.1 | 12.7 |
| | B | 1 | 12.9 | 9.0 | 10.9 | 10.4 | 13.2 | 9.3 | 7.4 | 9.6 | 6.8 | 4.2 |
| | | 2 | 13.4 | 9.4 | 11.5 | 10.8 | 13.7 | 9.6 | 7.6 | 9.9 | 7.3 | 4.6 |
| | | 3 | 13.6 | 9.5 | 11.7 | 11.0 | 14.0 | 9.9 | 7.7 | 10.1 | 7.3 | 4.8 |
| | | Average | 13.3 | 9.3 | 11.3 | 10.7 | 13.6 | 9.6 | 7.6 | 9.9 | 7.1 | 4.6 |
| | C | 1 | 10.2 | 10.9 | 9.6 | 11.8 | 5.2 | 9.1 | 16.4 | 9.6 | 11.7 | 13.7 |
| | | 2 | 11.2 | 11.3 | 10.1 | 12.1 | 5.4 | 9.7 | 17.1 | 9.9 | 12.1 | 14.2 |
| | | 3 | 11.7 | 11.5 | 10.3 | 12.3 | 5.5 | 9.9 | 17.3 | 10.2 | 12.3 | 14.5 |
| | | Average | 11.0 | 11.2 | 10.0 | 12.1 | 5.4 | 9.6 | 16.9 | 9.9 | 12.0 | 14.1 |
| 1 | A | 1 | 16.2 | 15.1 | 17.2 | 11.6 | 10.7 | 13.6 | 9.1 | 9.3 | 12.6 | 15.4 |
| | | 2 | 16.9 | 14.2 | 17.6 | 11.8 | 11.0 | 13.9 | 9.3 | 9.6 | 13.1 | 15.7 |
| | | 3 | 17.2 | 15.5 | 17.6 | 12.0 | 11.3 | 14.4 | 9.4 | 9.8 | 13.3 | 15.9 |
| | | Average | 16.8 | 14.9 | 17.5 | 11.8 | 11.0 | 14.0 | 9.3 | 9.5 | 13.0 | 15.7 |
| | B | 1 | 19.0 | 13.8 | 15.6 | 13.1 | 18.5 | 7.7 | 8.5 | 11.9 | 9.9 | 7.9 |
| | | 2 | 19.4 | 14.1 | 14.9 | 13.6 | 19.2 | 8.2 | 8.7 | 12.2 | 10.2 | 8.2 |
| | | 3 | 19.6 | 14.2 | 14.9 | 13.8 | 19.7 | 8.6 | 8.3 | 12.4 | 10.4 | 8.3 |
| | | Average | 19.3 | 14.0 | 15.2 | 13.5 | 19.1 | 8.2 | 8.5 | 12.2 | 10.2 | 8.1 |
| | C | 1 | 18.9 | 15.7 | 14.0 | 16.8 | 4.8 | 9.8 | 20.2 | 17.3 | 17.2 | 17.3 |
| | | 2 | 19.7 | 16.0 | 14.4 | 17.3 | 5.5 | 10.0 | 22.1 | 17.7 | 17.8 | 18.1 |
| | | 3 | 20.0 | 16.1 | 14.5 | 17.5 | 5.6 | 10.1 | 22.8 | 17.8 | 18.0 | 18.3 |
| | | Average | 19.5 | 15.9 | 14.3 | 17.2 | 5.3 | 10.0 | 21.7 | 17.6 | 17.6 | 17.9 |

# Table A-7: Nuclear Density Gauge Results

| Curing Time (days) | Measurement | Nuclear Density Gauge Readings | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Section A | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 0 | Wet Density (pcf) | 123.9 | 127.7 | 133.1 | 132.4 | 135.2 | 133.2 | 129.1 | 127.8 | 136.6 | 135.6 |
| | Moisture (pcf) | 9.0 | 13.5 | 13.7 | 13.5 | 11.1 | 12.8 | 14.1 | 12.8 | 13.8 | 11.4 |
| | Percent Moisture (%) | 7.8 | 11.8 | 11.5 | 11.4 | 8.9 | 10.6 | 12.3 | 11.1 | 11.2 | 9.2 |
| | | Section B | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| | Wet Density (pcf) | 134.0 | 134.3 | 140.7 | 120.5 | 130.9 | 132.8 | 126.0 | 130.6 | 130.7 | 133.2 |
| | Moisture (pcf) | 11.4 | 13.7 | 18.4 | 8.9 | 13.3 | 12.2 | 11.1 | 12.3 | 14.2 | 12.7 |
| | Percent Moisture (%) | 9.3 | 11.4 | 15.0 | 8.0 | 11.3 | 10.1 | 9.7 | 10.4 | 12.2 | 10.5 |
| | | Section C | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| | Wet Density (pcf) | 134.1 | 131.5 | 133.9 | 130.6 | 128.9 | 121.1 | 131.1 | 129.3 | 127.9 | 128.6 |
| | Moisture (pcf) | 12.3 | 12.8 | 14.5 | 12.5 | 12.5 | 14.6 | 13.1 | 15.0 | 10.9 | 11.9 |
| | Percent Moisture (%) | 10.1 | 10.8 | 12.1 | 10.6 | 10.7 | 13.7 | 11.1 | 13.1 | 9.3 | 10.2 |

## Table A-8: Dry Sieve Analysis Results

| Sieve Size | Percent Passing (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Section A | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 3/4" | 99.0 | 99.5 | 97.9 | 98.1 | 98.8 | 98.6 | 97.4 | 98.9 | 98.1 | 97.3 |
| 1/2" | 92.3 | 58.5 | 88.5 | 90.2 | 88.1 | 88.7 | 87.9 | 87.9 | 90.1 | 91.5 |
| 3/8" | 85.7 | 58.5 | 77.4 | 81.1 | 76.7 | 75.8 | 75.2 | 74.6 | 79.2 | 80.9 |
| No. 4 | 61.7 | 58.5 | 54.6 | 53.4 | 53.9 | 48.5 | 48.3 | 46.6 | 51.6 | 54.1 |
| No. 8 | 41.4 | 34.1 | 37.5 | 33.2 | 39.2 | 32.0 | 30.8 | 29.9 | 34.0 | 36.0 |
| No. 16 | 27.9 | 16.9 | 25.9 | 22.1 | 28.0 | 21.7 | 20.7 | 19.5 | 23.9 | 25.0 |
| No. 30 | 19.2 | 9.3 | 18.0 | 15.5 | 19.1 | 14.6 | 15.1 | 13.3 | 17.2 | 17.9 |
| No. 50 | 11.3 | 5.0 | 11.8 | 11.2 | 12.7 | 10.2 | 11.1 | 9.9 | 12.4 | 12.0 |
| No. 100 | 4.5 | 2.2 | 6.5 | 6.8 | 7.6 | 6.4 | 7.0 | 6.2 | 7.3 | 6.8 |
| No. 200 | 1.5 | 1.1 | 3.3 | 3.7 | 3.9 | 3.3 | 3.8 | 3.3 | 3.7 | 3.4 |
| | Section B | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 3/4" | 99.4 | 98.9 | 97.7 | 97.9 | 95.5 | 98.8 | 98.4 | 97.4 | 96.9 | 96.9 |
| 1/2" | 91.7 | 90.3 | 89.6 | 86.0 | 82.7 | 89.7 | 90.8 | 85.2 | 86.5 | 90.4 |
| 3/8" | 80.6 | 78.6 | 76.5 | 77.0 | 71.8 | 78.9 | 80.3 | 72.2 | 75.5 | 80.2 |
| No. 4 | 53.8 | 50.9 | 48.4 | 50.9 | 45.3 | 49.8 | 55.9 | 44.4 | 48.1 | 56.9 |
| No. 8 | 37.0 | 33.3 | 33.9 | 33.3 | 28.9 | 32.3 | 37.8 | 28.8 | 31.6 | 41.1 |
| No. 16 | 26.3 | 23.7 | 25.1 | 21.6 | 17.9 | 21.9 | 26.4 | 20.6 | 21.9 | 30.3 |
| No. 30 | 18.7 | 17.7 | 18.1 | 15.0 | 10.9 | 15.1 | 18.5 | 15.7 | 15.4 | 21.7 |
| No. 50 | 13.1 | 13.5 | 12.1 | 10.6 | 6.4 | 9.8 | 13.0 | 11.5 | 10.5 | 14.6 |
| No. 100 | 7.5 | 8.3 | 6.9 | 3.2 | 3.7 | 5.3 | 7.5 | 6.9 | 5.9 | 7.9 |
| No. 200 | 3.8 | 4.3 | 3.4 | 2.0 | 2.4 | 2.5 | 3.9 | 3.7 | 2.9 | 3.9 |
| | Section C | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 3/4" | 91.9 | 96.2 | 95.2 | 96.8 | 92.9 | 92.7 | 96.4 | 96.5 | 97.5 | 96.0 |
| 1/2" | 78.4 | 87.8 | 83.1 | 80.6 | 76.3 | 76.4 | 84.4 | 86.1 | 86.3 | 85.4 |
| 3/8" | 69.2 | 79.9 | 73.8 | 69.9 | 69.6 | 67.9 | 77.0 | 78.2 | 77.6 | 78.6 |
| No. 4 | 48.2 | 56.3 | 52.9 | 44.2 | 54.1 | 46.5 | 57.5 | 57.3 | 57.7 | 57.0 |
| No. 8 | 33.8 | 37.0 | 37.2 | 27.1 | 27.9 | 33.2 | 41.8 | 39.5 | 40.8 | 40.4 |
| No. 16 | 25.1 | 24.4 | 27.0 | 17.6 | 21.1 | 24.5 | 30.5 | 26.9 | 28.0 | 28.5 |
| No. 30 | 18.2 | 16.9 | 18.6 | 11.1 | 16.2 | 17.0 | 21.2 | 16.6 | 19.2 | 19.9 |
| No. 50 | 11.1 | 9.8 | 11.3 | 6.1 | 12.8 | 10.4 | 12.0 | 8.0 | 11.2 | 11.3 |
| No. 100 | 5.4 | 4.2 | 5.5 | 2.7 | 9.1 | 5.3 | 5.2 | 3.3 | 5.2 | 4.2 |
| No. 200 | 2.6 | 1.8 | 2.6 | 0.7 | 6.2 | 2.3 | 2.2 | 1.4 | 2.3 | 1.5 |

### Table A-9: Washed Sieve Analysis Results

| Sieve Size | Percent Passing |
|---|---|
| 1-1/2" | 100.0 |
| 1" | 95.7 |
| 3/4" | 92.9 |
| 1/2" | 88.1 |
| 3/8" | 78.8 |
| No. 4 | 58.9 |
| No. 8 | 43.7 |
| No. 16 | 35.1 |
| No. 30 | 29.0 |
| No. 50 | 23.4 |
| No. 100 | 14.7 |
| No. 200 | 10.5 |

### Table A-10: Atterberg Limits Results

| Soil Property | Value |
|---|---|
| Liquid Limit | 24 |
| Plastic Limit | 21 |
| Plasticity Index | 3 |

### Table A-11: Pre-Treatment Moisture Contents

| Section | Pre-treatment Moisture Content (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Station | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| A | 3.0 | 3.3 | 7.2 | 8.0 | 6.9 | 6.7 | 9.8 | 7.0 | 5.7 | 8.3 |
| B | 8.5 | 8.7 | 8.5 | 3.6 | 2.7 | 7.4 | 8.5 | 9.8 | 6.5 | 7.1 |
| C | 4.4 | 7.8 | 5.5 | 4.2 | 7.8 | 7.8 | 2.9 | 3.9 | 4.1 | 3.9 |

## Table A-12: Burn-off Test Results

| Time of Sampling | Binder Content (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Section A | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Before Treatment | 5.2 | 3.5 | 2.3 | 2.4 | 1.6 | 2.1 | 1.5 | 1.9 | 1.5 | 2.3 |
| After Treatment | 7.0 | 5.5 | 4.4 | 5.0 | 4.2 | 4.9 | 4.0 | 3.8 | 3.6 | 4.7 |
| | Section B | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Before Treatment | 1.5 | 1.6 | 1.6 | 4.0 | 3.9 | 2.2 | 1.3 | 1.6 | 2.3 | 1.3 |
| After Treatment | 4.6 | 3.8 | 3.3 | 6.2 | 6.0 | 4.6 | 3.1 | 4.4 | 5.3 | 4.1 |
| | Section C | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Before Treatment | 2.7 | 3.6 | 1.8 | 3.3 | 1.9 | 3.2 | 3.7 | 4.8 | 2.1 | 3.7 |
| After Treatment | 4.9 | 7.4 | 4.9 | 5.9 | 5.6 | 5.5 | 7.6 | 8.1 | 5.0 | 7.8 |

## Table A-13: Unconfined Compressive Strength Test Results

| Curing Time (days) | Unconfined Compressive Strength (psi) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Section A | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 38.6 | 27.5 | 31.4 | 31.8 | 33.0 | 33.4 | 27.9 | 33.0 | 30.6 | 36.6 |
| 28 | 40.6 | 22.7 | 29.4 | 31.8 | 28.6 | 32.6 | 28.6 | 29.8 | 39.0 | 31.4 |
| 181 | 43.0 | 44.6 | 37.8 | 42.2 | 35.4 | 48.9 | 36.2 | 34.6 | 45.4 | 38.6 |
| 365 | 54.5 | 33.4 | 35.8 | 36.2 | 40.6 | 48.1 | 35.4 | - | 52.1 | 43.8 |
| | Section B | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 29.0 | 25.5 | 35.4 | - | 25.1 | 28.6 | 30.6 | 30.2 | 32.6 | 35.4 |
| 28 | 23.9 | 27.1 | 40.2 | 11.1 | 22.3 | 30.2 | 35.0 | 30.2 | 25.9 | 33.0 |
| 181 | 46.6 | 33.8 | 51.3 | - | 32.6 | 44.6 | 33.4 | 32.6 | 26.3 | 39.0 |
| 365 | 48.1 | 37.4 | 59.7 | - | 41.0 | 54.5 | 44.2 | 39.8 | 38.2 | 53.3 |
| | Section C | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 29.4 | 18.3 | 24.7 | 27.5 | 31.8 | 28.3 | 24.7 | 22.3 | 37.0 | 17.9 |
| 28 | 30.2 | 17.9 | 27.9 | 33.8 | 21.9 | 22.7 | 21.1 | 19.1 | 24.7 | 15.9 |
| 181 | 50.9 | 31.4 | 31.8 | 33.0 | 29.0 | 29.4 | 26.7 | 32.2 | 43.4 | 26.3 |
| 365 | 46.2 | 25.9 | 41.0 | 38.6 | 29.8 | 33.0 | 43.4 | 46.2 | 39.4 | 28.6 |

## Table A-14: Moisture Contents of Unconfined Compressive Strength Samples

| Curing Time (days) | Moisture Content (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Section A | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 6.1 | 8.1 | 6.5 | 8.1 | 6.6 | 5.7 | 9.0 | 7.8 | 7.0 | 6.2 |
| 28 | 6.0 | 3.2 | 7.3 | 7.8 | 6.5 | 5.9 | 9.0 | 8.1 | 6.6 | 6.5 |
| 181 | 5.5 | 3.1 | 6.7 | 7.8 | 6.6 | 5.5 | 9.1 | 7.8 | 6.9 | 6.6 |
| 365 | 5.4 | 3.3 | 6.9 | 7.7 | 6.3 | 5.5 | 9.1 | - | 7.0 | 6.5 |
| | Section B | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 7.1 | 8.3 | 7.0 | - | 5.1 | 6.5 | 8.7 | 9.4 | 6.1 | 6.8 |
| 28 | 7.7 | 8.7 | 6.9 | 3.8 | 4.9 | 6.4 | 8.2 | 9.1 | 6.2 | 7.1 |
| 181 | 6.9 | 8.1 | 6.8 | - | 5.4 | 6.3 | 8.7 | 9.7 | 6.5 | 7.1 |
| 365 | 6.8 | 7.9 | 6.9 | - | 4.9 | 5.9 | 8.5 | 8.5 | 6.2 | 6.9 |
| | Section C | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 6.0 | 5.9 | 6.1 | 6.0 | 7.9 | 6.1 | 3.5 | 3.1 | 4.6 | 3.6 |
| 28 | 5.7 | 6.5 | 6.1 | 5.7 | 8.0 | 5.9 | 3.5 | 3.4 | 4.8 | 3.8 |
| 181 | 5.5 | 5.8 | 6.4 | 6.1 | 8.2 | 6.0 | 3.8 | 3.4 | 4.7 | 4.1 |
| 365 | 5.1 | 6.3 | 6.0 | 5.9 | 7.6 | 5.9 | 3.9 | 3.1 | 4.7 | 3.9 |

## Table A-15: Wet Density of Unconfined Compressive Strength Samples

| Curing Time (days) | Wet Density (pcf) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Section A | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 130.8 | 137.7 | 137.0 | 133.1 | 135.8 | 134.8 | 134.0 | 136.2 | 135.9 | 135.6 |
| 28 | 132.1 | 128.0 | 137.1 | 135.3 | 137.2 | 136.3 | 135.3 | 137.9 | 134.3 | 139.3 |
| 181 | 126.3 | 126.7 | 138.4 | 133.2 | 140.6 | 134.8 | 134.7 | 139.2 | 135.0 | 135.6 |
| 365 | 131.6 | 124.5 | 135.9 | 134.7 | 135.2 | 134.6 | 133.0 | - | 136.5 | 137.7 |
| | Section B | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 136.6 | 135.1 | 135.8 | - | 128.6 | 136.4 | 133.9 | 134.8 | 134.7 | 137.7 |
| 28 | 136.8 | 135.8 | 135.4 | 121.3 | 129.6 | 137.2 | 136.8 | 135.1 | 135.3 | 136.8 |
| 181 | 136.2 | 135.3 | 135.3 | - | 129.4 | 137.6 | 133.3 | 132.9 | 133.1 | 137.4 |
| 365 | 140.0 | 135.8 | 134.6 | - | 132.3 | 139.1 | 134.7 | 134.8 | 134.3 | 142.1 |
| | Section C | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 134.6 | 130.9 | 131.3 | 133.9 | 131.6 | 132.9 | 127.6 | 123.5 | 129.2 | 123.3 |
| 28 | 133.8 | 131.0 | 135.9 | 135.4 | 135.4 | 134.7 | 129.2 | 128.3 | 132.1 | 128.9 |
| 181 | 136.0 | 130.4 | 132.8 | 133.3 | 134.2 | 134.1 | 128.9 | 127.3 | 130.5 | 123.1 |
| 365 | 134.7 | 133.2 | 133.3 | 134.8 | 136.2 | 134.5 | 130.6 | 128.7 | 129.4 | 124.1 |

## Table A-16: Dry Density of Unconfined Compressive Strength Samples

| Curing Time (days) | Dry Density (pcf) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Section A | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 123.3 | 127.4 | 128.6 | 123.1 | 127.4 | 127.5 | 122.9 | 126.3 | 127.1 | 127.6 |
| 28 | 124.7 | 124.0 | 127.8 | 125.5 | 128.9 | 128.7 | 124.0 | 127.6 | 126.1 | 130.9 |
| 181 | 119.7 | 123.0 | 129.6 | 123.6 | 131.9 | 127.8 | 123.5 | 129.1 | 126.2 | 127.3 |
| 365 | 124.8 | 120.5 | 127.2 | 125.0 | 127.2 | 127.6 | 121.9 | - | 127.7 | 129.3 |
| | Section B | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 127.5 | 124.8 | 127.0 | - | 122.4 | 128.1 | 123.1 | 123.2 | 127.0 | 129.0 |
| 28 | 127.0 | 124.9 | 126.7 | 116.9 | 123.5 | 129.0 | 126.5 | 123.8 | 127.5 | 127.7 |
| 181 | 127.4 | 125.1 | 126.7 | - | 122.7 | 129.4 | 122.7 | 121.2 | 125.1 | 128.3 |
| 365 | 131.2 | 125.9 | 126.0 | - | 126.1 | 131.3 | 124.1 | 124.3 | 126.5 | 132.9 |
| | Section C | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 7 | 127.0 | 123.5 | 123.8 | 126.4 | 122.0 | 125.3 | 123.2 | 119.7 | 123.5 | 119.0 |
| 28 | 126.7 | 123.1 | 128.2 | 128.1 | 125.3 | 127.3 | 124.8 | 124.1 | 126.0 | 124.1 |
| 181 | 129.0 | 123.2 | 124.8 | 125.6 | 124.0 | 126.5 | 124.2 | 123.1 | 124.7 | 118.2 |
| 365 | 128.2 | 125.4 | 125.8 | 127.3 | 126.6 | 127.1 | 125.7 | 124.8 | 123.6 | 119.5 |

# APPENDIX B TEMPORAL DATA

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

## Table B-1: Surface and Subsurface Site Conditions

| Date | Curing Time (days) | Subsurface Properties | | | | Surface Properties | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | West Location | | East Location | | Temperature (°F) | | Relative Humidity (%) | Wind Speed (mph) |
| | | Moisture Content (%) | Temperature (°F) | Moisture Content (%) | Temperature (°F) | Pavement Surface | Air | | |
| 10/10/2010 | 0 | 8.9 | 73.0 | 9.0 | 73.9 | - | 63.3 | 48.7 | 0 |
| 10/11/2010 | 1 | 8.9 | 75.2 | 9.0 | 74.8 | - | 14.4 | - | - |
| 10/14/2010 | 4 | 6.6 | 48.6 | 7.2 | 50.2 | - | - | - | - |
| 10/20/2010 | 10 | 6.5 | 54.1 | 6.8 | 54.7 | - | - | - | - |
| 10/26/2010 | 16 | 9.0 | 57.9 | 7.5 | 57.4 | 62.4 | 52.3 | 23.2 | - |
| 11/8/2010 | 29 | 10.0 | 55.4 | 7.8 | 55.9 | 40.5 | 38.6 | 53.3 | - |
| 11/23/2010 | 44 | 9.0 | 41.2 | 7.5 | 41.4 | 38.0 | 41.4 | 46.9 | 12.0 |
| 12/8/2010 | 59 | 9.0 | 38.7 | 7.7 | 38.7 | 40.5 | 43.3 | 65.0 | 0.0 |
| 12/22/2010 | 73 | 9.4 | 37.8 | 7.6 | 37.9 | 39.0 | 42.1 | 89.2 | - |
| 1/5/2011 | 87 | 6.4 | 26.2 | 6.0 | 27.0 | 19.5 | 22.9 | 78.4 | 1.5 |
| 1/19/2011 | 101 | 8.6 | 37.9 | 6.8 | 38.1 | 30.0 | 40.0 | 61.3 | 5.0 |
| 2/2/2011 | 115 | 6.7 | 27.5 | 6.1 | 28.0 | 28.0 | 25.8 | 21.9 | 0.5 |
| 2/17/2011 | 130 | 8.7 | 39.6 | 7.6 | 39.7 | 31.5 | 43.4 | 44.8 | 0.2 |
| 3/2/2011 | 143 | 8.8 | 45.1 | 7.7 | 45.0 | 47.0 | 51.3 | 31.3 | 7.5 |
| 3/18/2011 | 159 | 8.9 | 45.9 | 7.8 | 45.9 | 47.5 | 50.1 | 47.1 | 5.2 |
| 3/30/2011 | 171 | 8.9 | 50.9 | 7.9 | 50.9 | 45.5 | 48.9 | 66.5 | 3.5 |
| 4/13/2011 | 185 | 9.1 | 56.3 | 8.1 | 55.9 | 69.5 | 64.9 | 38.4 | 1.7 |
| 4/27/2011 | 199 | 9.0 | 55.0 | 8.1 | 54.5 | 75.5 | 61.0 | 31.3 | 4.8 |
| 5/12/2011 | 214 | 9.2 | 64.0 | 8.4 | 64.0 | 76.5 | 65.8 | 46.4 | 2.7 |
| 5/26/2011 | 228 | 9.2 | 67.8 | 8.5 | 67.8 | 72.5 | 56.6 | 41.4 | 4.9 |
| 6/8/2011 | 241 | 9.3 | 82.2 | 8.7 | 81.0 | 106.0 | 72.3 | 21.6 | 1.6 |
| 6/22/2011 | 255 | 9.4 | 85.6 | 8.8 | 84.6 | 105.5 | 95.9 | 27.7 | 0.8 |
| 7/6/2011 | 269 | 9.2 | 90.1 | 8.9 | 89.4 | 104.5 | 94.2 | 38.7 | 0.0 |
| 7/20/2011 | 283 | 9.1 | 88.2 | 8.6 | 87.8 | 98.5 | 93.0 | 33.1 | 0.0 |
| 8/3/2011 | 297 | 9.0 | 86.0 | 8.5 | 85.6 | 95.5 | 84.5 | 47.2 | 0.9 |
| 8/17/2011 | 311 | 9.0 | 90.7 | 8.6 | 90.0 | 106.0 | 92.8 | 28.4 | 1.5 |
| 8/31/2011 | 325 | 8.9 | 86.7 | 8.5 | 86.5 | 92.0 | 90.5 | 34.8 | 1.7 |
| 9/13/2011 | 338 | 8.7 | 82.0 | 8.4 | 81.1 | 96.5 | 86.7 | 34.1 | 0.9 |
| 9/27/2011 | 352 | 8.7 | 78.6 | 8.2 | 77.7 | 95.0 | 85.4 | 36.3 | 1.5 |
| 10/11/2011 | 366 | 8.5 | 64.0 | 8.0 | 64.2 | 65.5 | 65.8 | 50.4 | 0.6 |
| Average | | 8.7 | 61.1 | 7.9 | 61.0 | 66.5 | 60.3 | 44.0 | 2.5 |
| Std. Dev. | | 0.9 | 20.0 | 0.8 | 19.6 | 28.9 | 23.4 | 16.8 | 2.9 |

**Table B-2: Backcalculated Modulus Values for the Emulsion-Treated Base Section**

| Date | Curing Time (days) | West Location | | | East Location | | |
|---|---|---|---|---|---|---|---|
| | | Asphalt | ETB | Subgrade | Asphalt | ETB | Subgrade |
| 10/10/2010 | 0 | - | 9.4 | 10.6 | - | 9.4 | 10.6 |
| 10/11/2010 | 1 | - | 15.2 | 10.4 | - | 15.2 | 10.4 |
| 10/14/2010 | 4 | - | - | - | - | - | - |
| 10/20/2010 | 10 | - | - | - | - | - | - |
| 10/26/2010 | 16 | - | - | - | - | - | - |
| 11/8/2010 | 29 | 511.0 | 91.8 | 18.2 | 581.8 | 102.7 | 16.8 |
| 11/23/2010 | 44 | 609.7 | 131.2 | 17.0 | 898.0 | 141.7 | 13.9 |
| 12/8/2010 | 59 | 642.8 | 125.3 | 17.1 | 648.5 | 142.2 | 16.4 |
| 12/22/2010 | 73 | 762.3 | 140.2 | 17.3 | 926.9 | 165.5 | 15.9 |
| 1/5/2011 | 87 | 1359.9 | 1066.4 | 26.0 | 3155.1 | 731.6 | 24.0 |
| 1/19/2011 | 101 | 674.4 | 141.2 | 16.2 | 805.7 | 129.8 | 16.3 |
| 2/2/2011 | 115 | 1639.8 | 518.3 | 21.3 | 1951.5 | 566.8 | 20.7 |
| 2/17/2011 | 130 | - | - | - | 871.2 | 144.1 | 15.7 |
| 3/2/2011 | 143 | 546.0 | 104.1 | 16.4 | 516.6 | 105.1 | 16.9 |
| 3/18/2011 | 159 | 521.4 | 104.6 | 17.0 | 603.0 | 99.0 | 16.7 |
| 3/30/2011 | 171 | 570.7 | 116.2 | 17.2 | 602.4 | 99.7 | 16.7 |
| 4/13/2011 | 185 | 389.4 | 58.1 | 17.6 | 343.3 | 49.0 | 16.9 |
| 4/27/2011 | 199 | 389.5 | 58.4 | 17.1 | 314.5 | 51.9 | 17.4 |
| 5/12/2011 | 214 | 380.8 | 53.6 | 17.1 | 333.5 | 47.3 | 17.6 |
| 5/26/2011 | 228 | 426.6 | 64.3 | 17.2 | 318.5 | 50.2 | 17.5 |
| 6/8/2011 | 241 | 127.4 | 28.8 | 18.1 | 152.5 | 25.2 | 17.5 |
| 6/22/2011 | 255 | 152.6 | 27.6 | 18.5 | 140.7 | 24.5 | 17.5 |
| 7/6/2011 | 269 | 145.3 | 26.4 | 18.2 | 123.6 | 25.0 | 17.6 |
| 7/20/2011 | 283 | 168.4 | 27.6 | 17.5 | 167.8 | 27.6 | 18.3 |
| 8/3/2011 | 297 | 192.8 | 31.5 | 19.1 | 180.1 | 29.4 | 19.2 |
| 8/17/2011 | 311 | 136.7 | 26.1 | 19.4 | 175.2 | 28.3 | 17.9 |
| 8/31/2011 | 325 | 198.5 | 39.1 | 19.8 | 221.1 | 37.1 | 19.8 |
| 9/13/2011 | 338 | 210.2 | 39.4 | 20.5 | 168.3 | 38.9 | 19.6 |
| 9/27/2011 | 352 | - | - | - | - | - | - |
| 10/11/2011 | 366 | 594.4 | 95.8 | 18.8 | 426.8 | 79.7 | 18.1 |
| Average | | 493.5 | 125.6 | 17.7 | 609.4 | 114.1 | 17.1 |
| Std. Dev. | | 377.0 | 219.7 | 3.0 | 676.1 | 165.9 | 2.7 |

**Table B-3: Backcalculated Modulus Values for the Untreated Base Course Section**

| Date | Curing Time (days) | West Location | | | East Location | | |
|---|---|---|---|---|---|---|---|
| | | Asphalt | UTBC | Subbase/ Subgrade | Asphalt | UTBC | Subbase/ Subgrade |
| 10/10/2010 | 0 | - | - | - | - | - | - |
| 10/11/2010 | 1 | - | - | - | - | - | - |
| 10/14/2010 | 4 | - | - | - | - | - | - |
| 10/20/2010 | 10 | - | - | - | - | - | - |
| 10/26/2010 | 16 | - | - | - | - | - | - |
| 11/8/2010 | 29 | 549.2 | 101.1 | 17.5 | 576.6 | 100.3 | 17.7 |
| 11/23/2010 | 44 | 1107.2 | 182.9 | 14.7 | 567.0 | 146.6 | 16.4 |
| 12/8/2010 | 59 | 677.4 | 122.2 | 16.7 | 889.6 | 140.4 | 16.2 |
| 12/22/2010 | 73 | 747.3 | 126.6 | 15.5 | 966.6 | 149.7 | 15.2 |
| 1/5/2011 | 87 | 1847.0 | 2157.0 | 34.8 | 1806.6 | 1839.5 | 35.1 |
| 1/19/2011 | 101 | 826.6 | 132.4 | 16.9 | 835.8 | 162.2 | 16.4 |
| 2/2/2011 | 115 | 1233.8 | 725.4 | 26.0 | 1637.6 | 616.5 | 25.1 |
| 2/17/2011 | 130 | 680.1 | 147.4 | 17.7 | 736.2 | 144.4 | 17.4 |
| 3/2/2011 | 143 | 806.0 | 128.9 | 17.0 | 623.5 | 124.4 | 17.5 |
| 3/18/2011 | 159 | 626.0 | 102.8 | 18.0 | 618.0 | 107.6 | 17.8 |
| 3/30/2011 | 171 | 511.0 | 109.1 | 17.8 | 574.2 | 101.7 | 17.9 |
| 4/13/2011 | 185 | 333.6 | 53.2 | 17.8 | 230.6 | 47.5 | 17.1 |
| 4/27/2011 | 199 | 290.3 | 50.4 | 18.3 | 335.1 | 47.7 | 17.6 |
| 5/12/2011 | 214 | - | - | - | - | - | - |
| 5/26/2011 | 228 | 313.3 | 44.0 | 17.4 | 356.6 | 47.3 | 17.3 |
| 6/8/2011 | 241 | 255.7 | 30.3 | 18.5 | 134.7 | 23.2 | 19.1 |
| 6/22/2011 | 255 | 124.6 | 22.5 | 19.0 | 133.7 | 23.9 | 18.9 |
| 7/6/2011 | 269 | 119.0 | 23.8 | 19.2 | 115.5 | 26.0 | 19.5 |
| 7/20/2011 | 283 | 130.2 | 29.8 | 20.4 | 140.0 | 27.0 | 20.0 |
| 8/3/2011 | 297 | 166.4 | 31.7 | 19.9 | 164.6 | 27.1 | 20.6 |
| 8/17/2011 | 311 | 131.9 | 27.6 | 19.2 | 144.1 | 29.6 | 20.6 |
| 8/31/2011 | 325 | 190.1 | 39.3 | 20.6 | 193.3 | 32.5 | 20.3 |
| 9/13/2011 | 338 | 201.6 | 42.6 | 18.9 | 190.2 | 34.9 | 21.3 |
| 9/27/2011 | 352 | - | - | - | - | - | - |
| 10/11/2011 | 366 | 501.9 | 100.8 | 16.6 | 494.0 | 92.1 | 19.3 |
| Average | | 537.8 | 197.0 | 19.1 | 541.9 | 177.9 | 19.3 |
| Std. Dev. | | 429.2 | 450.5 | 4.1 | 459.2 | 382.3 | 4.0 |