2007-03-21

Early Age Assessment of Cement Treated Materials

Tyler B. Young
Brigham Young University - Provo

EARLY-AGE STRENGTH ASSESSMENT OF CEMENT-TREATED BASE MATERIAL

by

Tyler Blaine Young

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirement for the degree of

Master of Science

Department of Civil and Environmental Engineering

Brigham Young University

April 2007

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Tyler Blaine Young

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

Date	W. Spencer Guthrie, Chair
Date	Mitsuru Saito
Date	Norman L. Jones

BRIGHAM YOUNG UNIVERSITY

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

Date

W. Spencer Guthrie
Chair, Graduate Committee

Accepted for the Department

E. James Nelson
Graduate Coordinator

Accepted for the College

Alan R. Parkinson
Dean, Ira A. Fulton College of Engineering and Technology

ABSTRACT

EARLY-AGE STRENGTH ASSESSMENT OF

CEMENT-TREATED BASE MATERIAL

Tyler Blaine Young

Department of Civil and Environmental Engineering

Master of Science

In order to avoid the occurrence of early-age damage, cement-treated base (CTB) materials must be allowed to cure for a period of time before the pavement can be opened to traffic. The purpose of this research was to evaluate the utility of the soil stiffness gauge (SSG), heavy Clegg impact soil tester (CIST), portable falling-weight deflectometer (PFWD), dynamic cone penetrometer, and falling-weight deflectometer for assessing early-age strength gain of cement-stabilized materials. Experimentation was performed at four sites on a pavement reconstruction project along Interstate 84 near Morgan, Utah, and three sites along Highway 91 near Richmond, Utah; cement stabilization was used to construct CTB layers at both locations. Each site was stationed to facilitate repeated measurements at the same locations with different devices and at different curing times.

Because of the considerable attention they have received in the pavement construction industry for routine quality control and quality assurance programs, the SSG, CIST, and PFWD were the primary focus of the research. Statistical techniques were utilized to evaluate the sensitivity to curing time, repeatability, and efficiency of

these devices. In addition, the ruggedness and ease of use of each device were evaluated. The test results indicate that the CIST data were more sensitive to curing time than the SSG and PFWD data at the majority of the cement-treated sites during the first 72 hours after construction. Furthermore, the results indicate that the CIST is superior to the other instruments with respect to repeatability, efficiency, ruggedness, and ease of use. Because the CIST is less expensive than the SSG and PFWD, it is more likely to be purchased by pavement engineers and contractors involved with construction of CTBs. For these reasons, this research suggests that the CIST offers greater overall utility than the SSG or PFWD for monitoring early-age strength gain of CTB. Further research is needed to identify appropriate threshold CIST values at which CTB layers develop sufficient strength to resist permanent deformation or marring under different types of trafficking.

ACKNOWLEDGMENTS

The author wishes to express sincere thanks and appreciation to Dr. Spencer Guthrie for providing invaluable insight and direction throughout the course of this research. Appreciation is also extended to Dr. Mitsuru Saito and Dr. Norman Jones for serving on the graduate committee.

The author also wishes to thank Dr. David Luhr of the Portland Cement Association for funding this research and the Utah Department of Transportation for allowing access to the two pavement reconstruction sites evaluated in this work. The author also expresses thanks to Dr. Maureen Kestler of the Forest Service for providing the PFWD utilized in the study. In addition, appreciation is extended to fellow students Brandon Blankenagel, Scott Chambers, Dane Cooley, Russell Lay, and Robert Tuttle for assisting with the huge task of collecting field data.

Last but not least, heartfelt gratitude is extended to the author's wife, Camila Jane Young, whose continual support and encouragement have enabled him to complete this phase of his education.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1 PROBLEM STATEMENT

Cement-stabilized roadbed materials have been successfully used in pavements for over 85 years (*1*). A cement-treated base (CTB), sometimes called soil-cement or cement-stabilized aggregate base, is a mixture of pulverized soil or crushed stone material, Portland cement, and water that is compacted to high density. As the cement hydrates, the mixture becomes a hard, durable paving material (*2*). In order to avoid the occurrence of early-age damage, CTB materials must be allowed to cure for a period of time before the pavement can be opened to traffic. Trafficking of a cement-treated material before sufficient strength gain has occurred can lead to marring and permanent deformation of the layer. For this reason, many transportation agencies require a 7-day curing period before a cement-treated layer may be opened to traffic (*3*). While this conservative approach avoids damage to the newly constructed CTB, it can delay construction, increase project costs, and cause greater inconvenience to the traveling public. Consequently, a reliable method is needed for determining when a newly constructed cement-treated roadway has achieved sufficient strength to prevent damage under early trafficking.

The purpose of this research was therefore to evaluate the utility of selected equipment available to pavement engineers and contractors for assessing susceptibility to bearing-capacity failure or excessive permanent deformation in cement-stabilized materials under traffic loading. In particular, the utility of individual devices for monitoring the strength gain of cement-stabilized materials immediately following construction was investigated.

1.2 SCOPE

The equipment utilized in this research for assessing the early-age strength gain of CTB included a soil stiffness gauge (SSG), heavy Clegg impact soil tester (CIST), dynamic cone penetrometer (DCP), portable falling-weight deflectometer (PFWD), and falling-weight deflectometer (FWD). Several parameters were used to evaluate each instrument, including sensitivity, repeatability, efficiency, ruggedness, and ease of use. Sensitivity is defined in this research as the degree to which instrument readings are correlated to CTB curing time. Repeatability is the relative proximity of repeated measurements to each other. Efficiency reflects the number of readings required to estimate the true value, or population mean, from the sample mean at specified tolerance and reliability levels. Ruggedness is a measure of the degree to which instrument readings are influenced by small variations in procedures or other testing conditions. Ease of use reflects the simplicity, speed, and operator comfort associated with instrument use.

These parameters are discussed in depth throughout the report and are the basis for the instrument comparisons performed in this study. The evaluations were conducted on two pavement reconstruction sites in northern Utah. The first was Interstate 84 (I-84) near Morgan, Utah, and the second was Highway 91 (US-91) near Richmond, Utah.

1.3 OUTLINE OF REPORT

This report consists of five chapters. Chapter 1 presents the objectives and scope of the research. In Chapter 2, descriptions are given for all of the instruments utilized in this study for assessing the mechanical properties of CTB materials. The procedures utilized in the research are explained in Chapter 3, and test results are discussed in Chapter 4. Chapter 5 contains a summary of the procedures, findings, and recommendations.

CHAPTER 2

MECHANICAL EVALUATION OF AGGREGATE LAYERS

2.1 OVERVIEW

Several destructive and non-destructive test devices are available for assessing the strength or stiffness of aggregate base materials. This chapter describes each of the five devices that were analyzed in this research, including the SSG, heavy CIST, DCP, PFWD, and FWD. The descriptions focus on properties related to the utility of each instrument for measuring early-age CTB strength gain.

2.2 SOIL STIFFNESS GAUGE

The SSG is a portable instrument weighing 25 lb and having a height and diameter of 12 in. and 11 in., respectively, as depicted in Figure 2.1. This device measures stiffness at the soil surface by imparting very small displacements, on the order of 0.00005 in., to the soil on a ring-shaped foot with a 3.5-in. inside diameter and 4.5-in. outside diameter (*4*, *5*). A thin layer of moist sand should be placed on the ground as bedding for the SSG foot, and the device should be removed and replaced between readings (*6*). According to the manufacturer, at least 60 percent of the foot should be in contact with the ground to facilitate a valid measurement. Testing is conducted via a harmonic oscillator that operates at 25 steady-state frequencies between 100 Hz and 196 Hz (*4*, *5*). Collection of data across this frequency spectrum requires about 1 minute and permits digital filtering of noise. Because preparing the ground, placing the sand, and seating the instrument also requires about 1 minute, the total time required per reading is about 2 minutes. The stiffness is determined at each frequency as the ratio of the force to the displacement and then averaged over all of the frequencies (*4*, *5*). The SSG is reportedly sensitive to depths of between 9 in. and 12 in. (*4*).

FIGURE 2.1 Soil stiffness gauge with bucket of moist sand.

Special care must be taken to ensure that the instrument is not disturbed when testing is in progress. Precautions recommended for preventing interference while measurements are being conducted include stepping away from the instrument, ensuring that no traffic passes by the instrument, and eliminating as many other ground vibrations as possible. This may be rather difficult due to the dynamic nature of most construction sites. A SSG costs approximately $6,000.

2.3 HEAVY CLEGG IMPACT SOIL TESTER

The heavy CIST is comprised of a 44-lb steel drop weight confined inside a 6-in.-diameter cylindrical metal guide tube mounted on wheels as shown in Figure 2.2. The weight has a hardened steel strike face and is instrumented with an accelerometer connected to a digital display unit. A 12-in. drop height is used for the heavy CIST, and the peak deceleration of the hammer upon impact is reported as the Clegg impact value (CIV), where 1 CIV is equivalent to 10 times the acceleration rate of gravity. Four successive blows of the hammer at the same location constitute one test, which can be completed in less than 30 seconds by a single operator. Because the CIST is equipped

FIGURE 2.2 Heavy Clegg impact soil tester.

with wheels, relatively quick transport between testing stations is possible. The depth of interrogation may be estimated to be about two times the diameter of the drop weight, or about 12 in. for this hammer (*7*). The heavy CIST costs about $3,000.

2.4 DYNAMIC CONE PENETROMETER

The DCP is comprised of a 17.6-lb dual-mass slide hammer assembly used to manually drive a standard cone tip to a maximum depth of 39 in. into the ground. The penetration in inches per blow is reported as a function of depth. The DCP is displayed in Figure 2.3. For the greatest ease of operation, two operators perform a manual DCP test. One person lifts and drops the weight, while the other person measures and records penetration. Depending on the resistance of the ground, tests may require 5 minutes to 10 minutes each. Disposable cone tips are available to facilitate easier DCP removal in very stiff soils that may otherwise require significant extraction effort. In soils with large aggregate particles, the DCP may begin to penetrate the soil at an angle as the cone tip is driven around a stone in its path. When the DCP handle deviates laterally more than 6 in.

FIGURE 2.3 Dynamic cone penetrometer.

from its original vertical position, the test should be stopped, and a second test should be attempted at a different location (*8*). The DCP costs about $2,000.

2.5 PORTABLE FALLING-WEIGHT DEFLECTOMETER

The PFWD shown in Figure 2.4 is comprised of a manually-operated slide hammer assembly capable of imparting approximately 4,000 lb of force to the ground. One sensor positioned at the center of the load plate measures deflection directly under the load, and two additional sensors affixed to a detachable sensor bar measure deflections at radial distances between 12 in. and 24 in. from the center of the load plate (*9*). A load cell measures the actual load generated by the falling weight during a test, and the load and deflection data are recorded in spreadsheet format on a handheld

FIGURE 2.4 Portable falling-weight deflectometer.

computer. If the layer thicknesses are known, the measured loads and deflections can be used to compute the modulus values of the tested layers using computer software such as BAKFAA.

Before each use, some assembly is required for the PFWD. The load plate, handle, and drop weight must be attached, and the sensors must be connected. Especially when the PFWD is manually carried between test locations, the sensor bar must be removed and reconnected at each site to avoid damaging the sensor wires. Because the PFWD is difficult to manually carry, a specially manufactured cart can be purchased for more easily transporting the PFWD between test locations. The cost of the PFWD is about $15,000, depending on the number of options purchased with the system.

2.6 FALLING-WEIGHT DEFLECTOMETER

The FWD is a truck- or trailer-mounted pavement evaluation apparatus that measures deflections of the pavement surface in response to impulse loads of magnitudes similar to truck traffic. In this case, seven deflection sensors are placed at specified radial distances from the loading plate, commonly 0 in., 8 in., 12 in., 18 in., 24 in., 36 in., and 60 in. (*10*). As with analysis of PFWD data, computer software can be used to compute the modulus values of the pavement layers if the thicknesses of the pavement layers are known. Figure 2.5 depicts an FWD.

Because of the heavy loads employed in FWD testing, the full depth of the pavement structure is usually within the zone of test influence. A single driver can conduct a test in less than 1 minute, although a second person often participates in the testing to ensure that the loading plate is positioned at the desired location. Because an FWD is expensive to purchase, government agencies and large firms are the primary owners; the only FWD in Utah is owned by the Utah Department of Transportation (UDOT), and the cost of that unit cost was approximately $120,000.

FIGURE 2.5 Falling-weight deflectometer.

2.7 SUMMARY

This chapter describes several destructive and non-destructive devices, including the SSG, CIST, DCP, PFWD, and FWD, available for assessing the strength or stiffness of pavement materials. While the operational characteristics and costs vary among the devices, they each have the potential to monitor early-age strength gain of CTB layers through time.

CHAPTER 3
PROCEDURES

3.1 OVERVIEW

This chapter provides descriptions of both the I-84 and US-91 sites tested in this research, as well as details of the field testing protocols utilized at each location. In addition, laboratory testing procedures and statistical analyses performed in the project are described.

3.2 SITE DESCRIPTIONS

This section contains descriptions of the I-84 site near Morgan, Utah, and the US-91 site near Richmond, Utah. Site conditions, construction procedures, and locations are discussed.

3.2.1 Interstate 84

The locations of the I-84 test sites are depicted in Figure 3.1. This section of road is located in Weber Canyon as shown in Figure 3.2. Research was conducted at four sites within the eastbound lanes over a distance of approximately 4 miles during June and July 2004. The I-84 reconstruction plan required the use of cement stabilization in conjunction with full-depth reclamation. In this process, a deteriorated asphalt pavement is pulverized in situ, and the resulting reclaimed asphalt pavement (RAP) is blended with a portion of the underlying base material and a specified quantity of cement to produce a CTB. The addition of Portland cement to the pulverized RAP and aggregate base material increases the strength and stiffness of the base layer, enabling improved bridging capacity over lower layers (*11*). This process thus creates a very attractive cement-based product when considering economic, environmental, and engineering perspectives.

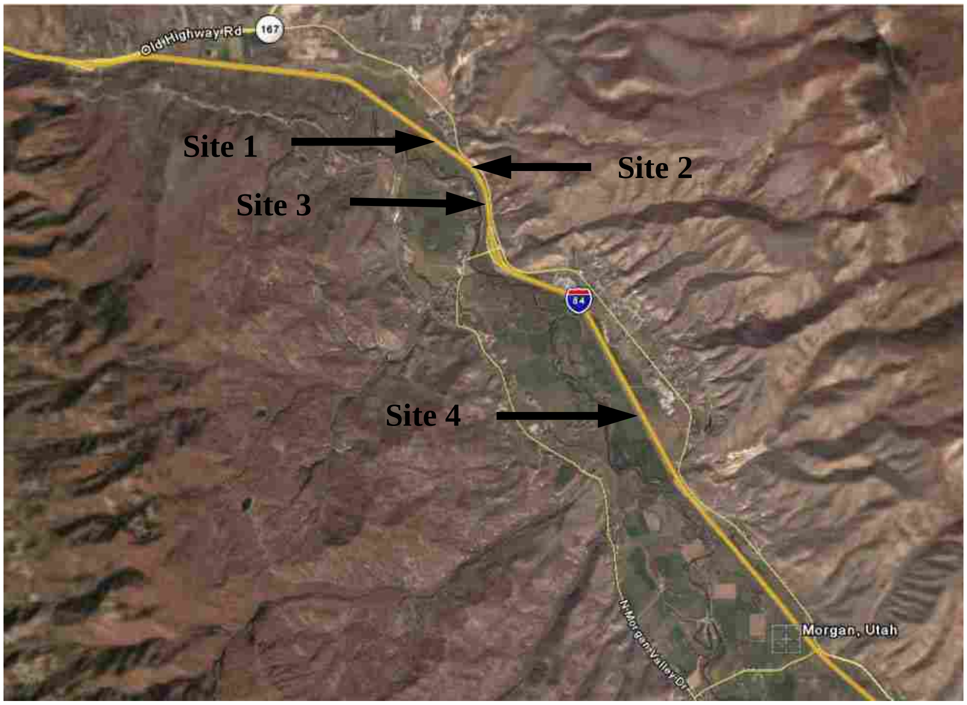

FIGURE 3.1 Map of I-84 (*12*).

FIGURE 3.2 I-84 site picture.

According to historical design records and ground-penetrating radar data obtained for the I-84 site, the original pavement structure, which was built in 1978, included an asphalt layer between 8 in. and 10 in. thick, a granular base layer between 6 in. and 8 in. thick, and a cement-stabilized subbase between 8 in. and 10 in. thick overlying the native subgrade soil. The pavement rehabilitation plan required removal of the upper 4 in. of asphalt by milling and pulverization of the next 4 in. to 6 in. of asphalt with sufficient base to achieve a total pulverization depth of 8 in. in one pass of a reclaimer. Thus, the ratio of RAP to base by thickness ranged from approximately 50:50 to 75:25. The blended material was then compacted and graded to within 0.75 in. of the final grade to be achieved following cement treatment.

Two percent Portland cement by weight of dry aggregate was placed with a spreader and then mixed with the pulverized base material in a second pass of the reclaimer as illustrated in Figure 3.3. The cement content was specified by UDOT engineers based on past experience with similar materials and the practices of other state departments of transportation in the region. Mixing water was introduced to the material in the pulverizing chamber, and compaction immediately followed.

FIGURE 3.3 Reclaimer with water truck.

3.2.2 Highway 91

The locations of the US-91 test sites are depicted in Figure 3.4, and Figure 3.5 is a picture of this location. Research on US-91 was performed at three locations within the southbound lanes over a distance of approximately 1 mile during August 2005. At this location, US-91 was originally a composite pavement comprised of a concrete layer overlain by asphalt. The reconstruction plan required milling and removal of the original asphalt layer and rubblization of the underlying concrete, which was then bladed to the side of the road. The original base layer and subgrade were then excavated an additional 2 ft below the bottom of the original concrete layer in order to facilitate a thicker pavement structure upon reconstruction.

Once the excavation was completed, the rubblized concrete was bladed back onto the roadway, compacted on top of the newly exposed subgrade, and overlain with an 8-in. layer of granular base material. This granular material was compacted and graded in preparation for the addition of cement. Two percent Portland cement by weight of dry aggregate was placed with a spreader and then mixed with the base material using a reclaimer to form the CTB. As on the I-84 site, water was introduced during CTB

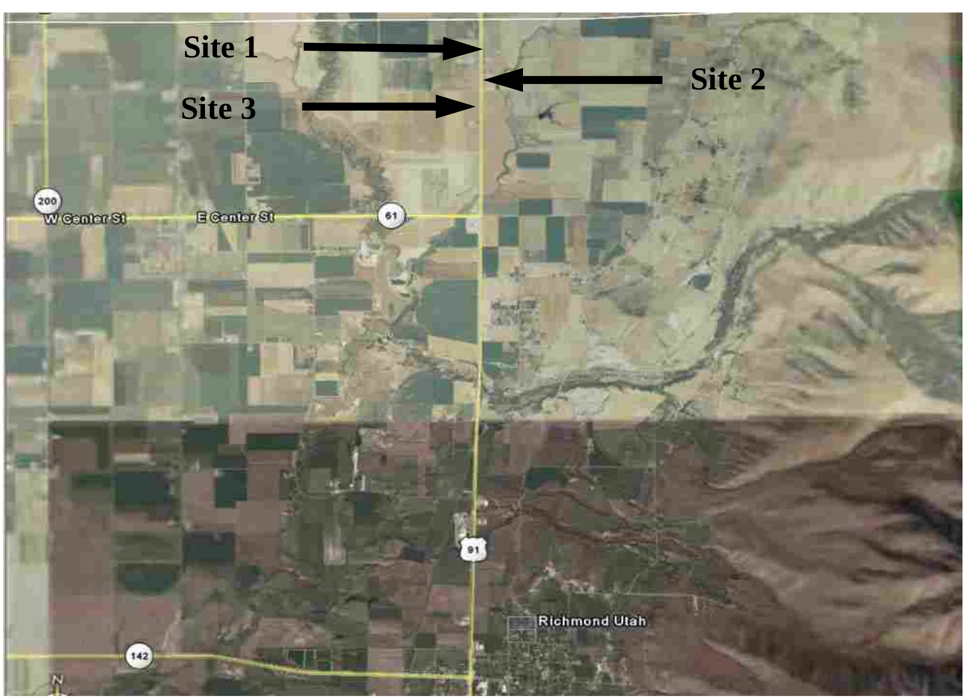

FIGURE 3.4 Map of US-91 (*12*).

FIGURE 3.5 US-91 site picture.

mixing, and compaction followed immediately afterwards. The full depth of the granular base layer was treated to achieve an 8-in-thick CTB.

3.3 FIELD TESTS

This section describes the field testing procedures utilized at the I-84 and US-91 sites.

3.3.1 Interstate 84

The first evaluations of the SSG, CIST, DCP, and FWD were performed along I-84 just east of Morgan, Utah, in late June 2004. The PFWD was not available for testing at this site. A total of four sites were selected along the construction corridor for this research. Sites 1, 2, and 3 were selected and tested after the CTB was compacted, while site 4 was an untreated section tested during the interim between the first and second passes of the reclaimer. At each site, stationing from 0 ft to 100 ft was marked at 20-ft intervals in a line down the middle of the road as shown in Figure 3.6. The stationing facilitated repeated measurements at the same locations at sites 1, 2, and 3, which were

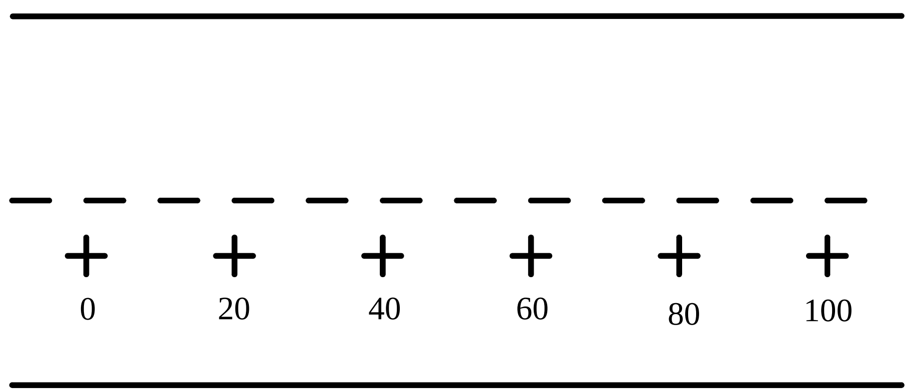

FIGURE 3.6 Typical site layout.

monitored for 6 days, 6 days, and 5 days, respectively. A single set of measurements was obtained from site 4 to characterize the untreated material. The area immediately around each of the three cement-treated sites was deliberately not sprayed with a prime coat in order to provide easy access to the test locations and to prevent possible fouling of the testing equipment.

At each station, two measurements were obtained with the SSG, three with the CIST, and one with the DCP at each testing time. The numbers of replicate measurements obtained at each station with each device were selected to approximately equalize the time required to obtain measurements with each device at each site. Figure 3.7 depicts the layout of a typical station within an approximately 4-ft-diameter testing zone. Within this zone, repeated SSG tests were all performed at the same locations as previous tests, while repeated testing using the CIST and DCP required testing at new locations; in the latter two cases, subsequent tests were conducted just adjacent to previous test locations.

Performing CIST and DCP tests in different locations than previous tests was required because the testing altered the soil; the CIST often created a footprint in the surface of the CTB, and the DCP left a hole. DCP test locations were therefore deliberately separated from the SSG and CIST test locations to minimize the potential impact of soil disturbance by the DCP on SSG and CIST measurements. Also, due to the reported sensitivity of the SSG measurements to environmental noise, the CIST and DCP tests were performed at a minimum distance of 40 ft from an active SSG test. Except for

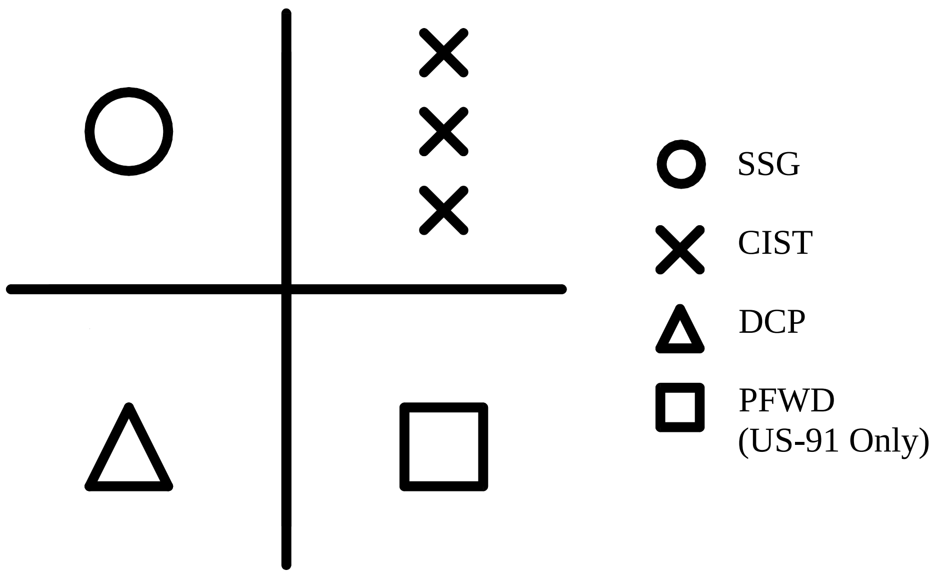

FIGURE 3.7 Typical station layout.

FWD testing, measurements with the various devices were obtained simultaneously at each site by four researchers working individually or in teams, depending on the testing needs. All four researchers were equally trained to operate each device and were arbitrarily assigned to different test devices at each site each time data were collected. Simultaneous testing was performed to ensure that measurements obtained from separate devices were representative of the same CTB curing condition; this enabled direct comparison of the measurements at each time interval.

FWD measurements were performed by UDOT personnel at each site, but not at locations always coinciding with the experimental stations defined for this research. The testing protocol for the FWD specified the use of two load levels, one at approximately 8 kips and the other at approximately 10 kips; this protocol enabled calculation of the modulus values at a load of exactly 9 kips, or half of an equivalent single axle load. The deflection sensors were spaced at 0 in., 8 in., 12 in., 18 in., 24 in., 36 in., and 60 in. from the center of the load plate. At each site, the number of tests performed varied between 12 and 80 at each testing time.

3.3.2 Highway 91

Testing of US-91 between Richmond, Utah, and the northern Utah border included the SSG, CIST, DCP, and PFWD. Due to scheduling conflicts, the FWD was not available for testing at this site. The field testing performed at the US-91 location followed the procedures utilized at the I-84 location but with a few modifications to improve the efficiency of the work and the quality of the measurements. First, in order to provide consistency in measurements and data, three tests were conducted with the SSG, CIST, and PFWD at each test location. Second, based on experience at the I-84 site, the researchers determined that fewer readings would be required with the DCP; therefore, DCP readings were taken less frequently at the US-91 site.

Three sites were selected along the construction corridor for this research, all of which were monitored for 7 days following compaction of the CTB. The sites were stationed similar to the I-84 site, and initial readings were obtained almost immediately after the compactor had made its final pass. Again, the area was not sprayed with a prime coat in order to ensure easy access, but the testing sites were covered with plastic to provide ideal curing conditions during the monitoring. Figure 3.8 depicts the curing plastic temporarily rolled away to facilitate testing. Otherwise, the testing proceeded exactly as described earlier for the I-84 site, with measurements taken according to the layout given in Figure 3.7. As with the SSG testing, repeated PFWD tests were performed at the same locations as previous tests, while repeated testing using the CIST and DCP required testing at new locations.

At site 2, the cement content was measured at stations 0 ft, 20 ft, and 60 ft to verify the actual amount of cement applied. As displayed in Figure 3.9, square sheets of plastic were placed on the CTB surface prior to the passing of the cement truck, and the cement spread onto the sheet was then transferred into a bucket and weighed as shown in Figure 3.10. The cement content was then determined by dividing the cement weight by the estimated weight of dry aggregate beneath the sheet. Compaction to 90 percent of the maximum dry density (MDD) and a treatment depth of 8 in. were assumed in the calculations.

FIGURE 3.8 Curing plastic.

FIGURE 3.9 Sampling cement.

FIGURE 3.10 Weighing cement.

3.4 LABORATORY TESTS

In addition to field monitoring of early-age CTB strength gain, laboratory sieve analyses, compaction tests, and unconfined compressive strength (UCS) tests were performed on material samples removed from both sites as described in the following sections.

3.4.1 Sieve Analyses

Samples of the RAP and original base material were obtained from the I-84 project, and samples of the granular base material were obtained from the US-91 project. All of the materials were dried at 140ºF and then separated across the following sieves: 0.75 in., 0.50 in., 0.375 in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200.

Separation of the materials in this manner enabled precise recombination of different particle sizes to produce replicate specimens having the same gradations as the bulk materials.

3.4.2 Compaction Tests

Compaction tests were performed to determine the optimum moisture content (OMC) and MDD associated with each material. Specimens of 4-in. diameter and 4.6-in height were prepared using modified Proctor compaction and a 50:50 weight ratio of RAP to base material with 2 percent Portland cement.

Aggregate particles coarser than the No. 4 sieve were soaked for 24 hours before compaction to ensure full water absorption, and Type I/II Portland cement was added as dry powder to the aggregate fines just before they were mixed with the moistened coarse aggregate. Immediately after mixing was completed, the samples were compacted. Specimen height measurements were made using a digital micrometer, and moisture contents were determined after 24 hours of drying at 230ºF. Figures 3.11 and 3.12 depict sample preparation and compaction, respectively.

FIGURE 3.11 Preparing a sample.

FIGURE 3.12 Compacting a sample.

3.4.3 Unconfined Compressive Strength Tests

UCS tests were performed daily from 0 to 7 days on laboratory-mixed specimens, with two or three replicate specimens evaluated on each day. The specimens were cured at 100 percent relative humidity and then capped with high-strength gypsum before being subjected to strength testing. The testing was performed at a constant strain rate of 0.05 in./minute in a computer-controlled mechanical press with a floating head. Figure 3.13 depicts the compression machine.

A limited amount of field-mixed material was also obtained from the I-84 and US-91 sites and compacted on site using manually operated, modified Proctor hammers. These specimens were cured in sealed plastic bags and subjected to the same UCS testing as the laboratory specimens. This testing was performed to enable approximate

FIGURE 3.13 Unconfined compressive strength testing.

correlations between UCS and the various measurements obtained from the field sites through time.

3.5 DATA ANALYSES

Although the SSG and CIST data did not require post-processing, the PFWD and FWD data were analyzed using software as described in Chapter 2. This section describes the modulus back-calculation procedures associated with the use of BAKFAA, as well as all of the statistical methods utilized in this research, including regression analyses, standard deviation and coefficient of variation (CV) computations, analysis of variance (ANOVA), and prediction intervals.

3.5.1 Deflectometer Data Reduction

Modulus values for the CTB and subbase layers were back-calculated from the FWD data collected at the I-84 sites and the PFWD data collected at the US-91 sites using BAKFAA computer software. BAKFAA is a software package developed by the Federal Aviation Administration for back-calculation of pavement layer modulus values.

For all sites, a two-layer model was used, in which Poisson's ratios for the CTB and subbase/subgrade materials were assumed to be 0.15 and 0.35, respectively (*13*). The CTB layer thickness was input as 8 in., and deflections measured by all of the sensors on each device were used in the back-calculation process. For the FWD testing, layer modulus values associated with a 9-kip load were determined by linear interpolation between the modulus values obtained under the approximately 8-kip and 10-kip loads.

3.5.2 Regression Analyses

The quantitative method selected to evaluate sensitivity, or the correlation of field measurements to curing time, was regression analysis. A regression analysis is used to predict the value of the response variable from the values of other variables through development of a mathematical equation that describes the relationship. In each case, a linear regression was performed for each data set using the simple general model $y = mx + b$. For each regression, the coefficient of determination (R^2) was computed using Equation 3.1:

$$R^2 = \frac{[\text{cov}(x, y)]^2}{s_x^2 \cdot s_y^2} \qquad (3.1)$$

where R^2 = coefficient of determination

$\text{cov}(x, y)$ = covariance between *x* and *y* variables

s_x = standard deviation of *x* variable

s_y = standard deviation of *y* variable

The R^2 value describes the fraction of variation in the dependent, or response, variable that can be explained by variation in the independent variable (*14*). The primary use of regression analysis in this research was to determine if the instruments readings were sensitive to curing time.

3.5.3 Standard Deviation and Coefficient of Variation Computations

Repeatability is a measure of the variability between independent test results obtained on the same experimental material and may generally be evaluated by considering the standard deviation or CV of repeated measurements (*15*). In this research, the standard deviation for a given set of readings was computed at a particular time from the six test means corresponding to the six test locations within each test site. While this approach jointly evaluates both spatial variability at each site and instrument variability, spatial variability was assumed to be the same from station to station for measurements taken with different devices. Because repeated CIST measurements, in particular, must be performed at different locations as described previously, some degree of confounding of instrument and spatial variability was inevitable.

The relationships between the averages and standard deviations for the SSG, CIST, and PFWD were then evaluated to compare numerical scales and to investigate the occurrence of heteroskedasticity, the statistical term given to describe an increasing variation, or scatter, of the response variable with increasing values of the independent variable (*16*). To compensate for the effects of differing scales and heteroskedasticity, the CV was used to compare the repeatability of the devices.

3.5.4 Analysis of Variance

A statistical test that can be used to determine whether or not two or more population means are different is the ANOVA. In this test, the averages and variances of samples taken from each population were considered to make specific inferences about the populations (*17*). The populations in this case were the sets of CVs associated with all possible SSG, CIST, and PFWD data hypothetically collected at each research site. In this research, the null hypothesis in each test was that the mean CVs were equal, and the alternative hypothesis was that they were not equal.

3.5.5 Prediction Intervals

Because variation inevitably occurs from observation to observation on the same experimental material, replications are necessary to reduce the variation of the average sample response from the "true" value, or population mean. With a greater sample size obtained by taking increased numbers of readings, an operator may have greater confidence that the sample average is more representative of the population mean (*16*). In the case of CTB monitoring, the greatest challenge associated with obtaining large sample sizes is the time and accompanying cost involved with more extensive testing.

To facilitate identification of the most efficient instrument for testing CTB layers, the numbers of readings that would be required to characterize a given CTB layer at a specified confidence level and within specified tolerances were calculated for different instruments from the US-91 data. Specifically, Equation 3.2 was used to calculate the numbers of SSG, CIST, or PFWD test locations that would be required to satisfactorily characterize a given CTB construction section (*16*):

$$n = \left(\frac{Z \cdot s}{\Delta x} \right)^2 \qquad (3.2)$$

where $n =$ number of required test locations

$Z =$ two-tailed probability statistic from the standard normal distribution

$s =$ standard deviation

$\Delta x =$ specified tolerance

An important assumption associated with this equation is that measurements come from normally distributed populations. In this application, all possible measurements hypothetically collected with a given device within a particular construction section can be treated as a population. At the I-84 and US-91 locations, each construction section was about 40 ft wide and 1000 ft in length, corresponding to the area that could be covered with one load of cement by the distributor truck operator. Given the similar material compositions and the controlled construction procedures within each section, the assumption of normally distributed data is reasonable.

In this research, the average of three replicate measurements collected at a given test location and time was assumed to constitute a single observation, the value of *Z* was specified in accordance with 95 percent reliability, and three potential tolerance values were selected for each instrument. The population standard deviation was estimated using field data collected in this project. If the estimate of the standard deviation were too low, then too few readings might be taken to establish the reading within the desired levels of tolerance and reliability. Conversely, if the estimate of the standard deviation were too high, then collection of a few additional readings would be the only consequence. A conservative estimate was therefore utilized in this study.

To minimize the effects of heteroskedasticity in the estimations, analyses were conducted to determine whether transformations of the instrument readings were necessary, and the data were adjusted as needed. The relationships between the means and standard deviations of the data collected using each instrument were then evaluated, where the mean was calculated as the average of the measurements obtained from all six of the test locations at a particular test site and time and the standard deviation was computed at a particular time from the six test means corresponding to the six test locations within each test site.

While a standard regression analysis of the relationship between mean values and corresponding standard deviations could have been used to estimate the standard deviation associated with a given instrument reading, such an approach would have yielded an estimate of standard deviation that was too low half of the time. Under-estimating the standard deviation would have potentially led to inadequate test reliability caused by testing of too few locations.

Therefore, a 90 percent prediction interval was constructed for the expected standard deviation as a function of instrument value. This 90 percent prediction interval includes upper and lower bounds for the dependent variable, standard deviation in this case, for every value of the independent variable, or test mean. So, with the prediction interval set at 90 percent, 10 percent of the data are outside of the bounds, with 5 percent being outside the upper bound and 5 percent being outside the lower bound. Therefore, for the purposes of this research, use of the upper bound for prediction of the standard deviation yields a 95 percent reliability level. The general equation for constructing the upper bound of a prediction interval for a linear regression is given below as Equation 3.3 (*16*):

$$y_{ub} = \hat{y} + t_{\frac{\alpha}{2}} \cdot s_{\varepsilon}\sqrt{1 + \frac{1}{n} + \frac{(x - \bar{x})^2}{S_{xx}}} \tag{3.3}$$

where y_{ub} = predicted value of the upper bound of the dependent variable y

$\hat{y}$ = estimated value of y from linear regression

$t_{\frac{\alpha}{2}}$ = probability statistic from the t-distribution having degrees of freedom $n-2$

$s_{\varepsilon} = \sqrt{\frac{\sum (y - \hat{y})^2}{n-2}}$

y = measured value of the dependent variable

n = number of observations of x

x = value of the independent variable

$\bar{x}$ = mean of the measured values of x

$S_{xx} = \sum (x - \bar{x})^2$, where x represents measured values of the independent variable

Since the minimum values of SSG, CIST, and PFWD readings for opening a CTB layer to traffic have not yet been established for specific vehicle types, graphs showing the number of suggested readings for each instrument were developed over a range of values.

3.6 SUMMARY

This research focused on two pavement reconstruction projects, I-84 and US-91. Both laboratory and field testing were conducted at both locations. Laboratory testing included sieve analyses, compaction tests, and UCS tests. The field testing was designed to monitor early-age strength gain of the CTB layers at each site and included the SSG, CIST, DCP, PFWD, and FWD. Statistical procedures were utilized to analyze the collected data and included regression analyses, standard deviation and CV computations, ANOVA, and prediction intervals.

CHAPTER 4
RESULTS

4.1 OVERVIEW

This chapter contains all of the research results. Laboratory and field results are presented together with analyses of sensitivity, repeatability, efficiency, ruggedness, and ease of use for the tested instruments.

4.2 LABORATORY TESTS

This section contains all laboratory test results for this research, including sieve analyses, compaction test results, and UCS test results.

4.2.1 Sieve Analyses

Particle-size distributions for the I-84 and US-91 materials are shown in Figures 4.1 and 4.2, respectively. These gradations were followed in preparation of replicate CTB specimens in the laboratory.

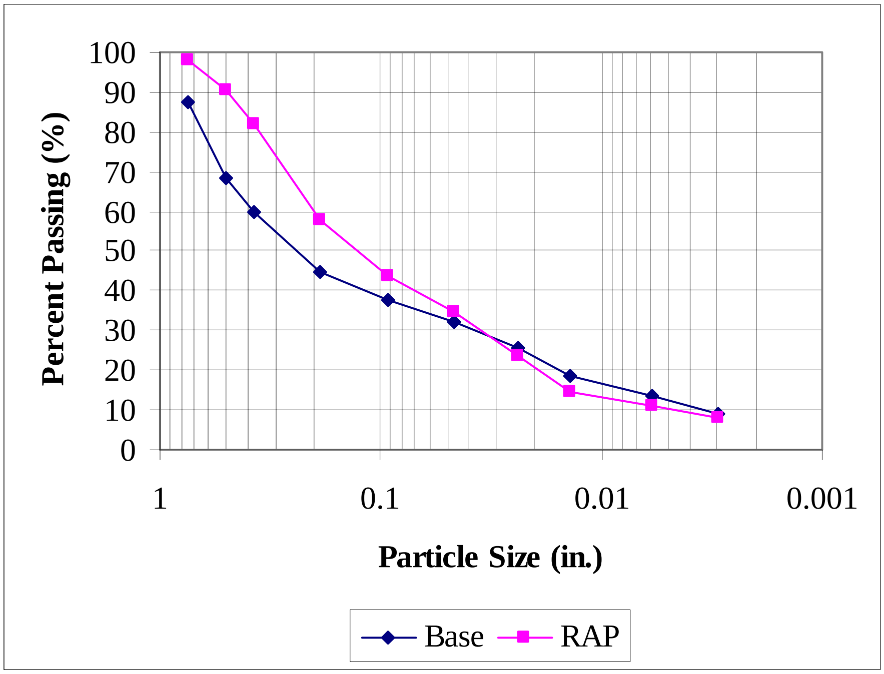

FIGURE 4.1 Gradations for I-84 base and RAP materials.

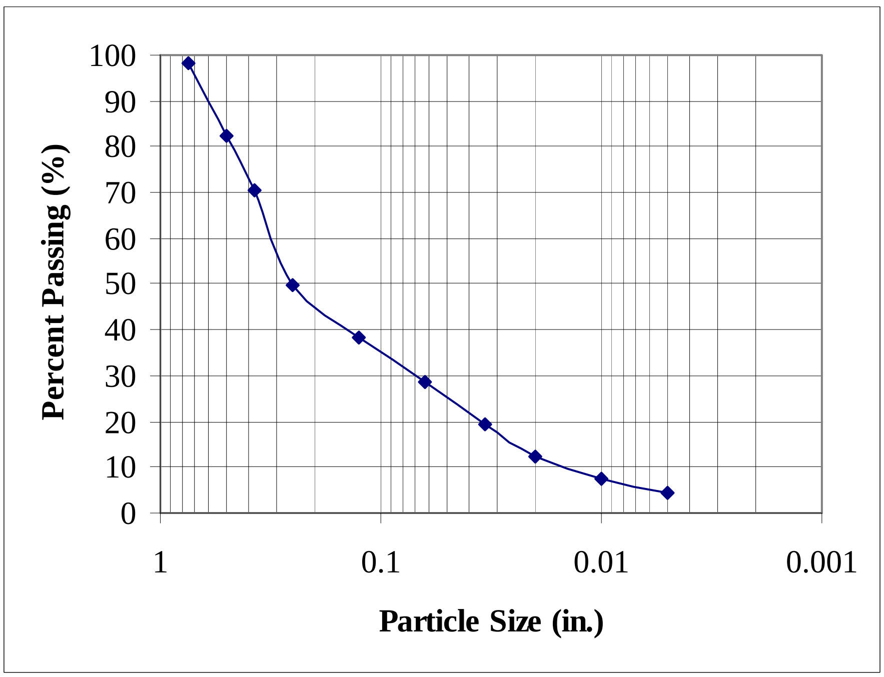

FIGURE 4.2 Gradation for US-91 base material.

4.2.2 Compaction Tests

The dry densities of compacted samples were plotted against gravimetric moisture contents as shown in Figures 4.3 and 4.4 for the I-84 and US-91 sites, respectively. For the I-84 material, the OMC was 5.7 percent, and the MDD was 130.6 pcf. For the US-91 material, the OMC was 6.3 percent, and the MDD was 139.3 pcf.

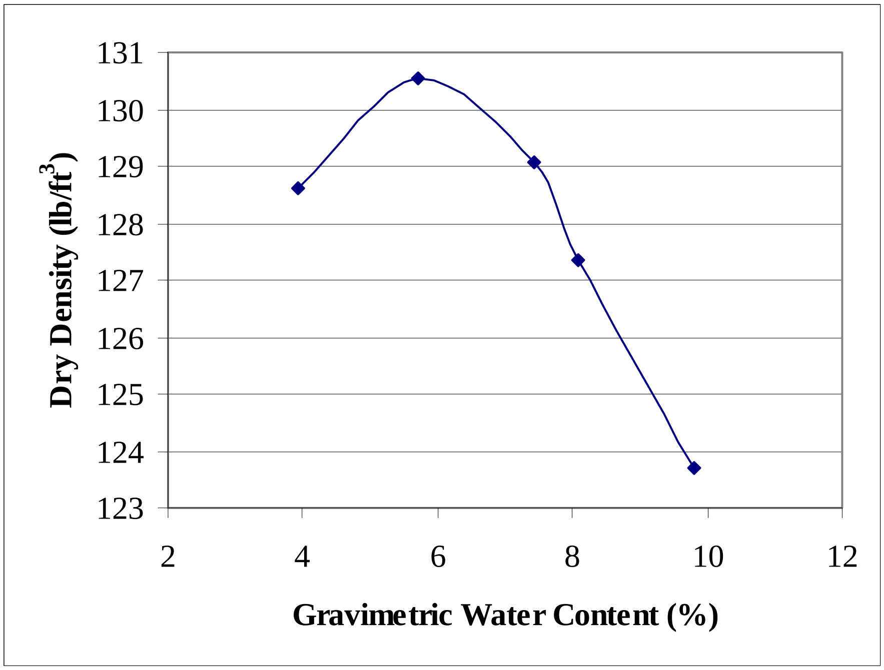

FIGURE 4.3 I-84 moisture-density curve.

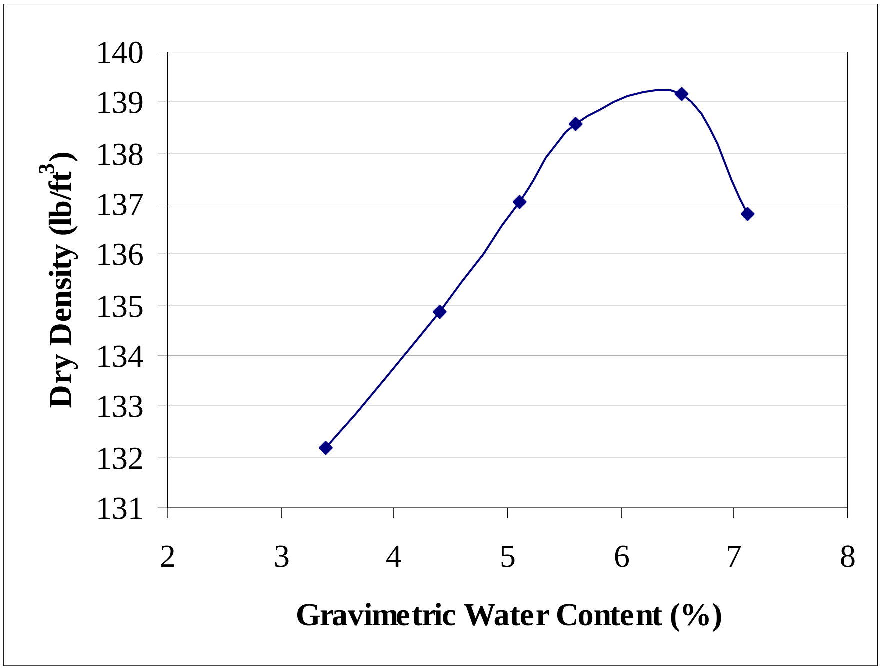

FIGURE 4.4 US-91 moisture-density curve.

4.2.3 Unconfined Compressive Strength Tests

Figures 4.5 and 4.6 show the increase in strength of the CTB materials through time. The I-84 laboratory-mixed samples exhibit a definite increase in strength over the first 2 days, and then the values reach a plateau. Due to preparation of a limited number of field-mixed specimens at the I-84 site, only 1-day and 2-day strengths were measured; the strengths of these field-mixed specimens were greater than the strengths of the laboratory-mixed specimens, possibly because a higher cement content was used in actual construction.

The UCS data associated with the US-91 specimens exhibit a positive correlation between strength and time through 7 days, but the UCS values of the field-mixed specimens are lower in every case than the corresponding values of the laboratory-mixed specimens. The cement content was measured along the US-91 reconstruction corridor to investigate the actual amount of cement applied at three locations. Measurements show that the cement contents were 2.7 percent, 2.8 percent, and 3.2 percent, respectively, for stations 0 ft, 20 ft, and 60 ft at site 2. While these cement contents all exceed the target cement content of 2 percent, other sections of the pavement, such as those from which the

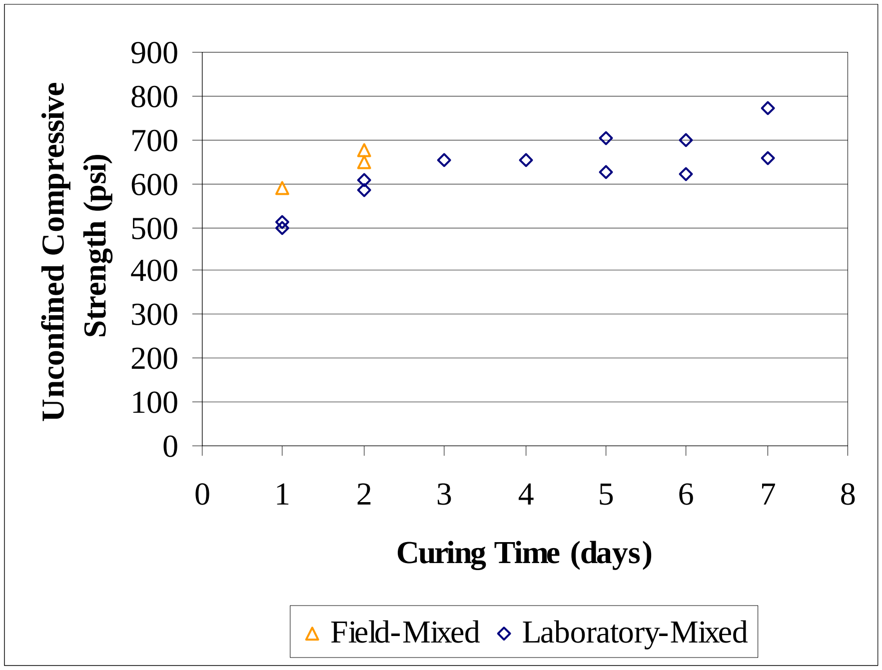

FIGURE 4.5 Compressive strengths of I-84 specimens.

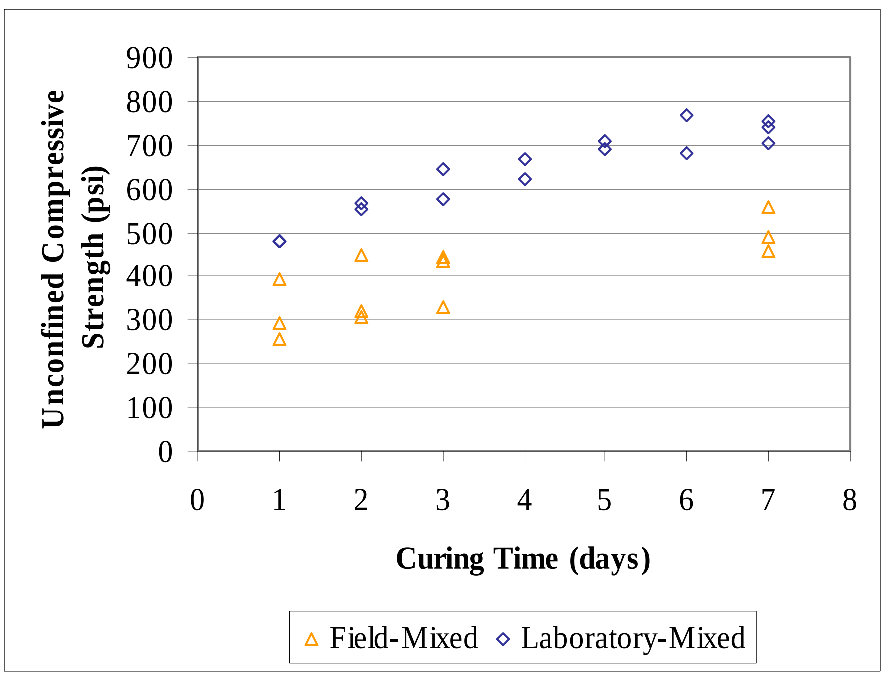

FIGURE 4.6 Compressive strengths of US-91 specimens.

field-mixed material was sampled for specimen preparation, may have been treated with inadequate amounts of cement as suggested in Figure 4.6. Although compacting test specimens is an unreasonable method for monitoring CTB strength gain, strength tests were useful in this research for documenting the typical relationships between strength gain and time for the CTB materials included in the study.

4.3 FIELD TESTS

This section presents the field data that were collected at the I-84 and US-91 locations and presents analyses of sensitivity, repeatability, efficiency, ruggedness, and ease of use. Compilations of the raw data collected at the I-84 and US-91 sites are given in Appendix A and Appendix B, respectively.

4.3.1 Sensitivity

This section contains analyses of the sensitivity of instrument readings to CTB curing time for both the I-84 and US-91 locations.

4.3.1.1 Interstate 84

At the I-84 sites, the SSG, CIST, DCP, and FWD were available for the sensitivity study, but sufficient data for sensitivity evaluations were collected for only the SSG and CIST. Those data are displayed in Figures 4.7 and 4.8, respectively, in which each data point is the average measurement obtained at a given station within a given site at a given time. Both the SSG and CIST data show increasing values through about 3 days, or 72 hours, after which the readings appear to gradually decrease. The decrease is probably the result of an actual reduction in stiffness associated with limited construction trafficking of the pavement, including an occasional water truck and some light truck traffic. Also, because the individual sites remained unsealed, drying of the sites through time likely slowed the CTB curing process considerably.

As explained in Chapter 3, the sensitivity of these instruments to curing time was evaluated using regression. Table 4.1 gives the slope, intercept, and R^2 values computed for each regression for the first 72 hours of curing at each site. While the absolute accuracy of the devices cannot be assessed, the CIST data exhibit much higher R^2 values

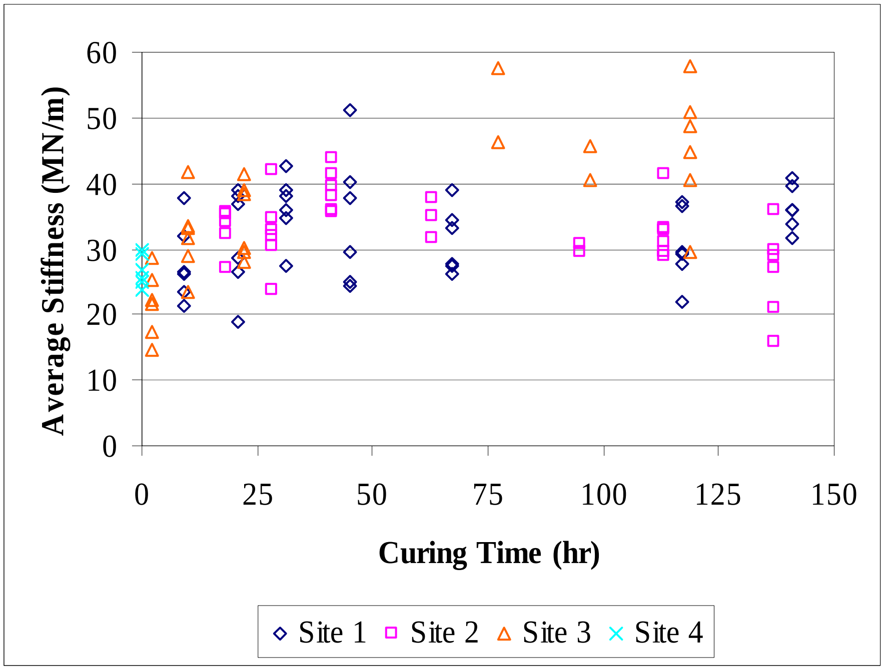

FIGURE 4.7 I-84 soil stiffness gauge data.

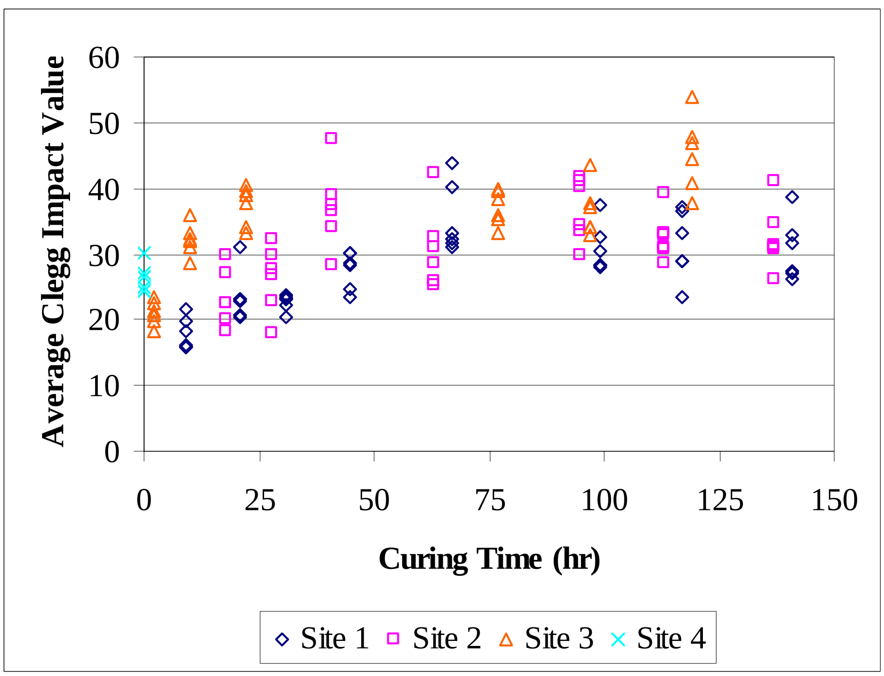

FIGURE 4.8 I-84 Clegg impact soil tester data.

TABLE 4.1 I-84 Regression Data

Site	SSG			CIST		
	Slope	Intercept	R^2	Slope	Intercept	R^2
1	0.053	30.473	0.021	0.284	15.579	0.735
2	0.090	31.927	0.081	0.189	22.327	0.192
3	0.604	22.561	0.431	0.788	21.252	0.812

than the SSG data at all three sites, indicating that the measurements obtained with the CIST are better correlated, or more sensitive, to curing time than those obtained with the SSG.

Concerning the CIST data, the highest R^2 values are associated with sites 1 and 3, while the lowest R^2 values are associated with site 2, where more frequent trafficking led to severe raveling of the surface. Although the low R^2 value associated with the SSG at site 1 cannot also be readily attributed to trafficking, the SSG data collected at site 2 seemed especially sensitive to the raveled surface condition of the CTB layer. The raveling was especially evident as testing locations were prepared for SSG measurements. As loose material on the CTB surface was manually brushed aside, particles previously embedded in the layer were readily dislodged, leaving a rough surface to which the SSG is apparently highly sensitive. The problem of raveling was further exacerbated when strong gusts of wind through the canyon caused further erosion of the surface. Careful placement of the thin layer of moist sand necessary to ensure adequate contact of the SSG with the ground was apparently still inadequate to obtain quality results.

As only one DCP test was performed at each station at each time of curing, formal sensitivity and repeatability evaluations were not conducted. Furthermore, a large amount of scatter occurred in the DCP readings obtained at different depths at any given station; the high variability resulted from the heterogeneous nature of the CTB layers. Nonetheless, the effect of curing on penetration can be readily assessed. As shown in Figure 4.9, in which each data point is the average penetration rate for the depth of the CTB layer for which data could be collected, penetration values approached 0.05 in./blow within 2 days of curing, and the drop hammer bounced upon impact, indicating refusal. Even though the utility of the DCP seems limited for monitoring early-age CTB strength

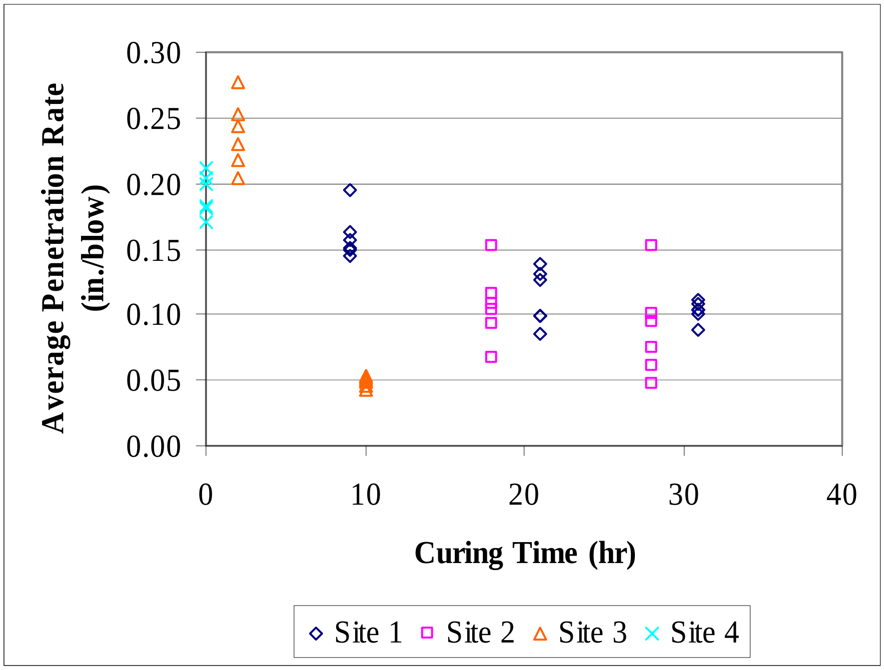

FIGURE 4.9 I-84 dynamic cone penetrometer data.

gain, the DCP seems to be quite useful for estimating pavement layer thickness. Figure 4.10 is an example of a DCP profile obtained from the I-84 project. The upper approximately 8 in. is the freshly compacted CTB layer, while the underlying layer is the stiffer, cement-stabilized subbase layer that comprised the original pavement structure.

Unfortunately, the availability of the FWD was limited during this study, resulting in collection of inadequate data for conducting a meaningful sensitivity study. The data shown in Figure 4.11 suggest that the stiffness of the CTB in some locations exceeded 100 ksi after just 1 day of curing and approached 300 ksi after a week. In the figure, each data point is the modulus determined for a load of 9 kips by interpolation between the modulus values back-calculated from the deflections measured under the approximately 8-kip and 10-kip loads utilized in the field testing. Because FWD tests load the full depth of the pavement structure rather than just the CTB layer, its utility for reliably monitoring early-age strength gain of cement-treated materials is probably limited. However, the data are consistent with the SSG, CIST, and DCP data in that they all show that site 3 gained strength more rapidly than sites 1 and 2. The FWD data were especially valuable

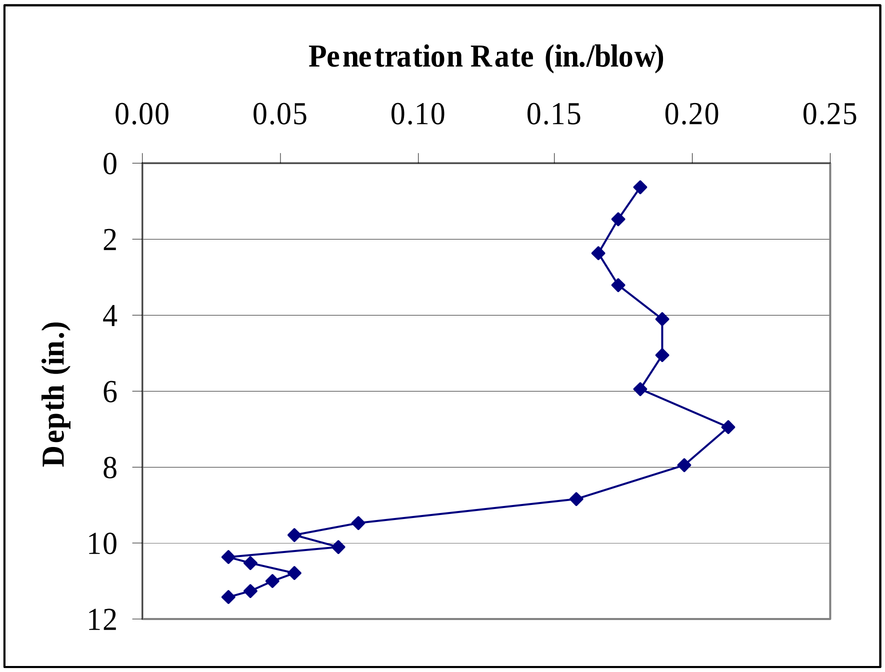

FIGURE 4.10 I-84 dynamic cone penetrometer profile.

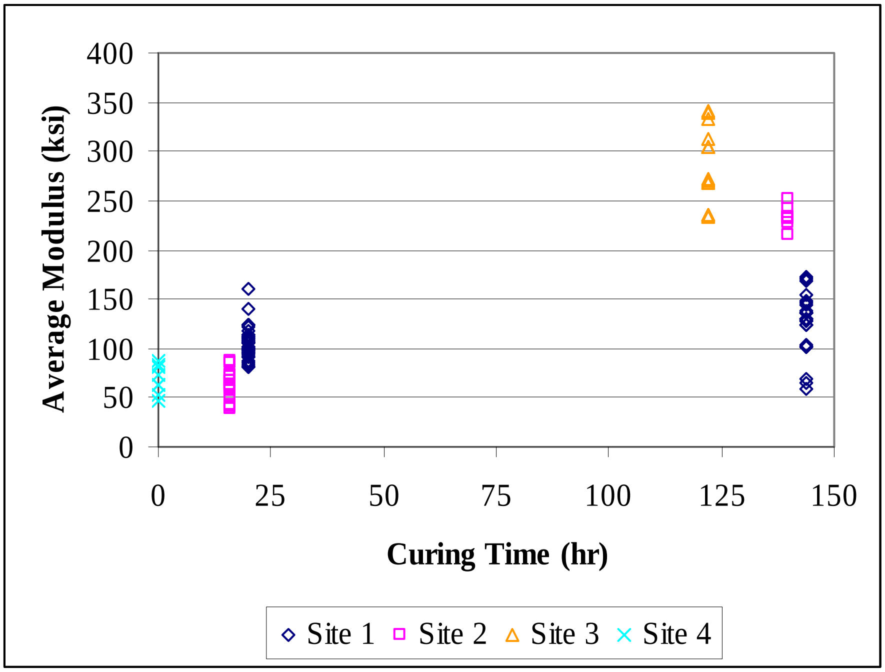

FIGURE 4.11 I-84 falling-weight deflectometer data.

for verifying the pavement design assumptions and generally characterizing the stiffness of the pavement structure.

4.3.1.2 Highway 91

At the US-91 site, the SSG, CIST, DCP, and PWD were available for the sensitivity study, but the data collection procedures focused mainly on the non-destructive SSG, CIST, and PFWD. The SSG, CIST, and PFWD data are plotted against time in Figures 4.12, 4.13, and 4.14, respectively, and all show increasing values through at least 72 hours. Due to the placement of the plastic sheets over the US-91 test stations, the data collected from US-91 represent a curing condition more ideal than that observed on I-84. Table 4.2 gives the slope, intercept, and R^2 values computed for each regression for the first 72 hours of curing at each site. At sites 1 and 2, the CIST data exhibit higher R^2 values than the data obtained from either the SSG or the PFWD, and at site 3 the R^2 value computed for the CIST is only marginally lower than the highest R^2 value, which is associated with the SSG. Therefore, consistent with the findings from the I-84 sites,

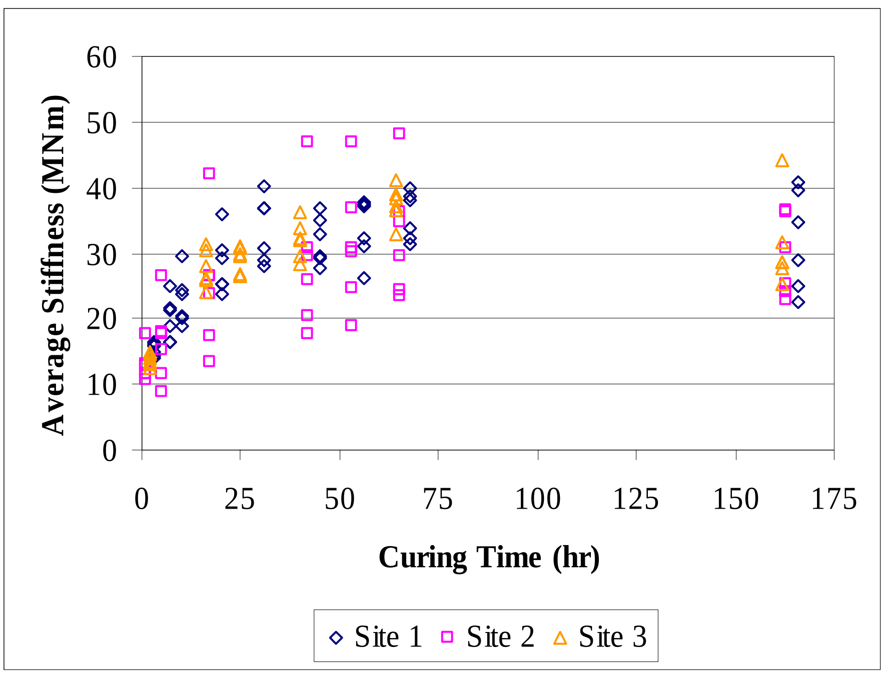

FIGURE 4.12 US-91 soil stiffness gauge data.

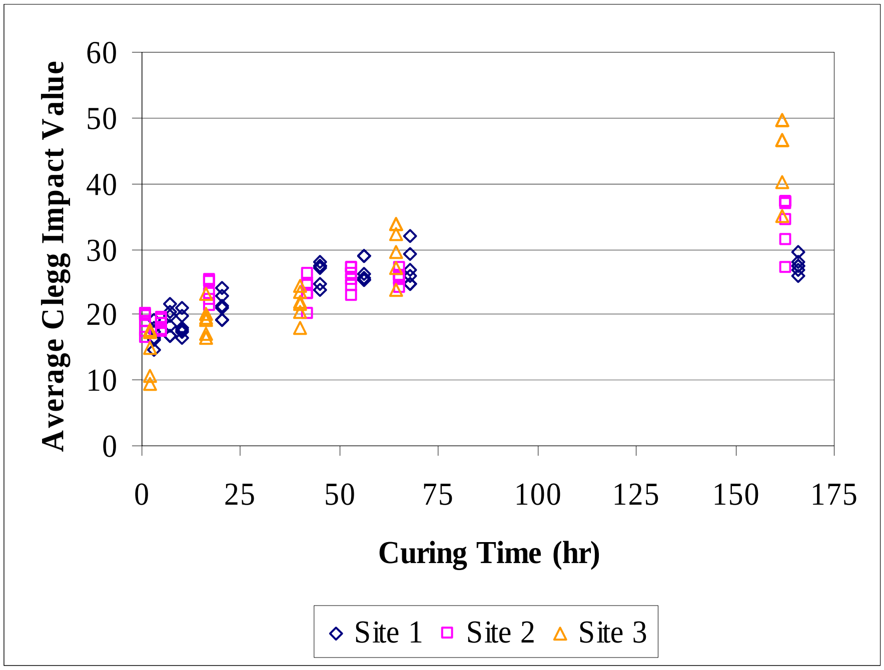

FIGURE 4.13 US-91 Clegg impact soil tester data.

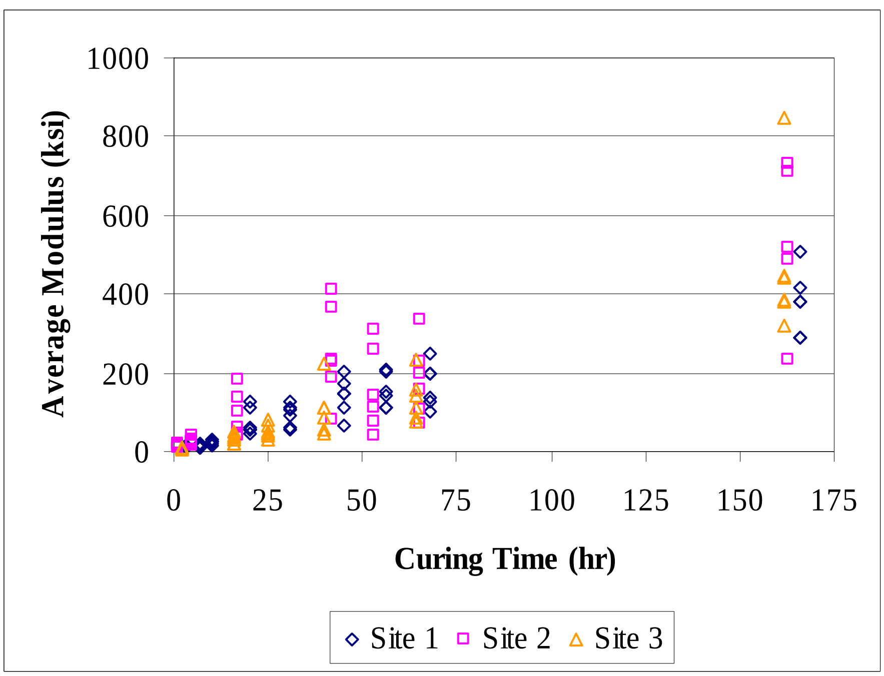

FIGURE 4.14 US-91 portable falling-weight deflectometer data.

TABLE 4.2 US-91 Regression Data

Site	SSG			CIST			PFWD		
	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
1	0.276	19.360	0.635	0.165	17.314	0.793	2.617	6.669	0.765
2	0.293	15.527	0.438	0.110	19.245	0.671	2.941	30.739	0.406
3	0.337	18.096	0.766	0.232	14.280	0.751	2.123	3.886	0.596

these data indicate that, overall, CIST measurements are the most sensitive to CTB curing time.

The US-91 DCP data were collected at all stations immediately after CTB layer compaction and only at stations 20 and/or 80 for subsequent readings. Figure 4.15 presents the average penetration rates within the CTB layer at each of the tested sites. Similar to the I-84 sites, the US-91 sites exhibited refusal after being allowed to cure for a few days. Although the data demonstrate that the DCP is sensitive to curing time, the primary purpose of the DCP testing performed at the US-91 location was to measure CTB layer thickness for use in PFWD data reduction.

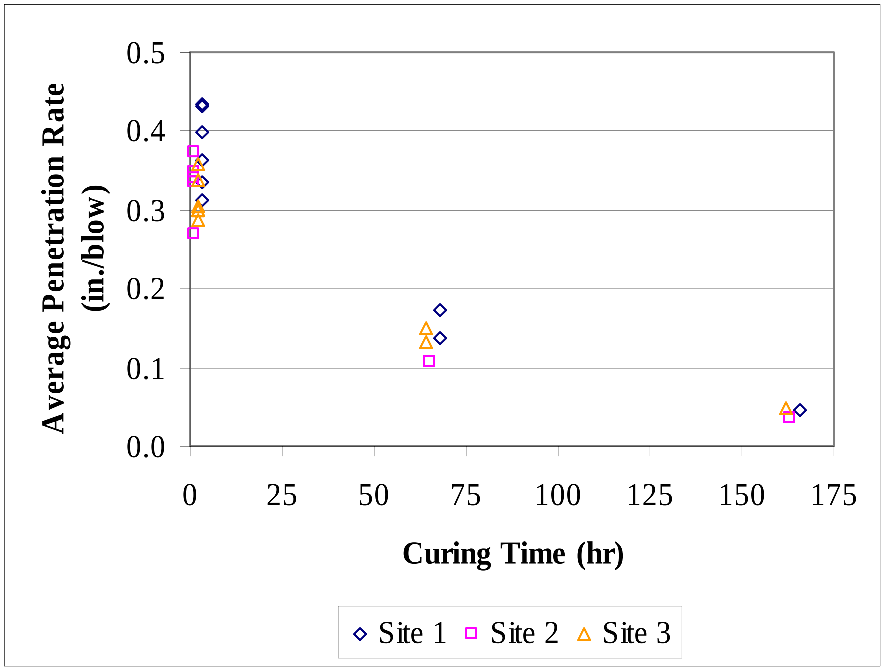

FIGURE 4.15 US-91 dynamic cone penetrometer data.

4.3.2 Repeatability

This section contains analyses of the repeatability of instrument readings at both the I-84 and US-91 locations.

4.3.2.1 Interstate 84

Repeatability evaluations at the I-84 location were limited to the SSG and CIST, and the repeatability analyses were based on CVs computed for each site at each curing time. In Tables 4.3 to 4.5, the average shown at a particular curing time is the mean value of the measurements obtained at all of the stations at that site. The standard deviations were computed from the mean values measured at each station at each curing time and were divided by the corresponding average to compute the CV. The average

TABLE 4.3 I-84 Repeatability Data for Site 1

Curing Time (hr)	Soil Stiffness (MN/m)			Clegg Impact Value		
	Average	St. Dev.	CV (%)	Average	St. Dev.	CV (%)
9	27.87	6.08	21.83	17.95	2.49	13.86
21	31.33	8.05	25.70	23.48	3.92	16.69
31	36.31	5.10	14.04	22.71	1.21	5.34
45	34.61	10.43	30.14	27.55	2.92	10.60
67	31.35	5.01	15.97	35.36	5.42	15.33
99	-	-	-	30.88	3.64	11.79
117	30.39	5.69	18.72	31.37	5.30	16.90
141	36.26	3.50	9.65	30.66	4.72	15.38

TABLE 4.4 I-84 Repeatability Data for Site 2

Curing Time (hr)	Soil Stiffness (MN/m)			Clegg Impact Value		
	Average	St. Dev.	CV (%)	Average	St. Dev.	CV (%)
18	33.23	3.29	9.89	23.39	4.34	18.57
28	32.66	6.00	18.37	26.23	5.11	19.49
41	39.13	3.20	8.18	37.12	6.34	17.09
63	34.82	3.11	8.92	30.98	6.28	20.28
95	30.19	1.01	3.36	36.79	4.80	13.05
113	32.82	4.62	14.08	32.63	3.68	11.27
137	26.49	7.08	26.74	32.56	5.06	15.53

TABLE 4.5 I-84 Repeatability Data for Site 3

Curing Time (hr)	Soil Stiffness (MN/m)			Clegg Impact Value		
	Average	St. Dev.	CV (%)	Average	St. Dev.	CV (%)
2	21.66	5.06	23.34	21.01	1.79	8.52
10	32.12	5.96	18.57	32.17	2.45	7.63
22	34.45	5.79	16.80	37.38	2.97	7.96
77	51.91	7.91	15.23	37.06	2.62	7.07
97	43.22	3.64	8.43	36.63	3.91	10.67
119	45.41	9.70	21.36	45.27	5.66	12.49

CVs at sites 1, 2, and 3 were 19.44, 12.79, and 17.29, respectively, for the SSG and 13.24, 16.47, and 9.06, respectively, for the CIST. Paired *t*-tests were performed to investigate the significance of the differences in these CVs between the SSG and the CIST, where the null hypothesis in each test was that the mean CVs were equal and the alternative hypothesis was that they were not equal. The testing yielded *p*-values of 0.0959, 0.2875, and 0.0164 for sites 1, 2, and 3, respectively. At the standard error rate of 0.05, this indicates that the differences in CV between the SSG and CIST at sites 1 and 2 are not significantly different; however, the CV of the SSG is significantly different than that of the CIST at site 3. Because lower CVs are associated with better repeatability, these analyses suggest that the measurements obtained with the CIST are more repeatable at site 3 than those obtained with the SSG.

Some of the variability associated with the SSG and CIST measurements was probably masked by manual filtering of field data by operators during the data collection process, which may have generated lower CVs for both the SSG and CIST. Measurements thought to be unreasonable by an operator were repeated during the field testing, thus reducing variability in both sets of readings. Unreasonable readings were observed with the CIST only when the falling weight would rebound laterally against the casing upon striking an uneven CTB surface. However, possible sources of unreasonable SSG values included CTB surface raveling, construction traffic, vibrations from the railroad line adjacent to I-84, and other unknown effects. Because SSG measurements were more often repeated than CIST measurements, the effect of filtering was greater on the SSG data.

In order to achieve these reported values of repeatability in future work, operators would need to be sufficiently trained to recognize an unreasonable measurement during field testing and repeat it before relocating to the next measurement site. Otherwise, if the operator simply records every value reported by each device without manually filtering unreasonable data, a greater percentage of unreasonable data will result from the SSG than from the CIST, and the repeatability of the SSG may be considerably worse than the CIST. Manual filtering was not allowed at the US-91 test location so that this hypothesis could be investigated.

4.3.2.2 Highway 91

Repeatability evaluations at the US-91 location included the SSG, CIST, and PFWD; the resulting CVs are displayed in Tables 4.6 to 4.8. The average CVs at sites 1, 2, and 3 were 14.55, 30.48, and 10.28, respectively, for the SSG. The average CVs at sites 1, 2, and 3 were 8.36, 7.27, and 14.90, respectively, for the CIST, and the average CVs were 27.62, 47.42, and 38.69, respectively, for the PFWD.

Paired *t*-tests were performed to investigate the significance of these differences between the SSG, CIST, and PFWD, where the null hypothesis in each test was that the mean CVs were equal and the alternative hypothesis was that they were not equal. For the *t*-test performed to compare the SSG and CIST, the *p*-values were 0.0313, 0.0006, and 0.4171 for sites 1, 2, and 3, respectively. Given the standard error rate of 0.05, these results indicate that the CVs associated with the SSG and CIST at sites 1 and 2 are

TABLE 4.6 US-91 Repeatability Data for Site 1

Curing Time	Soil Stiffness (MN/m)			Clegg Impact Value			Modulus (ksi)		
(hr)	Average	St. Dev.	CV (%)	Average	St. Dev.	CV (%)	Average	St. Dev.	CV (%)
3	15.24	1.04	6.84	16.91	1.60	9.48	11.54	2.48	21.44
7	19.90	3.34	16.79	18.85	2.02	10.72	13.77	2.40	17.45
10	22.86	3.93	17.17	18.32	1.75	9.56	23.53	4.58	19.49
20	28.31	4.54	16.02	21.29	1.92	9.02	76.67	34.45	44.93
31	33.63	5.08	15.10	-	-	-	92.50	27.34	29.56
45	31.88	3.65	11.44	26.36	1.72	6.51	140.96	47.94	34.01
56	33.73	4.65	13.77	26.71	1.73	6.46	154.67	42.19	27.28
68	35.66	3.60	10.11	27.19	2.84	10.43	167.86	54.81	32.65
166	31.91	7.57	23.73	27.47	1.28	4.66	377.42	82.27	21.80

TABLE 4.7 US-91 Repeatability Data for Site 2

Curing Time (hr)	Soil Stiffness (MN/m)			Clegg Impact Value			Modulus (ksi)		
	Average	St. Dev.	CV (%)	Average	St. Dev.	CV (%)	Average	St. Dev.	CV (%)
1	12.87	2.54	19.74	18.72	1.50	8.01	12.70	4.02	31.65
5	16.28	6.04	37.13	18.46	0.82	4.43	25.90	8.78	33.91
17	24.90	9.95	39.97	23.59	1.63	6.92	94.39	57.53	60.95
42	28.52	10.36	36.33	23.64	2.13	9.01	251.43	121.63	48.38
53	31.42	9.70	30.88	25.51	1.65	6.48	155.32	105.96	68.22
65	32.75	9.18	28.05	25.58	1.00	3.90	182.85	93.63	51.21
163	29.22	6.22	21.28	34.07	4.13	12.13	536.03	201.70	37.63

TABLE 4.8 US-91 Repeatability Data for Site 3

Curing Time (hr)	Soil Stiffness (MN/m)			Clegg Impact Value			Modulus (ksi)		
	Average	St. Dev.	CV (%)	Average	St. Dev.	CV (%)	Average	St. Dev.	CV (%)
2	13.72	0.90	6.54	14.54	3.58	24.60	8.79	1.12	12.75
16	27.71	2.84	10.26	19.23	2.45	12.77	32.94	12.19	36.99
25	29.10	1.99	6.84	-	-	-	52.32	19.94	38.10
40	31.98	2.85	8.90	21.63	2.27	10.51	104.47	63.42	60.71
64	37.51	2.70	7.20	30.06	4.06	13.51	133.00	57.56	43.28
162	31.04	6.82	21.96	44.61	5.84	13.09	471.98	190.17	40.29

significantly different, while at site 3 insufficient evidence exists to claim that the two are different. The mean CVs for the CIST were lower at sites 1 and 2, suggesting that the CIST is more repeatable than the SSG at those sites. For the *t*-test performed to compare the SSG and PFWD, the *p*-values were 0.0066, 0.0113, and 0.0066 for sites 1, 2, and 3, respectively. These results indicate that the CVs associated with the SSG and PFWD at sites 1, 2, and 3 are significantly different. The mean CVs obtained for the SSG were lower at all sites than the mean CVs obtained for the PFWD. For the *t*-test performed to compare the CIST and PFWD, the *p*-values were 0.0009, 0.0004, and 0.0758 for sites 1, 2, and 3, respectively. These results indicate that the CVs associated with the CIST and PFWD at sites 1 and 2 are significantly different, while at site 3 insufficient evidence exists to claim that the two are different. Because the mean CVs obtained for the CIST were lower than those obtained for the PFWD, the analyses suggest that the CIST is more repeatable than the PFWD at sites 1 and 2.

4.3.3 Efficiency

The numbers of test locations required to adequately characterize a given site were determined for the SSG, CIST, and PFWD based on the US-91 data, in which three measurements were obtained at each test location and no manual filtering was performed. Following the procedure previously described in Chapter 3, the averages and standard deviations presented in Tables 4.6 to 4.8 for each instrument were plotted as shown in Figures 4.16 to 4.18 or the SSG, CIST, and PFWD, respectively.

The models for the computed standard regression lines are represented by Equations 4.1 to 4.3 for the SSG, CIST, and PFWD, respectively:

$$\hat{s}^* = 0.0346x + 1.1909 \qquad (4.1)$$

where $\hat{s}^* = \hat{s}^{\frac{1}{2}}$

$\hat{s} =$ estimated value of the standard deviation for the SSG, MN/m

$x =$ stiffness, MN/m

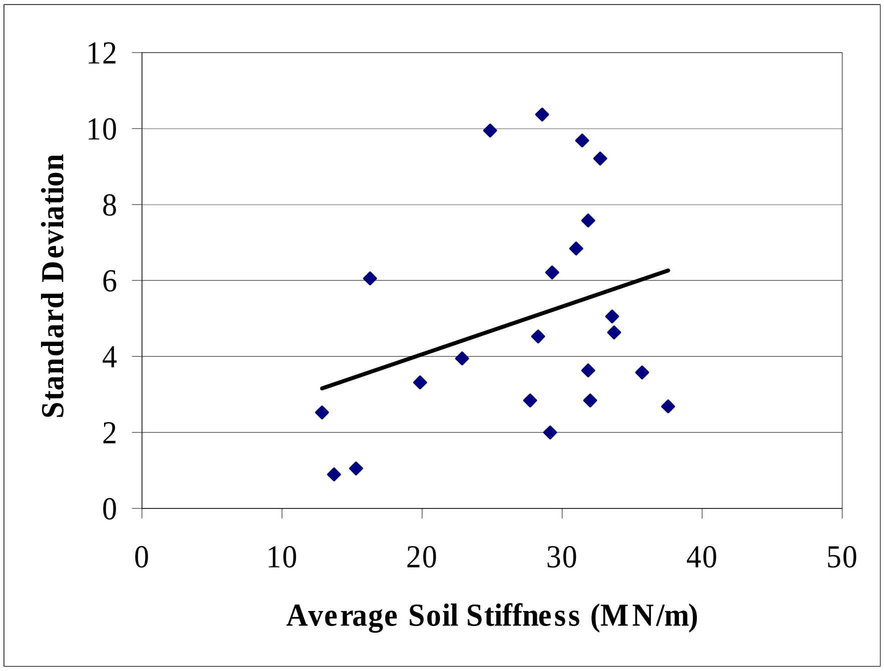

FIGURE 4.16 Soil stiffness gauge standard deviation data.

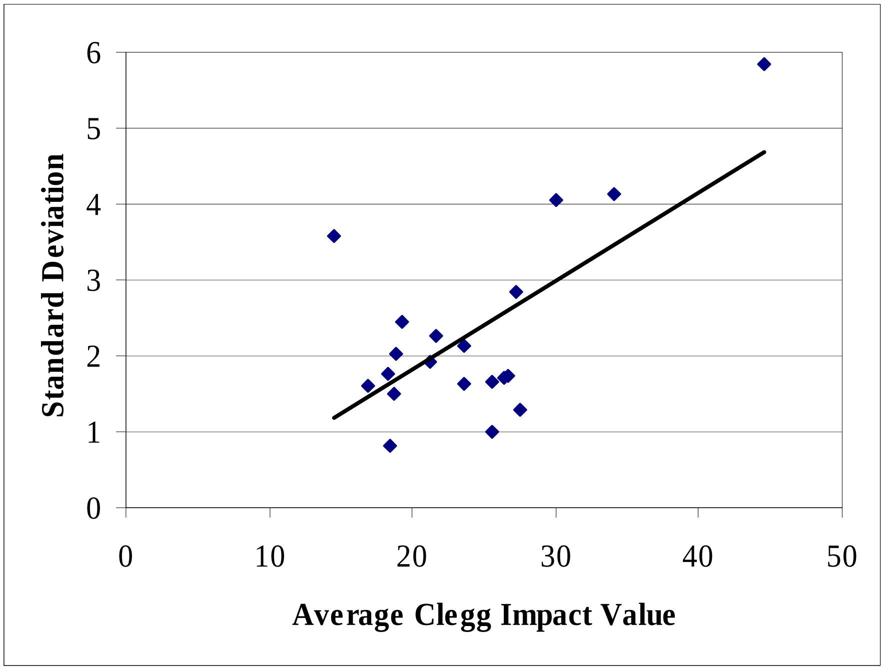

FIGURE 4.17 Clegg impact soil tester standard deviation data.

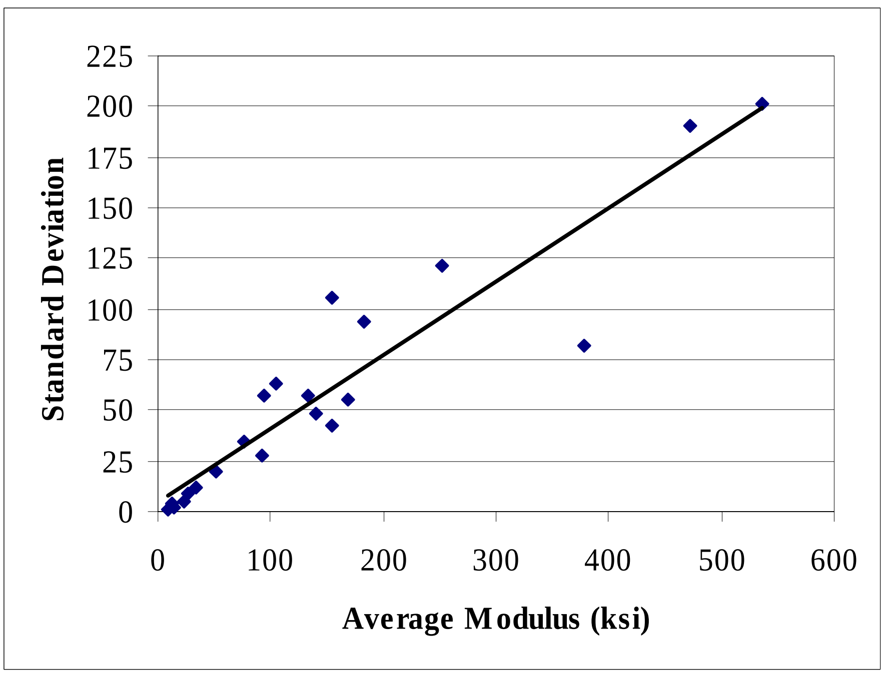

FIGURE 4.18 Portable falling-weight deflectometer standard deviation data.

$$\hat{s} = 0.1170x - 0.5275 \tag{4.2}$$

where $\hat{s}$ = estimated value of the standard deviation for the CIST

x = CIV

$$\hat{s} = 0.3630x + 4.6944 \tag{4.3}$$

where $\hat{s}$ = estimated value of the standard deviation for the PFWD, ksi

x = modulus, ksi

A one-half-power transformation was necessary on the standard deviation data for all of the SSG readings to reduce the effects of heteroskedasticity; as shown in Figure 4.16, which reflects the untransformed SSG data, the variation in standard deviation increases directly proportional to the mean for the SSG. A one-half-power transformation equalized the variability in standard deviation as a function of the mean value and thereby satisfied the requirements for linear regression. Transformations were not necessary for the data collected using the other devices. Values for s_ε of 0.6771, 1.2705, and 58.8588 were calculated for the SSG, CIST, and PFWD, respectively. Equations 4.4 to 4.6 show the upper bound of the 90 percent prediction interval computed for the regression lines associated with the SSG, CIST, and PFWD, respectively:

$$s_{ub}{*} = 0.0346x + 1.1909 + 1.4124 \cdot \sqrt{1 + \frac{1}{22} + \frac{(x - 27.28)^2}{1129.41}} \tag{4.4}$$

where $s_{ub}{*} = s_{ub}^{\frac{1}{2}}$

s_{ub} = predicted value of the upper bound of the standard deviation for the SSG, MN/m

x = stiffness, MN/m

$$s_{ub} = 0.1170x - 0.5275 + 2.6693 \cdot \sqrt{1 + \frac{1}{20} + \frac{(x - 24.14)^2}{895.30}} \tag{4.5}$$

where s_{ub} = predicted value of the upper bound of the standard deviation for the CIST

x = CIV

$$s_{ub} = 0.3630x + 4.6944 + 122.7795 \cdot \sqrt{1 + \frac{1}{22} + \frac{(x - 141.87)^2}{460072.85}} \tag{4.6}$$

where s_{ub} = predicted value of the upper bound of the standard deviation for the PFWD, ksi

x = modulus, ksi

Reversing the transformation of the $s_{ub}*$ variable in Equation 4.4 and then substituting directly for s in Equation 3.2 yields the following Equation 4.7 for estimating the number of test locations required for the SSG:

$$n = \left\{ \frac{Z}{\Delta x} \left[0.0346x + 1.1909 + 1.4124 \cdot \sqrt{1 + \frac{1}{22} + \frac{(x - 27.28)^2}{1129.41}} \right]^2 \right\}^2 \tag{4.7}$$

where n = number of replicate measurements

Z = two-tailed probability statistic from the standard normal distribution

Δx = specified tolerance in stiffness, MN/m

x = stiffness, MN/m

No transformation reversals were needed for the CIST or PFWD. Therefore, Equations 4.5 and 4.6 were substituted directly into Equation 3.2 to obtain Equations 4.8 and 4.9 for the CIST and PFWD, respectively:

$$n = \left\{ \frac{Z}{\Delta x} \left[0.1170x - 0.5275 + 2.6693 \cdot \sqrt{1 + \frac{1}{20} + \frac{(x - 24.14)^2}{895.30}} \right] \right\}^2 \tag{4.8}$$

where n = number of replicate measurements

Z = two-tailed probability statistic from the standard normal distribution

Δx = specified tolerance in CIV

x = CIV

$$n = \left\{ \frac{Z}{\Delta x} \left[0.3630x + 4.6944 + 122.7795 \cdot \sqrt{1 + \frac{1}{22} + \frac{(x - 141.87)^2}{460072.85}} \right] \right\}^2 \quad (4.9)$$

where n = number of replicate measurements

Z = two-tailed probability statistic from the standard normal distribution

Δx = specified tolerance in modulus, ksi

x = modulus, ksi

Equations 4.7 to 4.9 were used to prepare the efficiency charts shown in Figures 4.19 to 4.21, which may be used to estimate the numbers of different test locations that would be required to adequately characterize the mechanical properties of a CTB layer using specific instruments. Tolerance levels of 2, 3, and 4 MN/m were selected as reasonable values for the SSG, while tolerance levels of 2, 3, and 4 CIVs were selected for the CIST. Tolerance values of 30 ksi, 45 ksi, and 60 ksi were selected for the PFWD. The practitioner would need only to specify a threshold instrument value and a tolerance

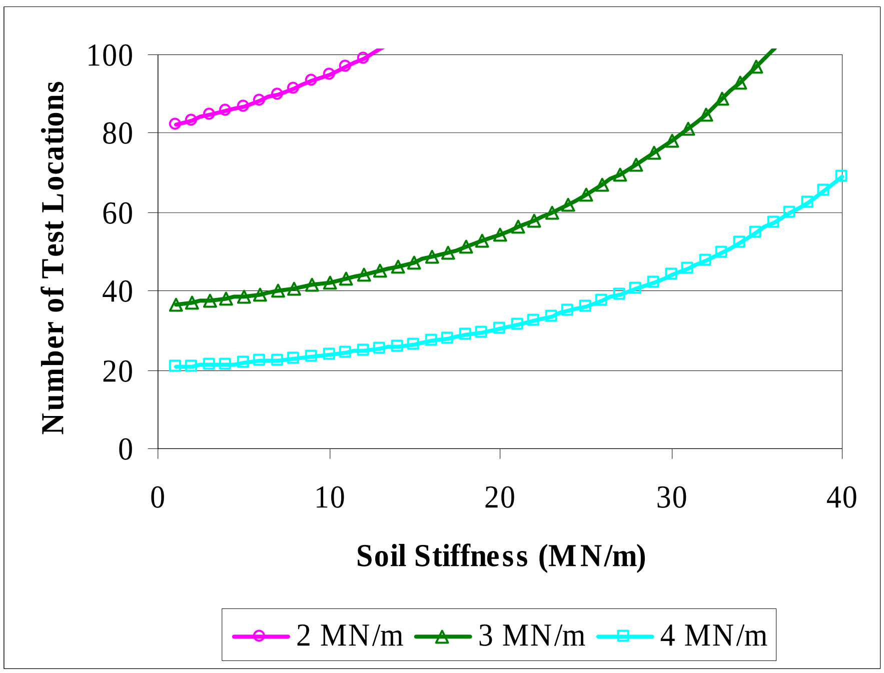

FIGURE 4.19 Soil stiffness gauge efficiency chart.

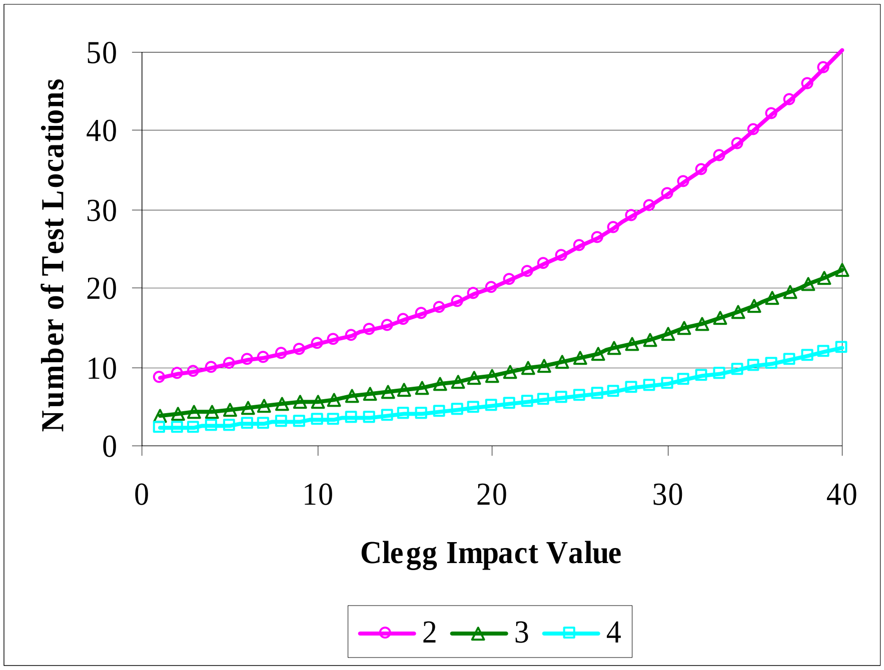

FIGURE 4.20 Clegg impact soil tester efficiency chart.

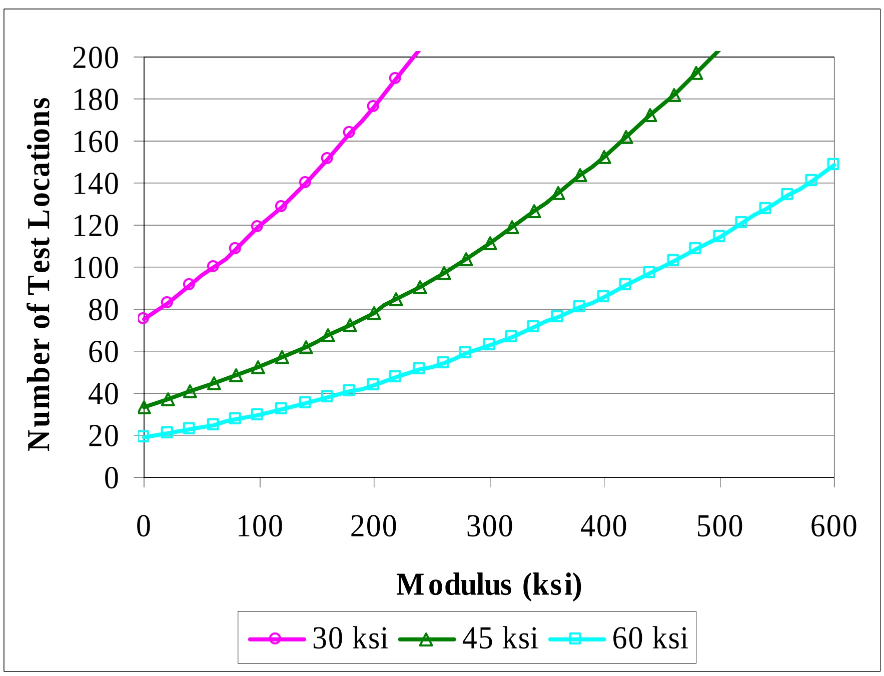

FIGURE 4.21 Portable falling-weight deflectometer efficiency chart.

to directly determine the number of locations to test in a given construction section, with the average of three instrument measurements being assumed to constitute one observation at each test location. All three charts demonstrate that the narrowest tolerances require the highest numbers of readings but that too few readings are associated with wide tolerances that may not allow acceptable characterization of the CTB layer. Therefore, intermediate tolerances are recommended.

Although threshold values for the SSG, CIST, and PFWD have not yet been established with regard to early trafficking of CTB layers, values of each instrument that represent the same CTB strength can be used to compare the efficiency of the testing devices. For example, at values of 30 for the SSG and CIST and 450 ksi for the PFWD, which represent approximately equivalent CTB strengths, and at tolerances of 3 for the SSG and CIST and 45 ksi for the PFWD, the charts suggest that 78, 14, and 177 test locations would be necessary for the SSG, CIST, and PFWD, respectively. Given these data, one can clearly conclude that the CIST provides the greatest efficiency.

While the length of the construction section does not theoretically influence the number of required readings, the test locations must be deliberately randomized within the section of interest. One technique for ensuring that the results are distributed in a random manner is to divide the road into equal segments of approximately the same length and width as depicted in Figure 4.22. After the road is partitioned into a hypothetical grid, the total number of grid cells can be multiplied by random numbers between 0 and 1. The number of random numbers selected should be equal to the number of required test locations. The product of each random number and the total number of grid cells should then be rounded to the nearest whole number; those numbers then designate the cells that should be tested. For example, if eight readings were required for a particular situation and the products of the random numbers and the total number of grid cells were 3, 6, 8, 9, 12, 15, 19, and 21, readings would need to be taken in the locations highlighted in Figure 4.23.

1	5	9	13	17	21
2	6	10	14	18	22
3	7	11	15	19	23
4	8	12	16	20	24

FIGURE 4.22 Example grid.

1	5	9	13	17	21
2	6	10	14	18	22
3	7	11	15	19	23
4	8	12	16	20	24

FIGURE 4.23 Random sampling from example grid.

4.3.4 Ruggedness

No quantitative methodology was developed to measure the ruggedness of the instruments included in the study, but several observations were made relative to this aspect of the testing. As mentioned earlier, the SSG data exhibited particular sensitivity to CTB surface raveling and may also have been adversely impacted by construction traffic, vibrations from the railroad line adjacent to I-84, or other unknown sources of noise. Furthermore, fluctuations in the moisture content and thickness of the sand layer placed beneath the SSG foot, as well as variability in the angle of twist applied to seat the unit before each test, may have influenced the data; if the twist exceeded more than about an eighth of a turn, the foot could often be felt grinding across the tops of protruding coarse aggregate particles.

Unreasonable CIST values were occasionally obtained when the hammer would laterally strike the inside of the casing after impacting an uneven CTB surface. The noise generated by the lateral rebound was readily recognizable, however, and alerted the operator of the need for another test. Besides this infrequent problem, the CIST data seemed robust against small changes in testing conditions.

The primary ruggedness issue with respect to the DCP was the influence of coarse aggregate particles near the surface of the CTB layer. The DCP shaft would begin to lean as the DCP tip was driven around such large particles, often necessitating a repeat of the test. Furthermore, especially as the CTB hardened, the hammer drops caused the shaft to rebound upwards in the hole, which would frequently cause the DCP shaft to be pulled out of the disposable tips that were initially tried in this research on the I-84 project to minimize DCP extraction effort. Although the tip loss produced invalid data, the operator could not easily discern whether tip loss had occurred. Therefore, after this problem was identified, only tips with threaded shaft connections were utilized.

As long as an initial seating test was performed, the PFWD also seemed robust against small variations in field conditions. However, about 2.5 percent of the deflection basins could not be analyzed. The most common problem in these instances was that deflections measured away from the load were greater than those measured immediately beneath the load. Specific reasons for the invalid data were not identifiable.

Similar to the PFWD data, about 3.0 percent of the FWD data could not be analyzed. UDOT engineers suggested that the unpaved nature of the CTB surface under the heavy FWD loads was the primary source of the problems. Given all of these observations, one may conclude that the CIST is the most rugged of the devices tested in this study.

4.3.5 Ease of Use

As with aspects of ruggedness, several observations were made with regard to the ease of use of each instrument included in the study. The SSG generally required the operator to work at ground level for placement of the sand layer and careful positioning of the SSG foot in the sand bedding, which was removed and replaced between successive measurements. Although the SSG software permits electronic storage of data, manually recording the measurements was desirable in this research to ensure proper record-keeping. Unfortunately, however, the SSG did not provide an audible signal, for example, before the results appeared on the small digital display located on the top of the instrument. Because the screen life of each number is only about 3 seconds, the operator was obligated to watch the digital screen attentively for the test to conclude so he or she could quickly write down the readings. Each reading required about 2 minutes to obtain. Although the SSG was not too heavy for most operators to comfortably carry, transporting the necessary bucket of moist sand and the SSG together was somewhat cumbersome.

The design of the CIST allowed operators to stand during testing. Although reaching the CIST hammer handle to lift the weight required minor bending for taller operators, the process was generally ergonomically friendly, and the digital readout of the single number produced for each test had a screen life of more than 10 seconds, allowing a single operator to both collect and record the data easily. Each reading could be accomplished in less than 15 seconds. Even though the CIST weighs approximately 44 lbs, the wheels mounted to the metal guide tube facilitated relatively easy transportation of the device between test stations.

Especially as the CTB hardened, DCP tests became increasingly labor-intensive. Manually lifting the slide hammer was exhausting, especially for shorter operators required to lift the heavy weight above chest level, and performing the test efficiently required at least two operators. While the person lifting and dropping the weight worked in a standing position, the person reading the depth of penetration after each set of blows usually kneeled on the ground. One DCP test usually required between 5 minutes and 10 minutes, although greater amounts of time were required at each station when the test had to be repeated due to excessive lateral displacement of the DCP shaft as the tip encountered coarse aggregates.

The PFWD required the most assembly at each testing site. Connecting the two lengths of shaft, the sensor wires, and the portable computer to the base unit and installing the contact foot on the sensor immediately beneath the load generally required about 10 minutes at each test site. Although the PFWD weight was heavier than the DCP weight, a test required just one drop, making use of the PFWD less exhausting and more efficient. Including the time required to type in the site identification information, a single PFWD test required about 30 seconds. Because of the heavy weight associated with the PFWD unit, however, a cart or dolly would have been appropriate for transporting the unit between test stations. Instead, two or three individuals carried the main unit, sensor bar, and portable computer between the stations at each test site. Repeated lifting of the main unit from the ground was exhausting, and carrying the collection of equipment was awkward even over short distances because of the short wires connecting the various components. After testing was finished at a particular site, the device was then dismantled and returned to its storage case for protection during travel to the next location. Because analysis of the collected data required use of advanced computer software, specialized training was required to complete the CTB modulus back-calculations from the PFWD data.

Because the FWD was a truck-mounted unit, issues of transportation between test locations were not a concern. The truck driver operated the FWD using controls in the truck cab, and a second person assisted with positioning of the FWD drop load along the road. UDOT engineers performed the FWD testing conducted in this research, so the actual level of testing complexity cannot be directly compared to the ease of use associated with the other instruments with which the researchers obtained extensive personal experience during the study. However, as with the PFWD data, analysis of FWD data requires use of advanced computer software; therefore, the PFWD and FWD are perhaps the most complicated of the devices evaluated in this work.

Overall, given these observations, one may conclude that the CIST is the easiest, simplest, and fastest to use for monitoring early-age CTB strength gain. As noted in Chapter 2, the CIST is also comparatively inexpensive; only the DCP costs less to purchase.

4.4 SUMMARY

The utility of the SSG, CIST, DCP, PFWD, and FWD for assessing early-age strength gain in CTB was investigated on pavement reconstruction sites along I-84 near Morgan, Utah, and US-91 near Richmond, Utah. The instruments were evaluated with regard to sensitivity, repeatability, efficiency, ruggedness, and ease of use.

A linear regression was performed to determine the R^2 value associated with each site at both the I-84 and US-91 test locations to determine the sensitivity to curing of each of the instruments. The I-84 analyses indicated that the CIST data were markedly more sensitive to curing time than the SSG data during the first 72 hours after construction. The US-91 analyses indicated that the CIST data were more sensitive to curing time than the SSG and PFWD data during the first 72 hours after construction at sites 1 and 2; at site 3, the SSG data were only slightly more correlated to curing time than the CIST data. Because the DCP test was performed only once at each station at each time of curing at the I-84 site and only periodically at the US-91 site, insufficient data were available for repeatability and sensitivity evaluations. However, the effect of curing on penetration was readily apparent. After a few days of curing at both the I-84 and US-91 sites, penetration values approached the point of refusal. FWD data were also limited but suggest that the stiffness of the CTB in some locations at the I-84 site exceeded 100 ksi after just 1 day of curing and approached 300 ksi in some locations after a week.

Repeatability evaluations were limited to the SSG and CIST at the I-84 location, while the SSG, CIST, and PFWD were evaluated at the US-91 location. The repeatability evaluations were based upon CVs computed for each device for each site at each time of curing. For the I-84 location, statistical analyses demonstrated that the corresponding CVs for the SSG and CIST were not significantly different at sites 1 and 2; however, the statistical analyses indicated that the CV for the CIST data was lower at site 3 than the CV for the SSG data, indicating that measurements obtained with the CIST at that site were more repeatable than those obtained with the SSG. However, because those data were subjected to manual filtering of unreasonable values during the field testing, further testing was performed at the US-91 location to evaluate the repeatability of each instrument. In that case, paired *t*-tests demonstrated that the CVs for the SSG and CIST were significantly different at sites 1 and 2, with the CIST measurements being more repeatable at those sites, and that the CVs for the SSG and PFWD were significantly different at all three sites, with the SSG measurements being more repeatable. In addition, the analyses indicated that the CVs for the CIST and PWD were significantly different at sites 1 and 2, with the CIST measurements being more repeatable at those sites. Overall, the CIST measurements were the most repeatable, and the PFWD measurements were the least repeatable. Insufficient data were available for repeatability analyses of the DCP or FWD.

The US-91 data were also utilized to develop efficiency charts for the SSG, CIST, and PFWD. The numbers of test locations required to estimate the population mean at a 95 percent confidence level and within specified tolerances were computed for each of the instruments. The results show that the CIST requires the fewest readings to acquire reliable results. In addition, the CIST was shown to exhibit the least sensitivity to small variations in testing conditions and was the simplest and quickest to use. As noted in Chapter 2, the CIST is also less expensive than the SSG, PFWD, and FWD, which adds an economic incentive as another basis for recommending its use. For these reasons, the CIST is recommended as the best tool for monitoring early-age strength gain of CTB layers.

CHAPTER 5
CONCLUSION

5.1 SUMMARY

In order to avoid the occurrence of early-age damage, CTB materials must be allowed to cure for a period of time before the pavement can be opened to traffic. The purpose of this research was to evaluate the utility of the SSG, CIST, DCP, PFWD, and FWD for assessing early-age strength gain of cement-stabilized materials. Experimentation was performed at four sites on a pavement reconstruction project along I-84 near Morgan, Utah, and at three sites along US-91 near Richmond, Utah. For both of the projects, cement was utilized to stabilize the pavement base course.

Each site was stationed to facilitate repeated measurements at the same locations with different devices and at different curing times. Because of the considerable attention they have received in the pavement construction industry for routine quality control and quality assurance programs, the SSG, CIST, and PFWD were the primary focus of the research. Statistical techniques were utilized to evaluate the sensitivity, repeatability, and efficiency of each device. The ruggedness and ease of use of each instrument were also evaluated.

5.2 FINDINGS

The results of sensitivity, repeatability, efficiency, ruggedness, and ease of use evaluations are described in the following sections.

5.2.1 Sensitivity

The quantitative method selected to evaluate the sensitivity of field measurements to curing time was regression analysis. For each site, a linear regression was performed for each data set, and the R^2 value was computed and reported. As the R^2 value is the fraction of variation in the SSG, CIST, or PFWD measurements that can be explained by variation in the curing time, higher R^2 values represent better correlations. The I-84 analyses indicated that the CIST data were markedly more sensitive to curing time than the SSG data during the first 72 hours after construction. The US-91 analyses indicated that the CIST data were also more sensitive to curing time than the SSG and PFWD data during the first 72 hours after construction at sites 1 and 2. These results indicate that CIST results are the most sensitive to curing time among the data analyzed in this research.

Although sensitivity and repeatability evaluations of the DCP data collected in this research were not performed, the effect of curing on penetration was readily apparent. After a few days of curing for both the I-84 and US-91 locations, penetration values approached the point of refusal. FWD data analyses were also limited but suggest that the stiffness of the CTB at the I-84 site exceeded 100 ksi after just 1 day of curing and increased to nearly 300 ksi in some locations after a week.

5.2.2 Repeatability

Repeatability evaluations of the SSG, CIST, and PFWD were based upon CVs computed for each device for each site at each time of curing. For the I-84 location, paired *t*-tests demonstrated that the CVs for the SSG and CIST were not significantly different at sites 1 and 2; however, the statistical analyses indicated that the CV for the CIST data was lower at site 3 than the CV for the SSG data, indicating that measurements obtained with the CIST at that site were more repeatable than those obtained with the SSG. However, because those data were subjected to manual filtering of unreasonable values during the field testing, further testing was performed at the US-91 location to evaluate the repeatability of each instrument. In that case, paired *t*-tests demonstrated that the CVs for the SSG and CIST were significantly different at sites 1 and 2, with the CIST measurements being more repeatable at those sites, and that the CVs for the SSG and PFWD were significantly different at all three sites, with the SSG measurements being more repeatable. In addition, the analyses indicated that the CVs for the CIST and PWD were significantly different at sites 1 and 2, with the CIST measurements being more repeatable at those sites. Overall, the CIST measurements were the most repeatable, and the PFWD measurements were the least repeatable. Repeatability analyses of the DCP and FWD were not performed.

5.2.3 Efficiency

Based on the US-91 data, efficiency charts for the SSG, CIST, and PFWD were prepared to show the number of test locations required to estimate the population mean at a 95 percent confidence level and within specified tolerances. All three charts demonstrate that the narrowest tolerances require the highest numbers of readings but that too few readings are associated with wide tolerances that may not allow acceptable characterization of the CTB layer. The results clearly show that the CIST requires the fewest readings to acquire reliable results.

5.2.4 Ruggedness

With regard to the influence of small variations in testing conditions on the collected data, SSG data were observed to be especially sensitive to raveling on the CTB layer surface, although characteristics of the sand bedding, angle of twist, construction traffic, vibrations from an adjacent railroad line, and other aspects of the testing may have also adversely affected the readings. Unreasonable CIST data were occasionally obtained when the hammer would laterally strike the inside of the casing after impacting an uneven CTB surface, but this problem was readily recognized by the operator when it occurred. The DCP was most influenced by the presence of coarse aggregate particles near the surface that would cause the DCP shaft to lean as the DCP tip was driven around the obstacle. When the end of the shaft deviated more than 6 in. from its original vertical position, the test was necessarily repeated. The disconnection of disposable tips from the shaft was also problematic, especially as the CTB hardened. About 2.5 percent of the PFWD data could not be analyzed because in many instances the deflections measured away from the load were greater than those measured immediately beneath the load. Similar problems were observed with the FWD. Although specific reasons for the invalid data were not readily identifiable, UDOT engineers suggested that the unpaved nature of the CTB surface under the heavy FWD loads was the primary source of the errors.

Overall, given these observations, one may conclude that the CIST is the most rugged of the devices tested in this study.

5.2.5 Ease of Use

Evaluations of ease of use mainly focused on simplicity, speed, and operator comfort. While the SSG is simple by design, proper placement of the sand layer and positioning of the SSG foot require the operator to work at ground level, and, if measurements are to be manually recorded, the operator must watch the digital screen attentively during the testing process so as not to miss the quick displays of results. Although the SSG is not too heavy for most operators to comfortably carry, transporting the necessary bucket of moist sand and the SSG together can be cumbersome. From start to finish, an SSG reading requires about 2 minutes. The design of the CIST allows operators to stand during testing, includes wheels that allow relatively easy transportation of the device between test stations, and requires less than 15 seconds to obtain a reading. The DCP becomes increasingly labor-intensive as the CTB layer hardens, and manually lifting the slide hammer is exhausting, especially for shorter operators required to lift the heavy weight above chest level. Two operators are needed to perform a DCP test efficiently, which generally requires between 5 minutes and 10 minutes. The PFWD requires extensive assembly prior to use and, due to its several components, is difficult to transport. However, only one drop of the weight is required for a test, allowing testing to proceed rapidly once the device is operational. Like the FWD, however, the PFWD requires the use of advanced computer software to analyze the collected data. For these reasons, the results of this research suggest that the CIST is the easiest, fastest, and simplest to use for monitoring early-age CTB strength gain.

5.3 RECOMMENDATIONS

The results of this research indicate that the CIST is the best instrument for monitoring early-age strength gain of CTB layers. Not only is the CIST superior to the other instruments with respect to sensitivity, repeatability, efficiency, and ruggedness, but it is the easiest, fastest, and simplest to use. Furthermore, the CIST is less expensive than the SSG, PFWD, and FWD, so it is more likely to be purchased by pavement engineers and contractors involved with construction of CTBs. Further research is needed to identify appropriate threshold CIST values at which CTB layers develop sufficient strength to resist permanent deformation or marring under different types of trafficking.

REFERENCES

1. State-of-the-Art Report on Soil Cement. *ACI Materials Journal,* Vol. 87, No. 4, July/August 1990, pp. 395-417.

2. *Soil-Cement Construction Handbook: Engineering Bulletin*. Publication EB003.10S. Portland Cement Association, Skokie, IL, 1995.

3. *Soil-Cement Information: Suggested Specifications for Soil-Cement Base Course Construction*. Publication IS008. Portland Cement Association, Skokie, IL, 2001.

4. *Jersey DOT's Tech Brief: Evaluation of the Humboldt Stiffness Gauge (HSG)*. New Jersey Department of Transportation, Trenton, NJ, January 2002.

5. Lenke, L. R., R. G. McKeen, and M. Grush. *Evaluation of a Mechanical Stiffness Gauge for Compaction Control of Granular Media*. Publication NM99MSC-07.2. New Mexico State Highway and Transportation Department, Albuquerque, NM, December 2001.

6. *GeoGauge User Guide*. Humboldt Manufacturing Company, Norridge, IL, 2002.

7. Clegg Impact Soil Tester. Lafayette Instruments, Lafayette, IN. http://www.licmef.com/clegg.htm. Accessed July 30, 2004.

8. *Corps Style Dual Mass Dynamic Cone Penetrometer: Application and Maintenance Manual*. Salem Tool Company, Salem, MI, 2003.

9. Kestler, M. A., and R. L. Berg. Framework for Evaluation of a Cost-Effective Method for Placing and Removing Seasonal Load Restrictions on Low Volume Roads: The Portable Falling Weight Deflectometer. In *Proceedings of the American Society of Civil Engineers Twelfth International Specialty Conference on Cold Regions Engineering.* CD-ROM. Edmonton, Alberta, Canada, 2004.

10. Von Quintus, H. L., and A. L. Simpson. *Back-Calculation of Layer Parameters for LTPP Test Sections, Volume II: Layered Elastic Analysis for Flexible and Rigid Pavements*. Publication FHWA-RD-01-113. Federal Highway Administration, U.S. Department of Transportation, Washington D.C., 2002.

11. *Soil-Cement Information: Cement-Treated Aggregate Base*. Publication ST221S. Portland Cement Association, Skokie, IL, undated.

12. Google Earth. http://www.googleearth.com. Accessed March 9, 2006.

13. Huang, Y. H. *Pavement Analysis and Design*, Second Edition. Prentice Hall, Upper Saddle River, NJ, 2004.

14. Ott, R. L., and M. Longnecker. *An Introduction to Statistical Methods and Data Analysis*, Fifth Edition. Duxbury, Pacific Grove, CA, 2001.

15. Picariello, P. Fact vs. Fiction: The Truth about Precision and Bias. *ASTM Standardization News*, Vol. 28, No. 3, March 2000, pp. 16-19.

16. Guthrie, W. S., P. M. Ellis, and T. Scullion. Repeatability and Reliability of the Tube Suction Test. In *Transportation Research Record 1772*, Transportation Research Board, National Research Council, Washington, D.C., 2002, pp. 151-157.

17. Keller, G. *Applied Statistics with Microsoft Excel*. Duxbury, Pacific Grove, CA, 2001.

APPENDIX A

TABLE A.1 I-84 Soil Stiffness Gauge Data for Site 1

Curing Time (hr)	Stiffness (MN/m)											
	Station 0		Station 20		Station 40		Station 60		Station 80		Station 100	
	1	2	1	2	1	2	1	2	1	2	1	2
9	34.9	40.8	22.7	19.8	22.6	24.2	25.8	26.5	25.1	27.8	32.5	31.5
21	31.0	26.5	34.6	38.9	35.9	40.4	35.3	42.8	20.1	17.4	26.1	26.8
31	35.2	43.0	28.6	26.4	44.7	40.6	36.4	39.5	34.7	37.1	34.5	35.2
45	51.3	51.0	37.5	38.2	40.4	39.8	28.9	30.0	23.3	25.3	23.3	26.4
67	27.8	-	26.3	-	27.5	-	33.1	-	32.2	36.8	42.9	35.1
99	-	-	-	-	-	-	-	-	-	-	-	-
117	28.0	31.0	29.3	-	35.6	37.4	37.7	36.7	27.2	28.3	20.9	23.2
141	32.3	39.5	44.5	37.1	34.7	37.1	38.4	24.6	29.5	38.1	41.9	37.6

Note: Missing data were not collected due to inclement weather.

TABLE A.2 I-84 Soil Stiffness Gauge Data for Site 2

Curing Time (hr)	Stiffness (MN/m)											
	Station 0		Station 20		Station 40		Station 60		Station 80		Station 100	
	1	2	1	2	1	2	1	2	1	2	1	2
18	33.4	34.9	36.4	34.7	35.9	18.1	37.1	33.4	36.1	34.5	31.2	33.1
28	27.3	33.5	33.8	32.0	36.0	33.7	31.2	32.9	21.4	26.0	41.7	42.5
41	39.6	39.7	38.4	37.5	36.3	35.7	36.7	34.8	44.3	43.6	41.8	41.1
63	35.1	-	31.6	-	37.8	-	-	-	-	-	-	-
95	-	-	29.5	29.5	-	-	-	-	31.0	30.8	-	-
113	33.4	32.5	35.0	31.2	25.2	32.5	29.4	29.4	41.9	41.2	26.6	35.6
137	20.7	21.6	13.6	18.1	29.3	30.2	30.9	27.3	37.5	34.7	23.3	30.9

Note: Missing data were not collected due to inclement weather.

TABLE A.3 I-84 Soil Stiffness Gauge Data for Site 3

Curing	Stiffness (MN/m)											
Time	Station 0		Station 20		Station 40		Station 60		Station 80		Station 100	
(hr)	1	2	1	2	1	2	1	2	1	2	1	2
2	13.8	15.6	16.8	18.1	21.9	21.3	22.5	22.1	25.1	25.5	28.1	29.1
10	42.4	40.8	32.4	31.1	32.5	34.7	29.3	28.8	32.6	33.9	22.1	24.8
22	40.0	42.8	38.6	39.4	37.9	39.1	29.9	29.5	30.5	29.8	27.3	28.8
77	-	-	60.0	55.0	-	-	-	-	47.9	44.8	-	-
97	-	-	46.0	45.6	-	-	-	-	39.2	42.1	-	-
119	49.0	48.6	58.4	57.4	43.3	46.5	38.6	42.3	50.1	51.5	26.8	32.4

Note: Missing data were not collected due to inclement weather.

TABLE A.4 I-84 Soil Stiffness Gauge Data for Site 4 (Untreated)

Curing	Stiffness (MN/m)											
Time	Station 0		Station 20		Station 40		Station 60		Station 80		Station 100	
(hr)	1	2	1	2	1	2	1	2	1	2	1	2
-	29.6	30.1	28.9	29.6	25.4	25.5	24.3	25.5	22.7	24.8	26.8	26.8

TABLE A.5 I-84 Clegg Impact Soil Tester Data for Site 1

Curing	Clegg Impact Value																	
Time	Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
(hr)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
9	21.9	21.3	22.1	17.4	20.1	17.1	20.9	19.3	19.6	17.1	16.3	15.4	15.6	16.6	15.3	17.3	15.5	14.3
21	34.6	29.2	29.4	22.9	23.7	22.5	20.4	23.0	24.8	24.7	24.5	20.3	19.3	20.7	21.7	20.0	22.3	18.7
31	29.5	22.1	20.1	21.6	21.6	26.5	21.7	24.7	20.2	20.6	19.8	21.1	25.7	20.6	23.1	23.8	20.3	25.8
45	29.8	29.2	26.9	29.5	29.1	32.2	28.5	25.1	31.5	23.0	24.3	22.6	28.1	23.5	22.2	29.0	25.5	35.9
67	50.4	37.4	44.2	30.9	32.6	33.0	32.4	32.9	27.6	32.6	32.4	29.6	49.1	42.1	29.5	39.3	32.9	27.6
99	32.6	25.5	33.5	29.6	29.3	38.7	25.1	27.0	32.9	41.7	36.1	34.5	34.6	24.2	25.5	27.4	23.3	34.4
117	37.3	27.7	45.1	31.0	28.8	27.1	30.8	30.7	25.5	24.4	22.6	22.9	39.0	35.6	36.5	32.1	36.2	31.4
141	41.4	37.8	36.9	26.3	28.7	39.6	30.7	26.6	24.2	26.0	26.5	26.5	32.5	24.6	25.2	28.9	32.6	36.8

TABLE A.6 I-84 Clegg Impact Soil Tester Data for Site 2

Curing	Clegg Impact Value																	
Time	Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
(hr)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
18	40.5	26.0	23.1	21.1	19.7	19.3	20.6	23.6	23.4	18.8	18.2	18.0	30.0	28.9	22.5	26.1	23.1	18.2
28	29.3	33.0	27.5	27.2	28.0	27.9	29.4	27.3	23.5	18.0	17.1	19.2	32.6	32.7	31.4	24.4	21.6	22.1
41	49.3	42.3	51.2	38.5	36.5	37.2	26.2	30.9	27.6	36.0	31.9	48.7	35.4	40.1	33.8	46.5	26.8	29.2
63	30.1	32.6	30.8	28.3	23.4	23.8	27.9	26.7	31.0	22.3	33.0	22.8	28.0	36.2	33.6	37.6	43.5	46.1
95	26.6	32.5	30.9	38.6	29.0	32.5	53.0	35.8	31.8	35.2	35.1	33.4	38.4	38.0	48.4	40.8	40.2	42.0
113	30.8	30.5	38.0	33.4	29.1	35.9	28.4	27.2	30.1	32.4	30.6	30.6	31.6	32.2	28.5	41.5	32.1	44.5
137	30.3	33.3	28.7	38.2	27.4	28.7	28.8	31.0	33.1	26.5	28.1	24.0	34.6	35.9	33.6	39.5	44.3	40.0

TABLE A.7 I-84 Clegg Impact Soil Tester Data for Site 3

Curing Time (hr)	Clegg Impact Value																	
	Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
2	18.1	18.4	18.7	22.6	21.9	22.7	24.2	22.7	23.3	22.0	23.0	18.7	21.6	21.3	19.5	19.1	20.2	20.1
10	29.7	29.1	34.4	28.4	34.0	37.1	28.9	36.2	31.4	31.9	27.4	26.3	34.7	32.7	40.6	32.2	32.1	32.0
22	41.6	33.8	43.2	41.0	35.0	45.4	32.9	33.3	33.4	39.0	38.9	35.8	36.5	34.9	31.3	40.7	38.0	38.1
77	36.2	38.5	40.5	44.3	39.0	36.1	21.2	43.0	42.1	49.0	32.3	37.2	33.3	38.2	36.7	36.6	32.1	30.7
97	37.8	44.7	30.5	34.2	33.1	31.5	43.4	45.3	42.4	38.3	29.5	34.9	40.6	37.5	33.0	36.3	33.7	32.7
119	35.7	49.5	55.1	46.5	48.6	48.7	48.7	57.7	55.2	40.4	48.6	44.5	39.0	40.8	42.5	42.0	39.2	32.2

TABLE A.8 I-84 Clegg Impact Soil Tester Data for Site 4 (Untreated)

Curing Time (hr)	Clegg Impact Value																	
	Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
-	29.5	28.4	32.5	24.2	27.6	29.3	24.3	22.0	26.9	22.2	24.2	26.4	26.9	26.6	25.8	26.0	25.3	23.5

TABLE A.9 I-84 Dynamic Cone Penetrometer Data for Site 1

Curing Time (hr)	Average Penetration for Upper 8" (in./blow)					
	Station 0	Station 20	Station 40	Station 60	Station 80	Station 100
9	0.16	0.14	0.15	0.15	0.20	0.16
21	0.10	0.13	0.13	0.10	0.14	0.09
31	0.09	0.10	0.11	0.10	0.11	0.10

TABLE A.10 I-84 Dynamic Cone Penetrometer Data for Site 2

Curing Time (hr)	Average Penetration for Upper 8" (in./blow)					
	Station 0	Station 20	Station 40	Station 60	Station 80	Station 100
18	0.07	0.12	0.11	0.15	0.10	0.09
28	0.05	0.09	0.10	0.15	0.06	0.07

Note: At station 0 at a curing time of 18 hours and at all stations at a curing time of 28 hours, refusal occurred before a penetration depth of 8 in. was achieved.

TABLE A.11 I-84 Dynamic Cone Penetrometer Data for Site 3

Curing Time (hr)	Average Penetration for Upper 8" (in./blow)					
	Station 0	Station 20	Station 40	Station 60	Station 80	Station 100
2	0.28	0.25	0.22	0.20	0.23	0.24
10	0.04	0.05	0.05	0.05	0.05	0.05

Note: Except for stations 0 and 20 at a curing time of 2 hours, refusal occurred before a penetration depth of 8 in. was achieved.

TABLE A.12 I-84 Dynamic Cone Penetrometer Data for Site 4 (Untreated)

Curing Time (hr)	Average Penetration for Upper 8" (in./blow)					
	Station 0	Station 20	Station 40	Station 60	Station 80	Station 100
-	0.17	0.18	0.18	0.20	0.20	0.21

TABLE A.13 I-84 Falling-Weight Deflectometer Data

Test	Modulus (ksi)											
	Site 1 (20 hr)		Site 1 (144 hr)		Site 2 (16 hr)		Site 2 (140 hr)		Site 3 (122 hr)		Site 4 (Untreated)	
	Layer 1	Layer 2	Layer 1	Layer 2	Layer 1	Layer 2	Layer 1	Layer 2	Layer 1	Layer 2	Layer 1	Layer 2
1	85.2	47.6	173.3	44.5	37.9	26.8	250.9	34.2	312.0	40.1	62.0	33.4
2	95.2	43.4	170.0	45.6	40.7	28.2	234.2	34.2	303.7	40.6	80.7	32.1
3	96.2	43.0	168.5	46.2	42.1	28.0	231.3	34.7	304.4	41.4	52.8	33.4
4	99.1	43.8	128.7	32.8	58.8	24.0	228.4	20.0	338.2	34.6	86.4	30.0
5	99.2	43.7	130.4	32.5	51.6	24.4	241.2	19.8	340.3	35.4	72.7	31.5
6	81.6	32.8	130.5	32.6	62.4	24.7	214.5	20.1	332.3	35.6	62.5	32.3
7	82.0	33.6	136.0	35.2	67.2	24.6			268.7	36.2	83.8	30.5
8	83.1	33.6	138.3	34.8	67.9	24.6			272.5	36.6	47.6	27.5
9	87.7	35.1	135.7	35.3	60.2	23.7			270.7	36.5		
10	91.1	35.6	58.4	32.7	86.5	25.1			235.1	40.9		
11	98.9	34.3	64.2	31.4	85.7	25.4			235.8	41.1		
12	98.2	34.8	68.9	31.6	85.5	25.4			232.9	41.5		
13	101.2	36.3	155.2	30.2	84.8	25.1						
14	99.2	38.2	148.4	31.0	66.3	21.8						
15	94.7	38.6	144.2	31.4	71.1	22.3						
16	98.5	38.3	101.3	36.2	73.1	22.4						
17	105.6	38.9	104.0	36.3	73.0	22.4						
18	106.4	39.7	101.0	37.4	60.1	19.3						
19	110.2	38.7	130.7	32.9	57.8	20.2						
20	106.2	39.8	123.3	33.5	72.3	20.2						
21	91.8	39.5	124.6	33.3	62.8	20.2						
22	94.3	40.0	146.0	31.2								
23	99.4	38.6	128.6	31.2								
24	98.4	39.4	136.0	31.7								
25	107.0	36.2										
26	110.2	37.7										
27	111.9	37.4										
28	112.3	37.2										
29	100.6	42.0										
30	139.8	40.6										
31	161.0	40.2										
32	107.7	41.3										
33	118.5	42.9										
34	121.2	43.7										
35	123.1	43.8										
36	123.8	43.6										
37	105.6	54.3										
38	112.5	53.9										
39	114.2	54.2										
40	114.3	54.3										

APPENDIX B

TABLE B.1 US-91 Soil Stiffness Gauge Data for Site 1

Curing	Stiffness (MN/m)																	
Time	Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
(hr)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
3	13.8	14.5	14.7	14.2	15.2	15.1	16.2	16.5	16.5	15.6	16.0	16.0	14.2	14.4	13.1	16.2	16.6	15.7
7	25.5	25.2	23.9	16.6	16.6	16.1	21.9	20.7	22.1	18.6	18.4	19.5	15.4	16.4	17.2	21.2	21.2	22.0
10	29.0	29.4	30.0	18.4	18.9	19.3	23.8	24.9	24.8	20.7	19.5	20.1	18.7	20.8	21.5	23.5	24.0	24.2
20	37.4	35.9	34.8	22.8	24.4	23.9	30.0	30.9	30.1	25.6	24.7	25.9	25.0	25.9	25.2	29.7	28.3	29.4
31	39.9	40.6	40.6	27.7	29.4	26.9	37.8	37.3	35.8	27.0	28.8	31.2	30.4	31.0	30.5	36.8	37.5	36.4
45	34.2	34.4	36.5	27.6	27.6	27.9	31.5	34.1	33.5	29.5	29.0	28.8	28.5	30.4	29.8	37.8	37.7	35.1
56	37.5	35.8	38.1	31.4	30.3	31.5	37.7	38.4	37.7	27.9	35.5	33.6	28.8	25.4	24.8	38.1	38.7	36.0
68	36.5	40.1	39.3	32.3	31.9	32.8	38.6	38.4	42.3	30.9	34.9	35.2	32.3	30.3	31.6	36.0	38.5	39.8
166	39.9	42.2	40.1	28.4	30.3	28.0	39.6	40.7	38.3	32.9	36.2	34.9	25.3	26.0	24.0	21.6	24.2	21.8

TABLE B.2 US-91 Soil Stiffness Gauge Data for Site 2

Curing	Stiffness (MN/m)																	
Time	Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
(hr)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	11.1	11.3	12.5	11.2	11.7	11.9	10.1	10.6	10.9	12.7	12.8	13.6	13.2	12.3	12.5	17.5	17.6	18.1
5	8.8	9.0	9.0	15.0	15.0	15.6	11.3	11.6	11.9	18.1	18.6	16.9	17.3	17.9	18.1	23.1	28.2	27.7
17	13.2	13.3	13.2	23.7	22.6	25.2	17.3	17.6	16.9	28.6	27.6	23.3	28.8	26.3	24.1	41.6	45.7	39.0
42	18.0	18.4	16.4	22.1	27.6	28.0	22.5	20.3	18.4	28.2	29.7	30.8	30.0	30.8	31.6	46.8	49.5	44.3
53	18.3	18.7	19.8	29.8	31.6	31.3	24.1	24.9	25.2	32.1	29.5	29.1	35.6	36.8	38.6	46.1	45.9	48.4
65	22.8	24.6	23.0	27.8	29.9	31.2	24.5	23.6	24.5	34.2	34.8	39.8	32.0	34.3	38.0	49.9	46.4	48.1
163	23.4	25.6	23.0	27.2	23.1	25.1	30.7	29.8	31.3	39.1	34.7	36.2	23.3	20.8	24.0	34.0	37.0	37.7

TABLE B.3 US-91 Soil Stiffness Gauge Data for Site 3

Curing	Stiffness (MN/m)																	
Time	Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
(hr)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
2	13.0	13.3	13.6	12.1	12.7	12.8	13.5	14.2	14.5	15.3	16.4	12.9	13.2	13.1	13.1	14.2	14.5	14.9
16	28.3	31.7	31.5	27.2	24.0	26.5	30.8	32.1	31.6	31.7	26.8	25.9	24.0	24.3	24.3	26.0	26.6	25.6
25	30.1	29.9	29.7	25.6	24.1	30.6	26.7	32.0	34.5	30.5	30.2	31.9	30.3	28.1	21.4	28.7	29.1	30.7
40	32.3	33.3	29.9	24.8	29.2	31.0	32.7	32.9	31.4	32.8	32.7	35.6	29.6	28.9	29.8	35.9	36.0	36.6
64	38.3	38.8	32.4	37.5	36.9	36.9	37.1	38.9	39.1	39.5	41.1	36.5	33.6	32.1	33.5	41.1	41.3	40.6
162	41.0	45.2	46.7	27.9	33.8	33.6	24.8	29.6	28.6	24.0	31.3	30.4	25.2	27.7	23.3	27.5	28.3	29.9

TABLE B.4 US-91 Clegg Impact Soil Tester Data for Site 1

Curing Time (hr)	Clegg Impact Value																	
	Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
3	22.1	18.3	16.8	17.1	17.0	17.9	16.6	15.6	16.0	18.7	17.6	17.8	17.1	16.1	16.1	14.7	13.4	15.4
7	21.7	20.3	17.1	16.6	23.5	24.6	17.3	19.3	18.0	20.9	20.0	20.1	15.9	16.7	17.3	15.9	15.9	18.2
10	21.6	22.4	19.0	18.1	16.5	17.1	17.3	20.9	21.4	17.6	19.4	16.5	19.5	16.6	16.7	18.1	13.4	17.6
20	22.1	23.4	22.8	24.4	24.6	23.3	19.8	18.2	19.5	22.9	18.6	21.7	18.5	20.2	19.3	20.9	22.6	20.5
31	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
45	27.7	27.6	28.6	32.0	24.2	26.2	27.4	26.0	27.7	28.0	26.6	27.2	24.5	23.0	23.7	26.0	24.2	23.9
56	30.3	27.7	28.7	24.4	25.8	25.9	28.0	28.9	29.8	27.2	24.9	24.9	26.8	25.0	24.0	24.4	27.0	27.0
68	28.0	26.2	26.0	25.4	24.0	24.8	32.9	31.8	31.1	27.6	29.9	29.9	25.8	23.8	24.7	27.6	26.5	23.4
166	26.9	27.7	29.4	29.1	27.5	25.3	27.5	28.1	24.4	27.6	28.3	25.9	26.6	25.5	25.7	29.4	31.8	27.8

Note: Missing data were not collected due to instrument damage.

TABLE B.5 US-91 Clegg Impact Soil Tester Data for Site 2

Curing Time (hr)	Clegg Impact Value																	
	Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	22.1	21.4	16.1	16.0	16.9	16.6	16.3	18.7	16.8	17.3	19.5	23.5	18.1	17.4	21.2	24.8	15.0	19.3
5	18.9	18.6	18.1	18.9	16.6	16.8	19.0	19.4	19.0	17.5	17.7	17.6	18.3	20.2	20.0	18.5	17.7	19.5
17	25.5	24.4	25.0	23.7	25.6	26.1	21.6	23.0	22.2	21.3	21.3	21.2	21.6	24.1	23.5	26.8	23.9	23.9
42	25.7	23.0	24.8	26.2	24.6	23.5	18.8	20.8	20.4	23.3	22.6	23.2	23.9	23.0	22.9	26.6	26.5	25.7
53	25.0	23.9	26.6	29.2	27.1	25.2	24.1	22.2	22.4	23.5	24.6	25.4	27.7	25.7	25.3	27.1	26.9	27.2
65	25.3	25.7	26.4	23.3	24.5	24.7	27.1	27.4	27.1	24.3	26.8	26.4	26.5	24.5	24.4	25.3	25.2	25.6
163	39.0	36.6	35.1	40.4	35.4	35.8	34.5	32.0	28.0	28.8	24.3	27.8	39.4	35.2	37.2	36.8	35.3	31.6

TABLE B.6 US-91 Clegg Impact Soil Tester Data for Site 3

Curing Time (hr)	Clegg Impact Value																	
	Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
2	9.2	9.0	10.4	11.5	10.6	10.1	15.0	13.6	15.9	13.5	20.5	18.1	20.3	15.8	16.5	17.0	18.2	16.6
16	15.4	15.9	17.6	15.4	18.2	17.3	19.3	19.7	18.6	19.6	20.3	19.0	19.6	20.1	20.6	22.6	24.7	22.2
25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
40	24.4	22.1	24.2	25.0	23.3	24.5	22.0	20.6	21.9	21.4	20.3	19.5	16.8	17.1	20.0	20.7	22.1	23.4
64	32.5	32.1	32.0	34.6	34.1	32.8	33.8	33.3	34.5	30.5	29.3	29.2	26.0	27.9	27.3	23.5	24.5	23.2
162	35.6	32.6	36.6	44.6	48.0	46.8	46.8	58.0	44.2	47.3	53.1	48.6	39.1	42.8	39.1	47.0	51.6	41.1

Note: Missing data were not collected due to instrument damage.

TABLE B.7 US-91 Dynamic Cone Penetrometer Data for Site 1

Curing	Average Penetration for Upper 8" (in./blow)					
Time (hr)	Station 0	Station 20	Station 40	Station 60	Station 80	Station 100
3	0.31	0.40	0.34	0.36	0.43	0.43
68	-	0.14	-	-	0.17	-
166	-	0.04	-	-	-	-

Note: Missing data were deliberately not collected.

TABLE B.8 US-91 Dynamic Cone Penetrometer Data for Site 2

Curing	Average Penetration for Upper 8" (in./blow)					
Time (hr)	Station 0	Station 20	Station 40	Station 60	Station 80	Station 100
1	0.27	0.34	0.34	0.37	0.35	0.35
65	-	0.11	-	-	0.11	-
163	-	0.03	-	-	-	-

Note: Missing data were deliberately not collected.

TABLE B.9 US-91 Dynamic Cone Penetrometer Data for Site 3

Curing	Average Penetration for Upper 8" (in./blow)					
Time (hr)	Station 0	Station 20	Station 40	Station 60	Station 80	Station 100
2	0.30	0.34	0.30	0.29	0.36	0.30
64	-	0.13	-	-	0.15	-
162	-	0.05	-	-	-	-

Note: Missing data were deliberately not collected.

TABLE B.10 US-91 Portable Falling-Weight Deflectometer Data for Site 1

Curing Time (hr)	Layer	Modulus (ksi)																	
		Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
3	1	5.5	12.9	14.5	4.7	11.7	12.8	5.4	11.3	12.7	4.8	11.6	12.6	12.0	13.6	14.7	14.5	16.2	16.3
	2	11.5	11.7	11.7	13.1	11.7	11.2	11.0	10.6	9.0	16.3	16.7	17.2	11.4	10.4	10.9	8.6	7.8	7.9
7	1	13.4	20.2	19.7	11.7	14.6	20.2	5.9	14.3	15.6	7.7	15.9	16.7	6.2	13.9	14.9	6.7	14.6	15.7
	2	11.5	11.7	11.5	11.2	11.2	11.7	11.0	11.6	11.9	16.1	17.1	16.9	10.9	12.4	12.5	9.1	9.4	9.6
10	1	21.1	26.9	26.8	23.6	28.5	33.2	18.6	26.8	27.4	15.2	22.7	24.7	12.4	17.4	17.5	25.4	26.8	28.3
	2	12.8	12.3	12.2	15.4	13.1	12.3	11.9	12.2	12.5	16.4	16.8	16.7	15.1	15.7	15.7	11.6	12.2	11.7
20	1	60.9	60.7	61.4	44.4	44.6	44.3	139.6	137.6	108.2	112.0	110.6	112.1	56.5	56.7	57.2	58.2	57.6	57.6
	2	16.2	16.1	16.3	16.4	16.5	16.4	13.0	12.9	13.2	17.3	17.1	17.3	17.4	17.4	17.6	13.3	13.2	13.2
31	1	84.8	110.8	85.9	111.9	110.0	114.2	57.1	57.3	57.2	105.2	105.1	105.1	149.0	112.3	112.6	61.9	62.5	62.2
	2	17.0	17.1	17.4	17.3	17.0	17.6	17.6	17.5	17.6	18.5	18.7	18.6	17.1	17.3	17.4	16.4	16.6	16.5
45	1	144.8	-	202.1	144.5	144.1	146.4	110.3	109.9	110.2	65.9	66.6	66.9	199.0	204.9	205.9	147.8	146.9	147.7
	2	16.6	-	16.4	16.6	16.5	16.8	17.1	17.0	17.0	24.4	24.7	24.8	17.5	16.6	16.7	17.0	16.8	16.9
56	1	205.8	205.1	207.5	150.4	150.7	-	142.0	143.6	-	202.6	207.3	203.1	112.7	111.9	111.3	112.1	112.4	112.2
	2	16.7	16.6	16.8	17.2	17.2	-	18.2	18.5	-	18.0	18.3	17.9	17.4	17.3	17.2	17.4	17.3	17.3
68	1	196.5	197.0	196.4	298.5	196.9	-	136.0	135.7	136.8	110.8	111.3	154.5	198.6	195.7	198.5	84.2	135.8	90.6
	2	17.3	17.5	17.4	16.8	17.3	-	17.4	17.5	17.8	24.2	24.3	24.0	17.7	17.5	17.8	16.9	12.7	15.9
166	1	196.5	328.5	335.9	371.4	379.8	389.0	38.7	757.4	722.1	375.9	379.9	388.0	673.0	368.2	214.7	284.0	298.8	291.7
	2	24.0	22.7	23.1	23.3	24.0	24.5	26.2	25.1	23.9	26.0	26.3	26.7	22.4	25.6	26.0	16.0	16.8	16.4

Note: Missing data correspond to deflection basins that could not be analyzed.

TABLE B.11 US-91 Portable Falling-Weight Deflectometer Data for Site 2

Curing Time (hr)	Layer	Modulus (ksi)																	
		Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	1	14.5	13.7	11.6	17.4	15.3	11.0	14.3	12.7	6.0	8.9	8.2	7.5	13.1	10.8	5.5	20.2	20.3	17.8
	2	13.5	13.4	13.3	13.2	13.3	13.1	15.5	15.5	13.7	5.8	6.5	6.5	5.7	6.2	5.6	7.0	7.1	7.0
5	1	12.9	22.4	22.5	21.3	24.6	26.4	27.1	30.2	30.6	14.5	16.2	17.3	18.4	29.2	29.4	34.4	44.3	44.4
	2	15.7	16.6	16.7	15.2	16.6	15.6	16.5	16.5	16.8	11.7	10.4	10.3	9.4	8.3	8.4	9.5	9.7	9.7
17	1	134.8	139.9	139.3	101.4	101.3	100.5	44.7	45.1	46.0	58.4	58.8	58.6	39.6	40.1	40.0	183.0	183.1	184.3
	2	17.7	18.0	18.0	18.0	18.0	17.9	24.5	24.7	25.2	13.3	13.5	13.4	12.9	12.9	12.9	12.7	12.6	12.7
42	1	227.7	232.6	231.4	233.2	231.2	232.9	370.7	365.3	366.6	85.6	85.4	69.0	184.7	185.9	185.8	304.9	630.6	302.1
	2	23.6	23.9	23.9	23.9	23.9	24.0	25.6	25.2	25.4	17.2	17.1	17.5	12.8	12.9	12.9	16.6	12.0	16.4
53	1	310.9	303.8	310.7	141.2	141.7	140.3	38.6	39.0	39.3	86.8	70.2	69.7	108.8	110.1	110.9	258.1	257.7	257.8
	2	17.6	17.3	17.6	18.3	18.4	18.2	24.7	25.0	25.2	13.3	13.2	13.3	13.2	13.3	13.4	12.7	12.7	12.7
65	1	228.4	228.6	230.7	197.8	196.1	196.1	155.5	154.3	156.1	68.3	74.7	74.9	108.3	108.7	108.8	372.3	374.3	257.5
	2	23.5	23.7	23.8	17.3	17.4	17.4	24.1	24.0	24.2	17.2	16.3	16.3	13.1	13.2	13.2	12.4	12.4	12.7
163	1	668.3	724.6	734.9	652.5	756.9	785.8	-	-	-	225.5	233.4	239.9	502.9	475.8	-	496.3	537.3	-
	2	22.1	24.0	24.4	21.7	25.1	26.1	-	-	-	23.4	24.3	24.7	16.4	15.6	-	16.2	16.9	-

Note: Missing data correspond to deflection basins that could not be analyzed.

TABLE B.12 US-91 Portable Falling-Weight Deflectometer Data for Site 3

Curing Time (hr)	Layer	Modulus (ksi)																	
		Station 0			Station 20			Station 40			Station 60			Station 80			Station 100		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
2	1	7.6	7.2	6.7	9.5	8.7	8.1	11.0	10.9	10.0	9.4	9.0	8.7	11.5	10.5	4.2	10.9	9.8	4.4
	2	23.4	23.7	23.5	23.2	23.2	23.2	23.5	23.4	23.4	23.0	22.9	23.1	25.9	25.9	22.4	23.3	23.0	20.5
16	1	22.1	20.4	20.3	22.1	21.9	21.8	26.8	29.4	29.3	33.2	33.6	33.0	53.0	53.0	53.3	44.7	38.0	37.2
	2	25.4	25.5	25.4	25.3	25.1	25.0	25.2	24.6	24.5	24.5	24.8	24.3	24.2	24.2	24.3	24.4	24.4	23.9
25	1	38.9	39.2	39.4	51.2	54.2	45.3	46.0	45.6	45.2	67.3	67.2	67.1	29.4	29.3	26.3	83.2	84.1	83.0
	2	24.9	25.1	25.2	23.0	24.7	24.8	25.2	25.0	24.7	24.9	24.9	24.9	24.6	24.5	24.7	24.2	24.5	24.1
40	1	109.9	112.2	111.2	110.0	110.4	110.3	83.5	84.5	84.4	45.2	45.7	46.3	54.1	54.5	54.2	221.8	221.4	220.8
	2	24.0	24.4	24.3	23.9	24.1	24.1	24.3	24.6	24.5	24.7	25.0	25.4	24.7	24.9	24.8	26.9	26.7	26.9
64	1	73.6	75.8	75.0	233.6	233.5	229.4	111.3	111.2	112.0	156.3	153.9	155.5	84.0	85.1	84.6	139.6	140.5	139.0
	2	26.9	27.4	27.0	24.1	24.0	23.6	24.2	24.2	24.4	24.2	23.9	24.2	24.4	24.7	24.6	26.4	26.6	26.3
162	1	367.9	385.0	395.5	385.2	388.1	390.7	199.1	383.2	381.8	-	871.1	825.8	423.4	465.7	442.9	396.2	482.7	463.0
	2	25.6	26.5	27.4	26.7	26.8	27.0	24.1	26.6	26.3	-	26.7	24.9	43.5	48.2	45.5	40.9	50.0	47.5

Note: Missing data correspond to deflection basins that could not be analyzed.