JOINT TRANSPORTATION RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION AND PURDUE UNIVERSITY

Using the Light Weight Deflectometer for Performance-Based Quality Assurance Testing of Cement Modified Subgrades

Peter J. Becker

SPR-4230 • Report Number: FHWA/IN/JTRP-2021/07 • DOI: 10.5703/1288284317304

RECOMMENDED CITATION

Becker, P. J. (2021). *Using the light weight deflectometer for performance-based quality assurance testing of cement modified subgrades* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2021/07). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317304

AUTHORS

Peter J. Becker
Pavement Structure Research Engineer
Indiana Department of Transportation
(765) 463-1521 x249
pbecker1@indot.in.gov
Corresponding Author

JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

NOTICE

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JTRP-2021/07		

4. Title and Subtitle Using the Light Weight Deflectometer for Performance-Based Quality Assurance Testing of Chemically Modified Subgrades	**5. Report Date** January 2021 **6. Performing Organization Code**
7. Author(s) Peter J. Becker	**8. Performing Organization Report No.** FHWA/IN/JTRP-2021/07
9. Performing Organization Name and Address Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907	**10. Work Unit No.** **11. Contract or Grant No.** SPR-4230
12. Sponsoring Agency Name and Address Indiana Department of Transportation (SPR) State Office Building 100 North Senate Avenue Indianapolis, IN 46204	**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

This report documents the findings from SPR-4230 (Alternative Quality Assurance Methods for Compacted Subgrade). The main objective of SPR-4230 involved establishing performance-related quality assurance (QA) test methods for pavement subgrade construction. Because INDOT generally prefers specifying subgrade treatment type IBC (i.e., 14-in. cement modified subgrade), this study focused on performance-based QA test methods for constructing cement modified subgrade. Moreover, INDOT prefers using light weight deflectometer (LWD) for chemically modified subgrade construction acceptance, so this study aimed to use LWD deflection measurements as performance-related construction acceptance criteria. A laboratory study was performed to relate LWD deflections with resilient modulus that is the key subgrade performance-related parameter in pavement design. In addition, LWD deflections were related with unconfined compressive strength increase that is the key parameter in chemical soil modification mix design. A rigorous field study consisting of LWD testing and falling weight deflectometer (FWD) testing at INDOT new pavement construction sites was conducted to verify the laboratory developed relationship. Recommendations for implementing results of this study into cement modified subgrade construction acceptance is provided, as are recommendations for future research.

17. Key Words	18. Distribution Statement
soil stabilization, subgrade (pavements), quality assurance, deflectometers, specifications	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	93 including appendices	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Introduction

INDOT has been implementing light weight deflectometer (LWD) testing for compaction acceptance since the introduction of the 2016 standard specifications. LWD acceptance testing had been limited to the compaction of aggregates; however, INDOT has sought to expand LWD implementation because LWD is an easily operated, rapid in situ test that assesses soil stiffness. INDOT began specifying LWD testing for chemically modified soil acceptance with the introduction of the 2018 standard specifications. However, acceptance criteria for LWD testing of chemically modified soils were based on limited research. Indeed, acceptance criteria was not associated with performance-related engineering parameters. Resilient modulus is the most critical performance-related engineering parameter for subgrades in pavement design, so chemically modified subgrade acceptance criteria should reflect resilient modulus design values. In addition, INDOT requires that chemical modification increases soil unconfined compressive strength, so chemically modified subgrade acceptance criteria should reflect unconfined compressive strength increase. Therefore, the goal of this study is establishing LWD acceptance criteria that relate to subgrade resilient modulus and unconfined compressive strength increase for chemically modified soil, particularly cement modified soil.

Objectives

Successful outcomes for this study involve completing the following objectives:

- Develop laboratory-based relationships for predicting resilient modulus and unconfined compressive strength increase from LWD measurements for cement modified subgrade.
- Gather in situ LWD test measurements from field studies at INDOT's cement modified subgrade construction projects for assessing the laboratory-generated relationships predicting resilient modulus and unconfined compressive strength increase from LWD.
- Revisit the INDOT construction project field studies after paving to conduct falling weight deflectometer (FWD) testing for additional assessment of cement modified subgrade performance properties predicted from LWD testing.
- Compare LWD predicted resilient modulus values with resilient moduli back-calculated from FWD testing for cement modified subgrade using rigorous statistical analysis.
- Provide recommendations for cement modified subgrade LWD acceptance criteria that adequately reflect design assumptions—resilient modulus and unconfined compressive strength increase.
- Provide general recommendations for improving pavement design, construction, and performance as they pertain to cement modified subgrade.

Findings

This report documents the findings from SPR-4230. The main objective of SPR-4230 involves establishing performance-related quality assurance (QA) test methods for pavement subgrade construction. Because INDOT generally prefers specifying subgrade treatment type IBC (i.e., 14-in. cement modified subgrade), this study focuses on performance-based QA test methods for constructing cement modified subgrade. Moreover, INDOT prefers using light weight deflectometer (LWD) for chemically modified subgrade construction acceptance, so this study aims to use LWD deflection measurements as performance-related construction acceptance criteria. A laboratory study was performed to relate LWD deflections with resilient modulus, which is the key subgrade performance-related parameter in pavement design. In addition, LWD deflections were related with unconfined compressive strength increase, which is the key parameter in chemical soil modification mix design. A rigorous field study consisting of LWD testing and falling weight deflectometer (FWD) testing at INDOT new pavement construction sites was conducted to verify the laboratory developed relationship. Recommendations for implementing results of this study into cement modified subgrade construction acceptance is provided, as are recommendations for future research.

Key Findings

The key findings from this study are as follows:

- Unconfined laboratory LWD elastic moduli for cement treated soil increases with increasing applied axial stress following an exponential growth relationship. Using the generalized form of Hooke's law, the laboratory LWD elastic moduli can be used in three-dimensional applications (e.g., in situ LWD testing). Combining the generalized laboratory LWD relationship with Bousinesq's solutions for distribution of vertical and radial stresses within a semi-infinite homogenous elastic solid, then integrating calculated vertical strains, allows for the prediction of in situ LWD deflection and in situ LWD elastic modulus (Section 3.3.1).
- At equivalent stress conditions (bulk stress and octahedral shear stress) and equal curing times, LWD elastic modulus is approximately equal to resilient modulus for cement modified soil. However, LWD testing for construction acceptance is typically conducted after only 1-day curing, well before fully developing strength/stiffness (>28 days). Therefore, as-constructed cement modified LWD elastic moduli can be multiplied by a curing coefficient for direct comparison with long-term resilient moduli (Section 3.3.2).
- INDOT requires cement modified subgrade resilient modulus pavement design inputs equaling 9,000 psi for clayey soils and 9,500 psi for sandy soils. Using a probabilistic model with LWD deflection equaling 0.45 mm, there is a 90% probability that resilient modulus meets or exceeds 9,000 psi. Likewise, with LWD deflection equaling 0.43 mm, there is a 90% probability that resilient modulus meets or exceeds 9,500 psi (Section 3.3.2).
- INDOT requires that cement modification increase subgrade soil unconfined compressive strength (UCS) by no less than 100 psi. However, field UCS values tend to equal approximately 70% laboratory UCS values, so LWD values should demonstrate 70 psi increases in UCS. Predicted LWD elastic modulus correlates well (R^2 = 0.695) with UCS increases, using an exponential growth model. If measured LWD deflection equals 0.27 mm, as specified in the INDOT standard specifications; then there is an 86% probability that ΔUCS will meet or exceed 70 psi. For there to be a 90% probability that ΔUCS meets or exceeds 70 psi, measured LWD deflection should equal 0.21 mm (Section 3.3.3).
- Detailed case histories for new pavement construction projects incorporating cement modified subgrade have been

developed—US 6, I 469, Cleveland Road, I 65, SR 46, SR 66, and CR 400 S. Case histories consist of laboratory mix designs, LWD elastic moduli during construction, and FWD-derived resilient moduli after pavement placement have been generated (Section 4.2).

- LWD deflections from all field test sites combine into a skewed right distribution; however, logarithmic (base 10) transformation yields a nearly normal distribution with -0.586 average (0.259 mm) and 0.158 standard deviation (Section 5.1).
- Bland-Altman comparison between LWD predicted resilient modulus and FWD back-calculated resilient modulus reveals that the vast majority of points (97.4%) fall between the 95% (i.e., $\alpha = 0.5$) limits of agreement. Therefore, resilient moduli predicted from LWD immediately following subgrade treatment adequately agree with resilient moduli back-calculated from FWD measured on the pavement surface (Section 5.1).
- A probabilistic model for LWD predicted resilient modulus was generated using statistics from LWD field results combined with the standard error for predicting resilient modulus from LWD elastic modulus. Predicted resilient modulus equals 13,200 psi at $p = 0.1$ that corresponds to 90% of construction acceptance tests yielding passing results. Therefore, INDOT can comfortably assign design resilient modulus values equal to 13,200 psi for subgrade treatment type IBC in pavement design based on results from LWD test measurements (Section 5.2).
- A probabilistic model for FWD back-calculated resilient modulus was generated using statistics from FWD field tests. FWD back-calculated resilient modulus equals 17,800 psi at $p = 0.1$ that corresponds to 90% of construction acceptance tests yielding passing results. Therefore, based on results from FWD test measurements, INDOT can comfortably assign design resilient modulus values equal to 17,800 psi for subgrade treatment type IBC in pavement design (Section 5.2).
- Because the current maximum LWD deflection criterion meets design resilient modulus assumptions, meets unconfined compressive strength increase requirements, and is consistent with actual measurements taken during construction; INDOT should continue specifying 0.27 mm maximum deflection for cement modified subgrade construction acceptance (Section 6.1).
- Conservative estimates for cement modified subgrade resilient modulus equaled 13,200 psi based on LWD testing and 17,800 psi based on FWD testing, which are both significantly greater than the 8,000 psi to 9,000 psi resilient moduli used in new pavement design. Therefore, it is recommended that additional testing (Automated Plate Load Testing) be conducted to explore this finding further (Section 6.2).

Implementation

Maximum Allowable LWD Deflection for Cement Modified Soil

INDOT standard specifications require that LWD deflection measured on cement modified subgrade equal no greater than 0.27 mm on average. Findings from the laboratory portion of this study suggests that 0.27 mm LWD deflection corresponds to 26,500 psi 28-day cure resilient modulus that is much greater than the 8,000 psi to 9,000 psi resilient modulus used in new pavement design. Therefore, the current maximum deflection criterion adequately assures that constructed cement modified subgrades meet design assumptions.

Besides meeting design resilient moduli, cement modified subgrades must be able to function as construction working platforms. INDOT design procedures for chemical modification and stabilization of soils require that cement modification increase laboratory unconfined compressive strength by 100 psi (70 psi in the field, see Section 3.1.3). Findings from the laboratory study suggest that 0.27 mm LWD deflection corresponds to 89 psi unconfined compressive strength increase. Therefore, the current maximum deflection criterion adequately assures that constructed cement modified subgrades function appropriately as construction working platforms.

LWD field testing conducted at INDOT new pavement construction projects showed that LWD deflection equals 0.26 mm on average. So, actual LWD deflections are consistent with the 0.27 mm required by INDOT standard specifications. Moreover, resilient moduli predicted from LWD measurements conducted during construction are in agreement with resilient moduli determined from FWD testing measured atop pavement layers.

Because the current maximum LWD deflection criterion meets design resilient modulus assumptions, meets unconfined compressive strength increase requirements, and is consistent with actual measurements taken during construction; INDOT should continue specifying 0.27 mm maximum deflection for cement modified subgrade construction acceptance.

Cement Modified Soil Design Resilient Modulus Implementation Study

A key finding from this study involved typical resilient modulus values for cement modified subgrade. Conservative estimates for cement modified subgrade resilient modulus equaled 13,200 psi based on LWD testing and 17,800 psi based on FWD testing, which are both significantly greater than the 8,000 psi to 9,000 psi resilient moduli used in new pavement design. However, neither the LWD- nor the FWD-based methods directly measure resilient modulus. Therefore, there is no assurance that either method truly predict resilient modulus. Rather, it is recommended that additional testing be conducted to explore this finding further.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

1. INTRODUCTION

1.1 Project Background

INDOT has been implementing light weight deflectometer (LWD) testing for compaction acceptance since the introduction of the 2016 standard specifications. LWD acceptance testing had been limited to the compaction of aggregates; however, INDOT has sought to expand LWD implementation because LWD is an easy to operate, rapid in situ test that assesses soil stiffness. INDOT began specifying LWD testing for chemically modified soil acceptance with the introduction of the 2018 standard specifications. However, acceptance criteria for LWD testing of chemically modified soils were based on limited research. Indeed, acceptance criteria was not associated with performance-related engineering parameters. Resilient modulus is the most critical performance-related engineering parameter for subgrades in pavement design, so chemically modified subgrade acceptance criteria should reflect resilient modulus design values. In addition, INDOT requires that chemical modification increase soil unconfined compressive strength, so chemically modified subgrade acceptance criteria should reflect unconfined compressive strength increase. Therefore, the goal of this study involves establishing LWD acceptance criteria that relate to subgrade resilient modulus and unconfined compressive strength increase for chemically modified soil, particularly cement modified soil.

1.2 Research Objectives

Successful outcome for this study involves completing the following objectives:

- Develop laboratory-based relationships for predicting resilient modulus and unconfined compressive strength increase from LWD measurements for cement modified subgrade.
- Gather in situ LWD test measurements from field studies at INDOT cement modified subgrade construction projects for assessing the laboratory generated relationships predicting resilient modulus and unconfined compressive strength increase from LWD.
- Revisit the INDOT construction project field studies after paving to conduct falling weight deflectometer (FWD) testing for additional assessment of cement modified subgrade performance properties predicted from LWD testing.
- Compare LWD predicted resilient modulus values with resilient moduli back-calculated from FWD testing for cement modified subgrade using rigorous statistical analysis.
- Provide recommendations for cement modified subgrade LWD acceptance criteria that adequately reflect design assumptions—resilient modulus and unconfined compressive strength increase.
- Provide general recommendations for improving pavement design, construction, and performance as they pertain to cement modified subgrade.

2. BACKGROUND

2.1 Cement Modified Subgrade Current INDOT Practice

When specifying new pavement construction (e.g., added travel lanes, new alignment, etc.), INDOT requires that pavement subgrades be constructed using some form of subgrade treatment. Table 2.1 provides a list of subgrade treatment types currently allowed by INDOT for use in design. INDOT pavement engineers commonly specify subgrade treatment type IB (i.e., chemical modification) for contracts requiring new pavement construction. Subgrade treatment type IB involves treating subgrade soil to a depth of 14 in. with either type I Portland cement or lime (calcium oxide or calcium hydroxide). However, INDOT generally prefers that cement be used for subgrade chemical treatment because cement production tends to have better quality control. Moreover, cement treatment is applicable for nearly all soil types, while lime treatment only is only applicable for cohesive soils (INDOT, 2015). So, the majority of INDOT new pavement construction contracts involve chemical modification using type I Portland cement (i.e., subgrade treatment type IBC).

INDOT requires that pavement contractors submit a mix design for cement modified subgrade conducted in accordance with *INDOT Design Procedures for Soil Modification or Stabilization* (INDOT, 2015). Cement modification must increase the unconfined compressive strength of subgrade soil compacted to 95% relative

TABLE 2.1
Pavement subgrade treatment types allowed by INDOT

Treatment Type	Subgrade Description
I	24-in. soil compacted in accordance with INDOT standard specification 203.23
IBC	14-in. chemical soil modification with cement
IBL	14-in. chemical soil modification with lime
IC	12-in. coarse aggregate No. 53
II	6-in. coarse aggregate No. 53
IIA	8-in. chemical soil modification
III	In-place compaction in accordance with INDOT standard specification 203.23
IV	12-in. coarse aggregate No. 53 with Type IB geogrid in accordance with INDOT standard specification 214
IVA	12-in. coarse aggregate with Geocell confining system with INDOT standard specification 214
V	3 in. of subgrade excavated and replaced with 3 in. coarse aggregate No. 53

compaction by no less than 100 psi after curing at room temperature for 48-hours. Cement contents identified in cement modification mix designs typically range from 4% to 5% dry weight of soil.

Section 215 of the INDOT standard specifications details construction requirements for subgrade cement modification. Acceptance testing of chemically modified subgrade is conducted in accordance with section 203.24 of the INDOT standard specifications. INDOT specifies use of light weight deflectometer (LWD) for chemically modified subgrade acceptance testing. The LWD is a stiffness-based in situ test typically used for construction quality control (QC) and quality assurance (QA). LWD testing involves dropping a 22 lb. weight from about 28 in. onto a 11.81-in. diameter steel loading plate and measuring the resulting deflection (see Section 4.1.1 of this report for more information). INDOT currently requires that LWD testing of cement modified subgrades yield average deflections no higher than 0.27 mm, and testing may occur as soon as 1-day following mixing operations.

2.2 Cement Modified Subgrade in Pavement Design

INDOT currently uses the mechanistic-empirical pavement design guide (MEPDG) for designing new pavements. MEPDG software predicts structural distresses (e.g., percent fatigue cracking) over the course of a pavement structure design life due to traffic and climactic loading. An MEPDG user can use trial and error with established failure criteria to select an optimum pavement configuration. Although MEPDG software allows users to input chemically stabilized material pavement layers, INDOT prefers to model cement modified subgrade as an unbound material requiring input of resilient modulus. Resilient modulus is a stress-dependent measure of stiffness, so the MEPDG recommends the following constitutive model (Equations 2.1–2.3) for predicting resilient modulus:

$$M_r = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \quad \text{(Eq. 2.1)}$$

$$\theta = \sigma_1 + \sigma_2 + \sigma_3 \quad \text{(Eq. 2.2)}$$

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \quad \text{(Eq. 2.3)}$$

Where,

M_r = resilient modulus (psi),
θ = bulk stress (psi),
τ_{oct} = octahedral shear stress (psi),
σ_1 = major principal stress (psi),
σ_2 = intermediate principal stress (psi),
σ_3 = minor principal stress (psi),
k_1, k_2, k_3 = regression constants, and
p_a = atmospheric pressure (14.7 psi).

In general, resilient modulus increases with increasing bulk stress (i.e., confinement) and decreases with increasing octahedral shear strain (i.e., shear strain). When resilient moduli are determined from laboratory testing (AASHTO, 2017), INDOT selects resilient modulus values corresponding to σ_1 = 8 psi and $\sigma_2 = \sigma_3$ = 2 psi. However, resilient moduli for cement treated subgrade are assumed equal to 9,000 psi for clayey soils and 9,500 psi for sandy soils.

2.3 Performance-Related Construction Specifications

The Federal Highway Administration (FHWA, 2020) advocates for the implementation of construction performance-related (PR) specifications that are essentially improved quality assurance (QA) specifications. Product acceptance using QA specifications is based on statistical sampling of a measured quality level for key quality characteristics (e.g., dry density). If the key quality characteristic being measured for acceptance influences product performance or can be used to predict product performance, then the QA specification becomes a PR specification. Resilient modulus is the key subgrade property predicting pavement performance in the MEPDG, so PR specifications for cement modified subgrade should involve measurement of resilient modulus. However, INDOT currently does not measure resilient modulus during construction. Moreover, INDOT requires that cement modification increase subgrade soil unconfined compressive strength, so unconfined compressive strength increase should be measured for PR specifications as well.

3. LABORATORY TESTING PROGRAM

3.1 Laboratory Testing Methods

3.1.1 Laboratory Light Weight Deflectometer

Shown in Figure 3.1, the laboratory light weight deflectometer (LLWD) was used to measure soil specimen stiffness. The LLWD is a scaled down version of the Zorn light weight deflectometer (refer to Section 4.1.1 of this report). LLWD testing involves dropping an 11 lb. drop weight from an adjustable height (no greater than 17.8 in.) onto a 5.91-in. diameter loading plate resting atop a specimen. The impulse generated by the drop weight striking the loading plate induces vertical deflection of the specimen that is inversely proportional to its stiffness. An accelerometer housed inside of the loading plate measures acceleration of the loading plate over time, and an external data acquisition device twice integrates the acceleration response with respect to time to compute deflection. The data acquisition device determines the maximum deflection reported in millimeters.

The peak applied loading from LLWD testing is determined from 3.1 that takes into account mass of the drop weight, drop height, and stiffness of the buffer between the drop weight and loading plate. The LLWD

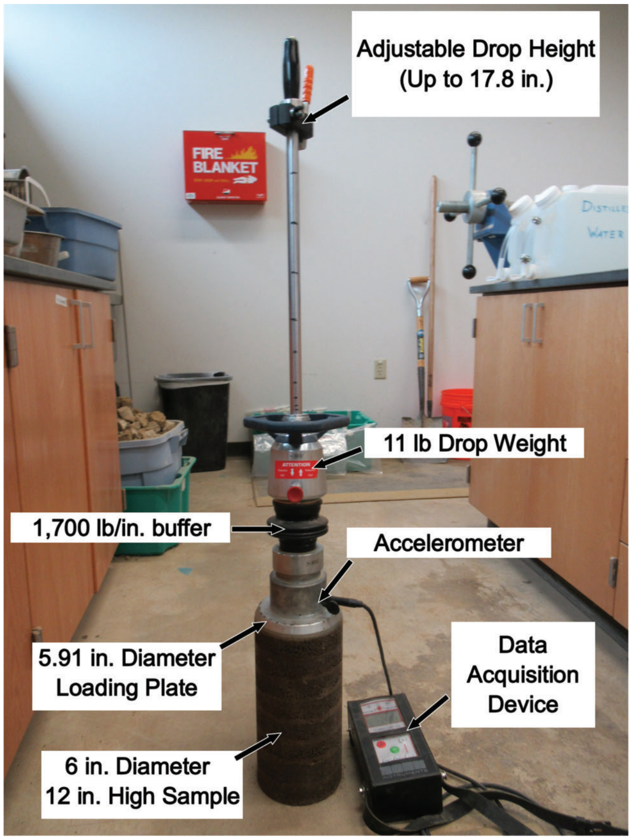


Figure 3.1 Zorn laboratory light weight deflectometer test setup.

used in this study had a buffer stiffness of about 1,700 lb./in.

$$F = \sqrt{2Whk} \qquad \text{(Eq. 3.1)}$$

Where,

F = peak applied force (lb.),
W = weight of drop weight (lb.),
h = drop height (in.), and
k = buffer stiffness (lb./in.).

Because no confinement was applied to specimens during LLWD testing, LLWD secant elastic moduli (E_s) were calculated from Equation 3.2 that is simply stress over strain.

$$E_s = \frac{4F\ell}{\pi D^2 \delta_{LLWD}} \qquad \text{(Eq. 3.2)}$$

Where,

E_s = LLWD secant modulus (psi),
F = peak applied force (lb.),
ℓ = specimen height (nominal 12 in.),
D = specimen diameter (nominal 6 in.), and
δ_{LLWD} = LLWD measured deflection (in.).

LLWD testing was conducted on specimens after curing for 1 day, 2 days, 3 days, 7 days, and 28 days. E_s values were determined at nominal applied axial stresses equal to 3.5 psi (1/4″ drop height), 4.9 psi (1/2″ drop height), 6.9 psi (1″ drop height), 9.8 psi (2″ drop height), and 13.9 psi (4″ drop height).

3.1.2 Resilient Modulus Test (AASHTO T 307)

A Geocomp LoadTrac II resilient modulus setup (Figure 3.2) was used to measure specimen resilient modulus. Resilient modulus values were determined in accordance with AASHTO T 307 (2017). As prescribed by AASHTO T 307, a total of 16-testing sequences (Table 3.1) were used to quantify the resilient modulus stress dependency (bulk stress and octahedral shear stress) for each specimen. Resilient modulus testing was conducted on specimens after curing for 28 days.

3.1.3 Unconfined Compressive Strength Test (AASHTO T 208)

A Geocomp LoadTrac II load frame machine (Figure 3.3) was used to conduct unconfined compressive strength (UCS) tests in accordance with AASHTO T 208 (2019). Because cement treated soil tends to exhibit brittle stress-strain behavior, loading was applied at a relatively slow 1% axial strain per minute strain rate to capture proper stress-strain curves. Unconfined compressive strength values correspond to the maximum axial stress applied during testing. UCS testing was conducted on specimens after curing for 28 days.

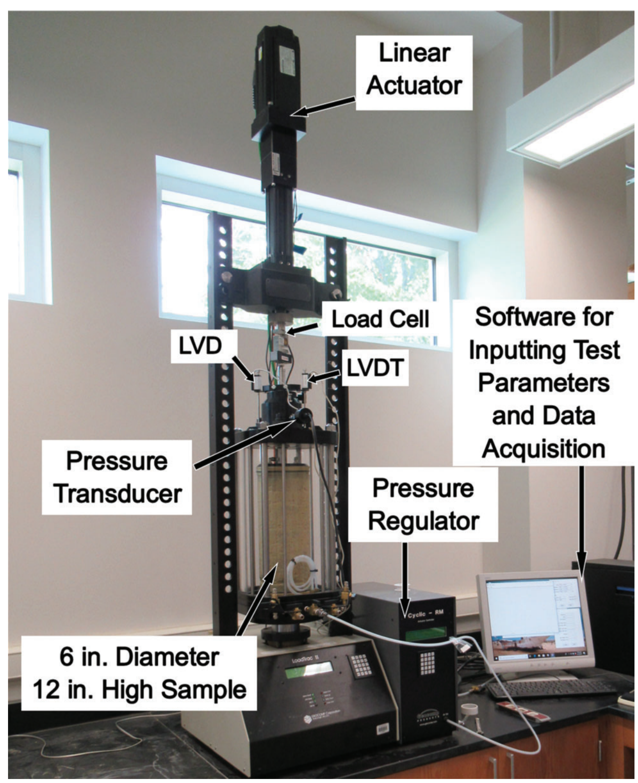


Figure 3.2 Geocomp LoadTrac II resilient modulus setup.

TABLE 3.1
Resilient modulus testing sequence used in this study

Sequence	Confining Pressure (psi)	Maximum Axial Stress (psi)	Cyclic Axial Stress (psi)	Constant Axial Stress (psi)	Number of Cycles
0	6	4	3.6	0.4	750
1	6	2	1.8	0.2	100
2	6	4	3.6	0.4	100
3	6	6	5.4	0.6	100
4	6	8	7.2	0.8	100
5	6	10	9.0	1.0	100
6	4	2	1.8	0.2	100
7	4	4	3.6	0.4	100
8	4	6	5.4	0.6	100
9	4	8	7.2	0.8	100
10	4	10	9.0	1.0	100
11	2	2	1.8	0.2	100
12	2	4	3.6	0.4	100
13	2	6	5.4	0.6	100
14	2	8	7.2	0.8	100
15	2	10	9.0	1.0	100

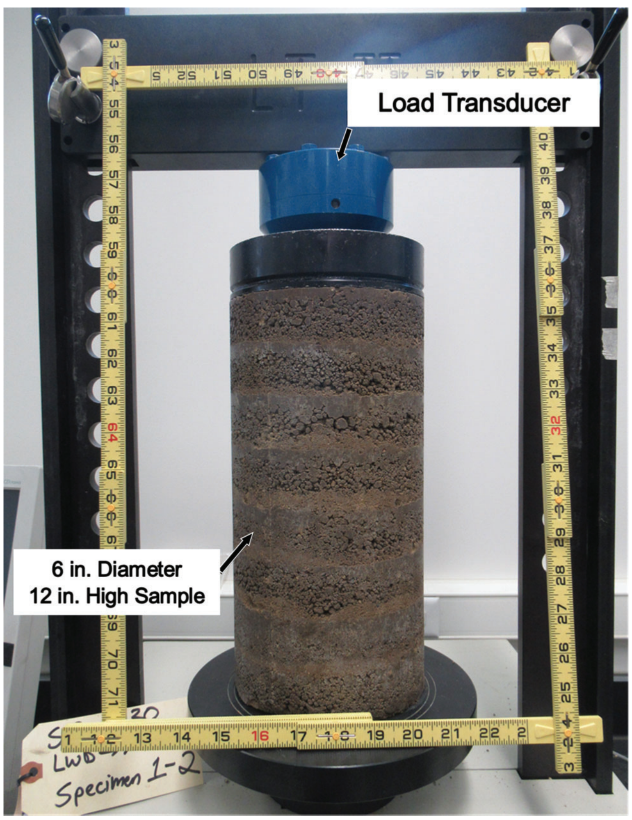


Figure 3.3 Geocomp LoadTrac II unconfined compressive strength setup.

3.2 Laboratory Testing Materials

Laboratory testing was conducted on two different soils native to Indiana—Soil No. 1 and Soil No. 2. Both soils are representative of subgrade soil typically encountered in INDOT pavement construction. The following sections summarize index properties, compaction characteristics, and strength properties for the Soils No. 1 and No. 2.

3.2.1 Soil No. 1

Soil No. 1 was sourced from the construction of I-69 RP 219+50 to RP 233+95 added travel lanes near Anderson in Greenfield District (R-39093). Figure 3.4 shows the particle size distribution for Soil No. 1, and Table 3.2 summarizes soil index properties and classifications for Soil No. 1.

A moisture-density curve for Soil No. 1 (Figure 3.5) was generated in accordance with AASHTO T 99 (2015) that specifies standard Proctor energy (i.e., 12,400 ft-lb/ft^3). Soil No. 1 had a maximum dry unit weight of 119.9 pcf at a 12.5% optimum moisture content. Soil No. 1 has a dry unit weight of 113.9 pcf at 95% relative compaction.

Figure 3.6 provides unconfined compressive strength test results for 2-samples of Soil No. 1 compacted to 95% relative compaction at optimum moisture content. Unconfined compressive strength for Soil No. 1 equaled 17.6 psi on average, and maximum axial stress tended to occur at about 2% axial strain.

Figure 3.7 shows the moisture-density curve for Soil No. 1 mixed with a nominal 4% Portland cement by weight and compacted in accordance with AASHTO T 99 (2015). When mixed with 4% Portland cement, Soil No. 1 has a dry unit weight of 117.8 pcf at a 12.8% optimum moisture content. Dry density at 95% relative compaction for the Soil No. 1 and 4% Portland cement mixture equals 111.9 pcf.

3.2.2 Soil No. 2

Soil No. 2 was sourced from the construction of the Accelerated Pavement Test (APT) facility at INDOT Research and Development in West Lafayette. Figure 3.8 shows the particle size distribution for Soil No. 2, and

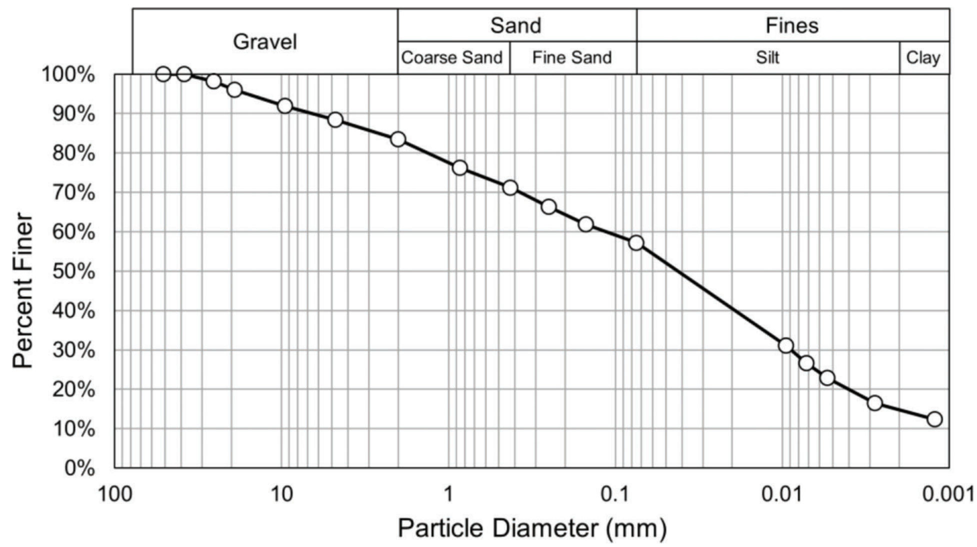


Figure 3.4 Particle size distribution for Soil No. 1.

TABLE 3.2
Soil No. 1 index properties and classifications

Property	
Particle Size Distribution	
Percent Gravel	16.6%
Percent Sand	26.2%
Percent Silt	42.4%
Percent Clay	14.8%
Plasticity	
Liquid Limit	24
Plasticity Index	9
Soil Classification	
AASHTO	A-4 (3)
USCS	CL (Sandy Lean Clay)
Textural	Loam

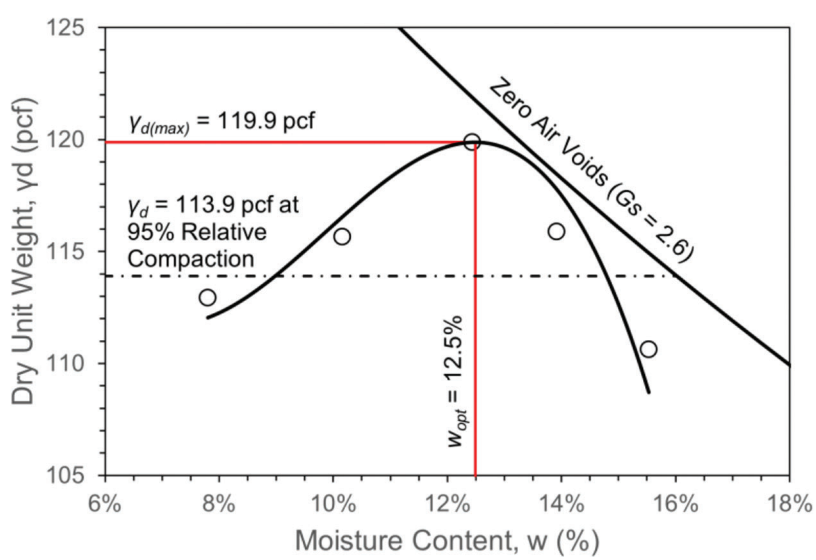


Figure 3.5 Soil No. 1 moisture-density curve in accordance with AASHTO T 99.

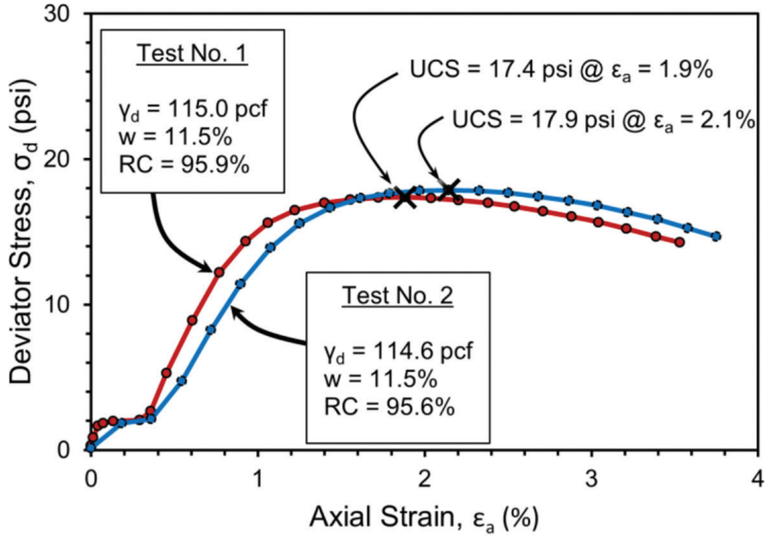


Figure 3.6 Soil No. 1 unconfined compressive strength test results.

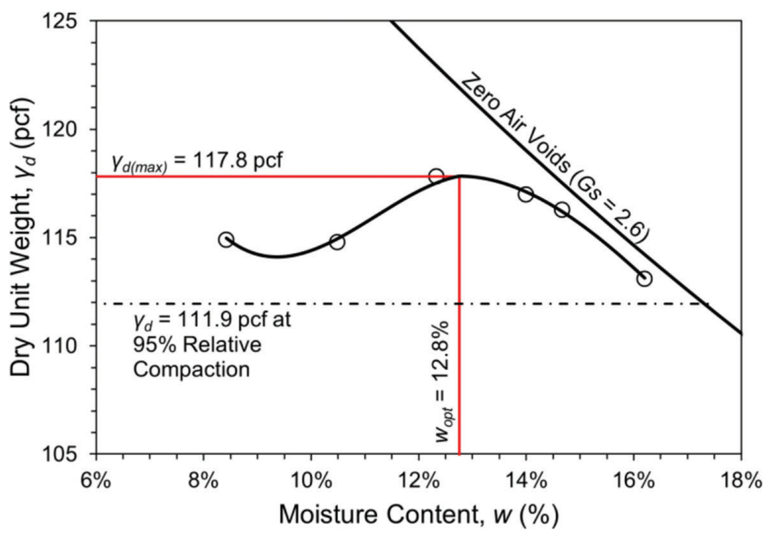


Figure 3.7 Soil No. 1 mixed with 4% Portland cement moisture-density curve in accordance with AASHTO T 99.

Table 3.3 summarizes soil index properties and classifications for Soil No. 2.

A moisture-density curve for Soil No. 2 (Figure 3.9) was generated in accordance with AASHTO T 99 (2015). Soil No. 2 had a maximum dry unit weight of 112.0 pcf at a 15.5% optimum moisture content. Soil No. 2 has a dry unit weight of 106.4 pcf at 95% relative compaction.

Figure 3.10 provides unconfined compressive strength test results for 2-samples of Soil No. 2 compacted to 95% relative compaction at optimum moisture content. Unconfined compressive strength for Soil No. 2 equaled 24.2 psi on average, and maximum axial stress tended to occur at about 1.5% axial strain.

Figure 3.11 shows the moisture-density curve for Soil No. 2 mixed with a nominal 4% Portland cement by weight and compacted in accordance with AASHTO T 99 (2015). When mixed with 4% Portland cement, Soil No. 2 has a dry unit weight of 109.4 pcf at a 16.6% optimum moisture content. Dry density at 95% relative compaction for the Soil No. 2 and 4% Portland cement mixture equals 104.0 pcf.

3.3 Laboratory Testing Results

3.3.1 LLWD Testing Results

A total of eleven 6-in. diameter, 12-in. high specimens were prepared at different relative compactions, moisture contents relative to optimum, and nominal cement contents as prescribed in Table 3.4. The ranges in compaction properties and cement contents were prescribed to generate variation in LLWD stiffnesses, UCS values, and resilient moduli among the specimen samples.

Table 3.5 summarizes LLWD testing results for Soil No. 1 specimens (specimens 1-1 to 1-7), and Table 3.6 summarizes LLWD testing results for Soil No. 2 specimens (specimens 2-1 to 2-4). All specimens in

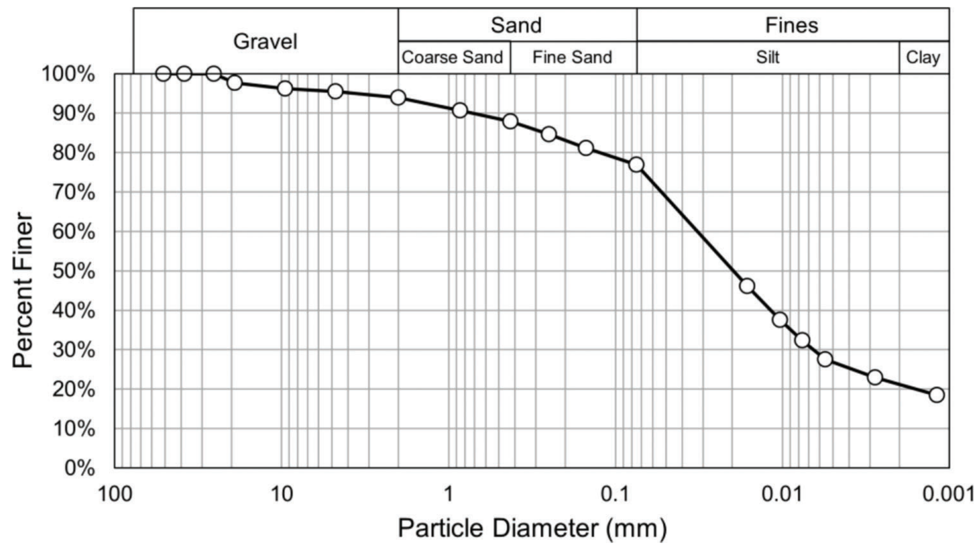


Figure 3.8 Particle size distribution for Soil No. 2.

TABLE 3.3
Soil No. 2 index properties and classifications

Property	
Particle Size Distribution	
Percent Gravel	6.1%
Percent Sand	17.0%
Percent Silt	55.7%
Percent Clay	21.2%
Plasticity	
Liquid Limit	33
Plasticity Index	20
Soil Classification	
AASHTO	A-6 (7)
USCS	CL (Lean Clay with Sand)
Textural	Silty Clay Loam

the laboratory study exhibited strain-hardening stress dependency since LLWD secant modulus (E_s) values increased with increasing applied axial stress (σ_a). Appendix A shows the relationships between E_s and σ_a for the laboratory specimens that best correlated using an exponential growth function (Equation 3.3).

$$E_s = C_1 e^{C_2 \sigma_a} \qquad \text{(Eq. 3.3)}$$

Where,

E_s = LLWD secant modulus (psi),
σ_a = axial stress (psi), and
C_1, C_2 = regression constants.

Equation 3.3 only accounts for one-dimensional loading; however, the equation may be expanded to three dimensional loading after incorporating the generalized form of Hooke's law (Equation 3.4).

$$\varepsilon_z = \frac{1}{E_s}[\sigma_z - \nu(\sigma_r + \sigma_\theta)] \qquad \text{(Eq. 3.4)}$$

Where,

E_s = LLWD secant modulus (psi),
ε_z = vertical strain (in./in.),
ν = Poisson's ratio (0.3 assumed)
σ_z = vertical stress (psi),
σ_r = radial stress (psi), and
σ_θ = tangential stress (psi).

When subjected to symmetric loading (e.g., under the center of an LWD loading plate) radial and tangential stresses are equivalent, so the generalized relationship between stress and *E*s becomes:

$$E_s = C_1 e^{C_2(\sigma_z - 2\nu\sigma_r)} \qquad \text{(Eq. 3.5)}$$

Where,

E_s = LLWD secant modulus (psi),
ν = Poisson's ratio (0.3 assumed)
σ_z = vertical stress (psi),
σ_r = radial stress (psi), and
C_1, C_2 = regression constants.

As discussed later in this report (Section 4.1.1), LWD testing in situ involves applying a 1,590 lb. vertical load to an 11.81-in. diameter steel loading plate. Because the stiffness of the loading plate is much greater than that of the cement treated subgrade, the loading plate was assumed plate as rigid leading to an inverse-parabolic contact stress (Equation 3.6) applied to the ground surface.

$$q(\rho) = \frac{F}{2\pi\sqrt{r^2 - \rho^2}} \qquad \text{(Eq. 3.6)}$$

Where,

$q(\rho)$ = contact stress at ρ (psi),
ρ = radial distance from center of loading plate (in.),
r = vertical stress (psi),
σ_r = loading plate radius (in.), and
F = peak applied force (lb.).

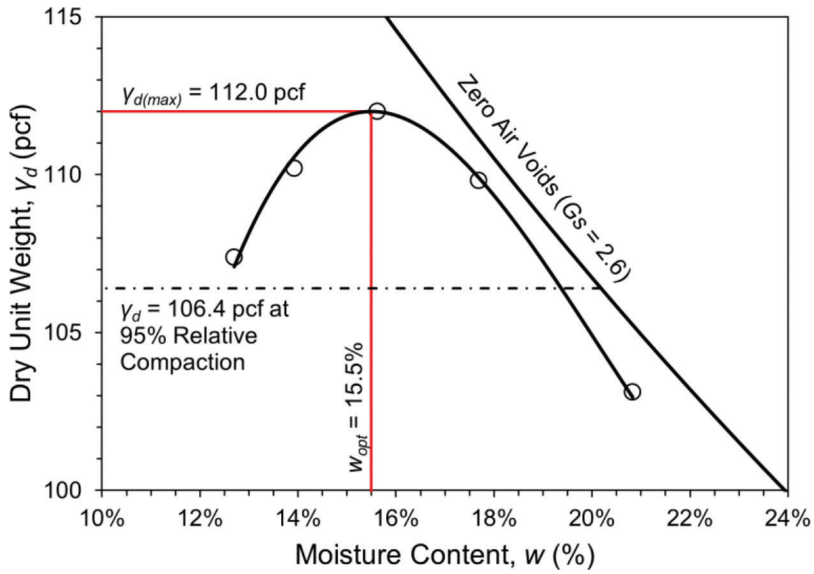


Figure 3.9 Soil No. 2 moisture-density curve in accordance with AASHTO T 99.

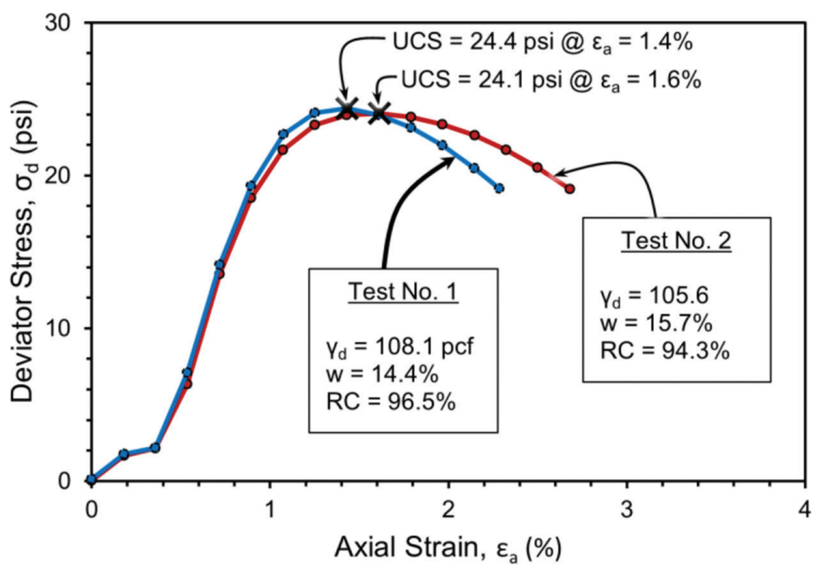


Figure 3.10 Soil No. 2 unconfined compressive strength test results.

Combining Equation 3.6 with Boussinesq's solution for determining stresses within a semi-infinite elastic solid allows for calculation of in situ vertical stress (Equation 3.7) and in situ radial stress (Equation 3.8):

$$\sigma_z = \int_0^{2\pi} \int_0^{r} \left\{ \frac{3F\rho z^3}{4r\pi^2(\rho^2+z^2)^{5/2}\sqrt{r^2-\rho^2}} \right\} d\rho d\phi \qquad \text{(Eq. 3.7)}$$

$$\sigma_r = \int_0^{2\pi} \int_0^{r} \left\{ \frac{F\rho\left[\frac{3\rho^2 z}{(\rho^2+z^2)^{5/2}} - \frac{1-2v}{\sqrt{\rho^2+z^2}\left(z+\sqrt{\rho^2+z^2}\right)}\right]}{4r\pi^2\sqrt{r^2-\rho^2}} \right\} d\rho d\phi \qquad \text{(Eq. 3.8)}$$

Where,

σ_z = vertical stress (psi),
ρ = radial distance from center of loading plate (in.),
r = vertical stress (psi),
z = depth below ground surface (in.),
ϕ= polar angle (radians),
v = Poisson's ratio (0.3 assumed),
σ_r = loading plate radius (in.), and
F = peak applied force (lb.).

Vertical deflection at the ground surface equals the integration of vertical strain with respect to z. So, combining Equations 3.4, 3.5, 3.7, and 3.8 and then integrating the result from zero to infinity (i.e., no effect from bedrock) produces the predicted in situ LWD deflection. White et al. (2013) found that the in situ

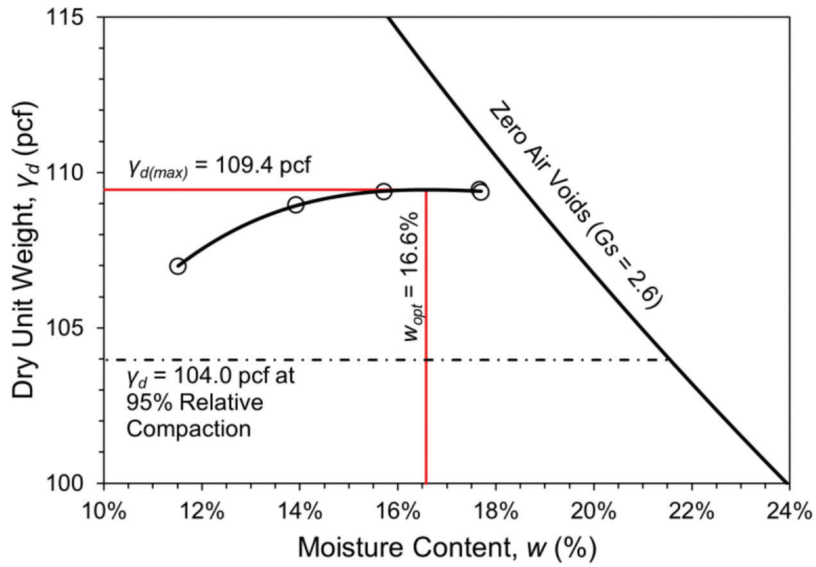


Figure 3.11 Soil No. 2 mixed with 4% Portland cement moisture-density curve in accordance with AASHTO T 99.

TABLE 3.4
Nominal cement contents and target compaction properties for specimens in laboratory study

Specimen ID	Soil No.	Nominal Cement Content (%)	Relative Compaction		Moisture Content Relative to Optimum	
			Target Value (%)	Actual Value (%)	Target Value (%)	Actual Value (%)
1-1	No. 1	4	95	94.2	0	+0.7
1-2	No. 1	4	90	91.0	0	-0.3
1-3	No. 1	4	100	99.9	0	-0.2
1-4	No. 1	4	95	91.9	-2	-2.8
1-5	No. 1	4	95	96.1	+2	+1.3
1-6	No. 1	3	95	95.2	0	+0.0
1-7	No. 1	5	95	95.0	0	-0.1
2-1	No. 2	4	95	95.2	0	-0.8
2-2	No. 2	4	90	90.1	0	-0.6
2-3	No. 2	4	100	99.0	0	+1.6
2-4	No. 2	4	95	92.9	-2	+0.3

LWD measurement influence depth is approximately equal to the loading plate diameter, so this integration approach should be valid as long as the loading plate diameter (i.e., 11.81 in.) does not exceed the thickness of the cement treated subgrade layer (i.e., 14 in.). Because the mathematics involved was rather rigorous, integration was approximated using 6-point Gaussian quadrature.

Table 3.5 reports predicted LWD modulus values for Soil No. 1 specimens (specimens 1-1 to 1-7), and Table 3.6 reports predicted LWD modulus values for Soil No. 2 specimens (specimens 2-1 to 2-4).

3.3.2 Resilient Modulus Testing Results

Table 3.7 summarizes resilient modulus testing results for both Soil No. 1 specimens (specimens 1-1 to 1-7) and Soil No. 2 specimens (specimens 2-1 to 2-4). Appendix B provides detailed resilient modulus test results for all specimens in the laboratory study. Resilient modulus testing results were fit to Equation 2.1 that is the MEPDG preferred model for unbound material resilient modulus. Reported specimen resilient moduli were normalized to 6.9 psi deviator stress (σ_d) and 2.1 psi confining pressure (σ_3) because average in situ stresses from LWD loading equaled 8.0 psi vertical stress (Equation 3.7) and 2.1 psi radial/tangential stress (Equation 3.8).

Figure 3.12 plots a comparison of 28-day cure resilient moduli (M_r) with predicted 28-day cure LWD elastic moduli (E_{LWD}) that suggests that E_{LWD} is approximately equal to M_r on average. However, construction quality control/assurance procedures require that LWD testing be conducted shortly after cement treatment (no sooner than 1-day after treatment), so 28-day cure M_r was compared with 1-day cure E_{LWD} (Figure 3.13). Because specimens have only cured for 1-day, M_r (28-day cure) is approximately equal to 2.3

TABLE 3.5
LLWD testing results for specimens 1-1 to 1-7

Specimen ID	Curing Time	Regression Analysis ($E_s = C_1 e^{C_2 \sigma_a}$) Regression Constants C_1	C_2	R^2	Predicted LWD Modulus, E_{LWD} (psi)
1-1	1 day	1.46E+04	9.01E-02	0.961	19,610
	2 days	1.47E+04	9.41E-02	0.971	20,070
	3 days	9.78E+03	9.73E-02	0.967	13,470
	7 days	1.38E+04	1.04E-01	0.950	19,410
	28 days	1.19E+04	1.01E-01	0.964	16,510
1-2	1 day	1.35E+04	8.88E-02	0.974	18,160
	2 days	1.24E+04	9.39E-02	0.970	16,840
	3 days	1.18E+04	9.66E-02	0.937	16,280
	7 days	1.32E+04	9.40E-02	0.969	18,000
	28 days	1.61E+04	9.93E-02	0.979	22,360
1-3	1 day	1.24E+04	8.09E-02	0.967	16,310
	2 days	1.32E+04	8.99E-02	0.954	17,770
	3 days	1.61E+04	7.87E-02	0.956	20,950
	7 days	2.07E+04	7.90E-02	0.957	27,010
	28 days	3.94E+04	3.80E-02	0.905	44,980
1-4	1 day	1.33E+04	8.95E-02	0.983	17,960
	2 days	1.29E+04	8.76E-02	0.984	17,280
	3 days	1.38E+04	9.66E-02	0.940	18,950
	7 days	1.24E+04	9.92E-02	0.943	17,160
	28 days	1.16E+04	8.91E-02	0.968	15,520
1-5	1 day	1.00E+04	8.74E-02	0.964	13,410
	2 days	1.11E+04	8.93E-02	0.960	14,860
	3 days	1.15E+04	9.46E-02	0.962	15,690
	7 days	1.27E+04	1.10E-01	0.876	18,230
	28 days	1.42E+04	9.87E-02	0.951	19,600
1-6	1 day	1.11E+04	7.38E-02	0.997	14,200
	2 days	1.44E+04	8.04E-02	0.962	18,820
	3 days	1.40E+04	8.15E-02	0.968	18,320
	7 days	1.53E+04	9.82E-02	0.955	21,170
	28 days	1.65E+04	9.78E-02	0.935	22,810
1-7	1 day	1.20E+04	9.89E-02	0.953	16,630
	2 days	1.31E+04	9.70E-02	0.922	18,050
	3 days	1.11E+04	1.00E-01	0.958	15,390
	7 days	1.57E+04	9.73E-02	0.941	21,600
	28 days	1.58E+04	1.01E-01	0.959	21,930

times E_{LWD} (1-day cure). Therefore, E_{LWD} values must be multiplied by a curing coefficient (C_c) to take into account the effect of curing time on stiffness:

$$M_r = C_c E_{LWD} \quad \text{(Eq. 3.9)}$$

Where,

M_r = resilient modulus (psi),
E_{LWD} = LWD elastic modulus (psi), and
C_c = curing coefficient.

Likewise, comparisons between 28-day cure M_r and 2-day cure, 3-day cure, and 7-day cure predicted E_{LWD} values yield the following C_C values:

- C_c equals 2.1 for 2-day cure E_{LWD} values (Figure 3.14),
- C_c equals 1.8 for 3-day cure E_{LWD} values (Figure 3.15), and
- C_c equals 1.5 for 1-day cure E_{LWD} values (Figure 3.16).

Figure 3.17 provides the comparison between 28-day M_r and 28-day E_{LWD} that yields the relationship 28-day M_r is approximately equal to 1.2 times 28-day M_r on average (i.e., C_c = 1.2). However, the calculated C_c is relative to the specimen data sample and is not necessarily the true average for all specimens. Therefore, Figure 3.17 provides the 95% confidence intervals for C_c that ranges from 0.87 to 1.6. Because unity falls within the 95% confidence range, the null hypothesis

TABLE 3.6
LLWD testing results for specimens 2-1 to 2-4

Specimen ID	Curing Time	Regression Analysis ($E_s = C_1 e^{C_2 \sigma_a}$) Regression Constants C1	C2	R2	Predicted LWD Modulus, E_{LWD} (psi)
		C_1	C_2	R^2	
2-1	1 day	1.15E+04	1.01E-01	0.946	16,070
	2 days	1.47E+04	1.03E-01	0.950	20,610
	3 days	2.09E+04	8.59E-02	0.961	27,870
	7 days	1.63E+04	1.06E-01	0.959	22,980
	28 days	5.24E+04	2.78E-02	0.860	75,040
2-2	1 day	1.22E+04	9.95E-02	0.937	16,950
	2 days	1.43E+04	9.56E-02	0.946	19,630
	3 days	1.69E+04	1.00E-01	0.940	23,540
	7 days	5.57E+04	3.22E-02	0.815	62,330
	28 days	5.65E+04	4.24E-02	0.998	41,330
2-3	1 day	1.40E+04	9.92E-02	0.932	19,380
	2 days	1.46E+04	1.08E-01	0.959	20,810
	3 days	4.09E+04	5.11E-02	0.997	48,690
	7 days		Data Unavailable		
	28 days	6.92E+04	4.46E-02	0.942	48,180
2-4	1 day	1.18E+04	1.00E-01	0.961	16,400
	2 days	1.33E+04	1.12E-01	0.964	19,170
	3 days	2.06E+04	9.05E-02	0.968	27,750
	7 days		Data Unavailable		
	28 days	4.42E+04	5.23E-02	0.990	64,950

TABLE 3.7
Resilient modulus testing results for specimens 1-1 to 1-7 and 2-1 to 2-4

Specimen ID	NCHRP 1-37A Resilient Modulus Model[a] $M_r = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3}$				
	k_1	k_2	k_3	RSME (psi)	Resilient Modulus (psi)[a]
1-1	852	0.001	2.18	536	19,350
1-2	4,170	0.247	-1.17	5,420	47,230
1-3	1,090	0.053	1.99	998	23,730
1-4	10,677	0.805	-7.18	8,950	34,270
1-5	2,970	0.287	-0.548	4,110	34,270
1-6	752	0.109	3.78	2,000	23,280
1-7	4,340	0.216	-1.86	7,930	43,550
2-1	9,350	0.082	-3.07	13,300	75,040
2-2	4,400	0.243	-0.484	3,490	41,330
2-3	4,250	0.484	-1.03	3,720	48,180
2-4	6,170	0.350	-1.48	8,640	64,950

[a]Resilient modulus at σ_d = 6.9 psi and σ_3 = 2.1 psi after 28-day cure time.

that M_r equals E_{LWD} on average cannot be rejected. Therefore, the assumption that M_r is approximately equal to E_{LWD} is valid.

Figure 3.18 illustrates the effect of curing time on curing coefficient that fits wells (R^2 = 0.993) with power relationship. The limit of the curing coefficient as curing time approaches 1-day (i.e., the soonest time after treatment in which acceptance testing can occur) equals 2.3. Therefore, E_{LWD} values measured for construction acceptance should be multiplied by a curing coefficient equal to 2.3 when translating to 28-day cure M_r.

Resilient modulus inputs for cement treated subgrade in new pavement design at INDOT range from 9,000 psi (clayey soils) to 9,500 psi (sandy soils). For subgrade cement treatment to be deemed acceptable, an appropriate number (90% typical) of locations should either meet or exceed the design resilient modulus value. Using the variation in 1-day E_{LWD} curing coefficient (i.e., standard deviation), probabilistic models for predicting 28-day cure M_r were generated (Figure 3.19). If measured LWD deflection equals 0.45 mm (Figure 3.19a), then there is a 90% probability that 28-day cure resilient modulus will meet or exceed 9,000 Psi. If measured LWD deflection equals 0.43 mm (Figure 3.19b), then there is a 90% probability that 28-day cure resilient modulus will meet or exceed 9,500 psi. INDOT standard specifications require that measured

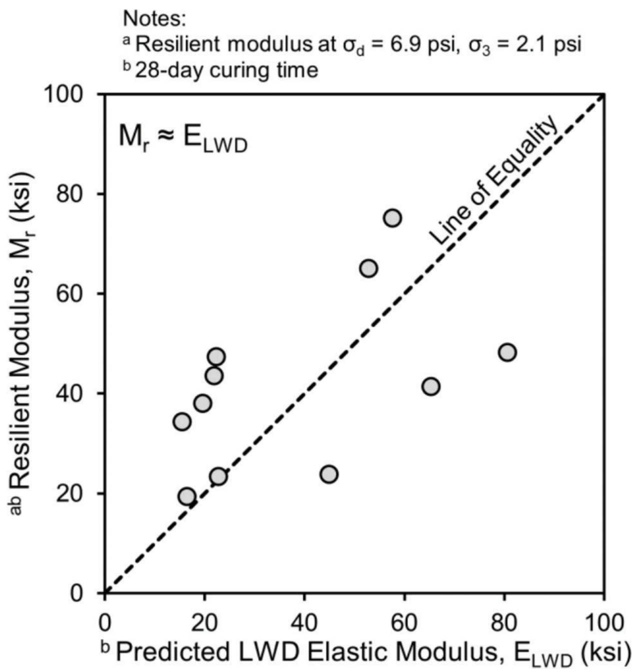


Figure 3.12 Comparison of 28-day cure resilient modulus with 28-day cure predicted LWD elastic modulus.

LWD deflections for cement treated subgrade not exceed 0.27 mm on average, which is far less than both 0.45 mm (9,000 psi resilient modulus) and 0.43 mm (9,500 psi resilient modulus). Therefore, current LWD acceptance guidelines for cement treated subgrade satisfactorily represent design resilient moduli.

3.3.3 Unconfined Compressive Strength Results

INDOT Design Procedures for Soil Modification or Stabilization requires that cement treatment increase laboratory unconfined compressive strength (UCS) by at least 100 psi after curing 2 days. Based on decades of experience working with cement treated soils, University of Illinois: Urbana-Champaign civil engineering professor Marshall Thompson reports that soils cement treated in the field should expect to have 30% lower UCS than their counterparts treated in the laboratory (M. R. Thompson, personal communication, 2019) due to the inherent challenges with pulverizing, mixing and compacting on such a large scale. Therefore, cement treated subgrades should demonstrate a 70 psi UCS increase in situ for INDOT to accept their approval.

Table 3.8 reports results of unconfined compressive strength testing on Soil No. 1 specimens (specimens 1-1 to 1-7) and Soil No. 2 specimens (specimens 2-1 to 2-4). Appendix C provides the UCS stress-strain relationships for all specimens in the laboratory study. Because UCS testing was conducted immediately following resilient modulus testing (28-day cure), UCS increase (ΔUCS) was compared with 28-day cure E_{LWD} (Figure 3.20). E_{LWD} correlates well with ΔUCS (R^2 = 0.695) using an exponential growth model. Using the

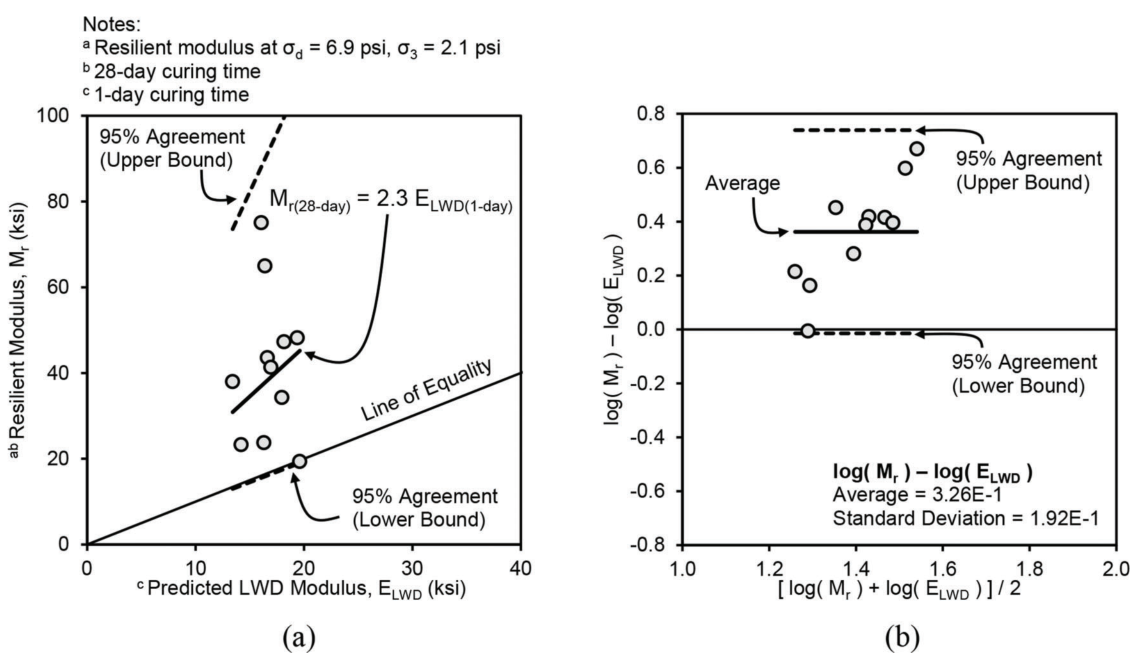
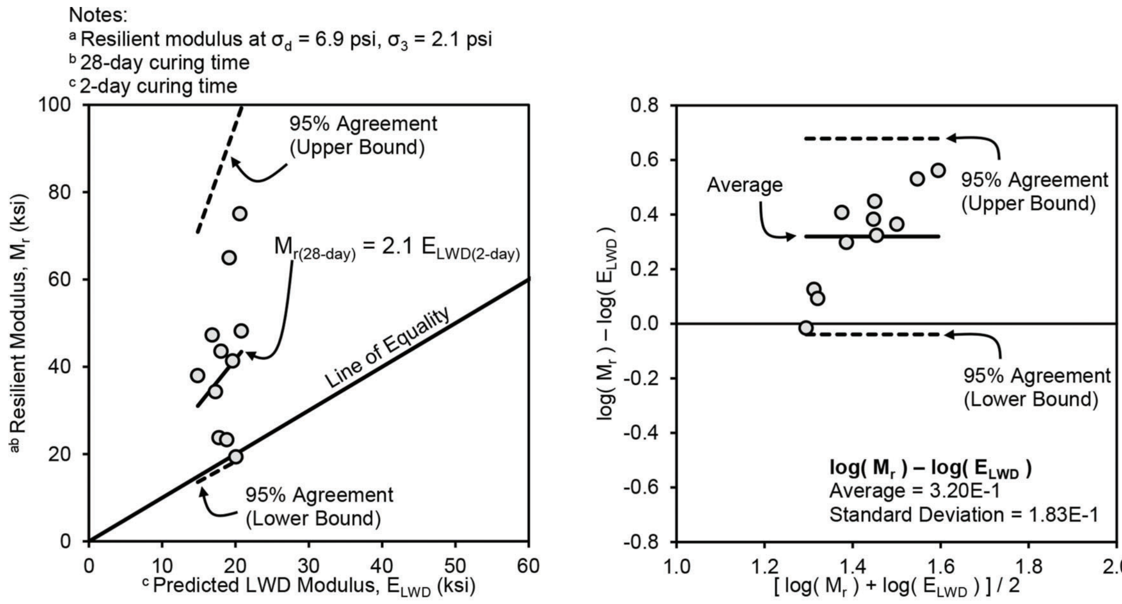
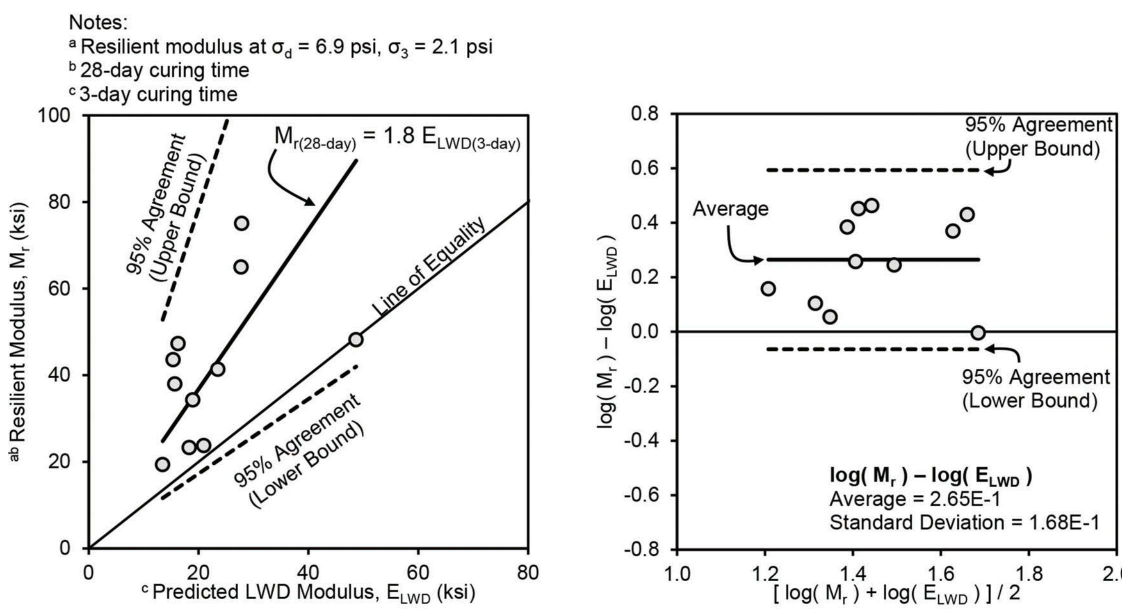


Figure 3.13 Comparison of 28-day cure resilient modulus with 1-day cure predicted LWD elastic modulus: (a) conventional plot and (b) Bland-Altman plot.



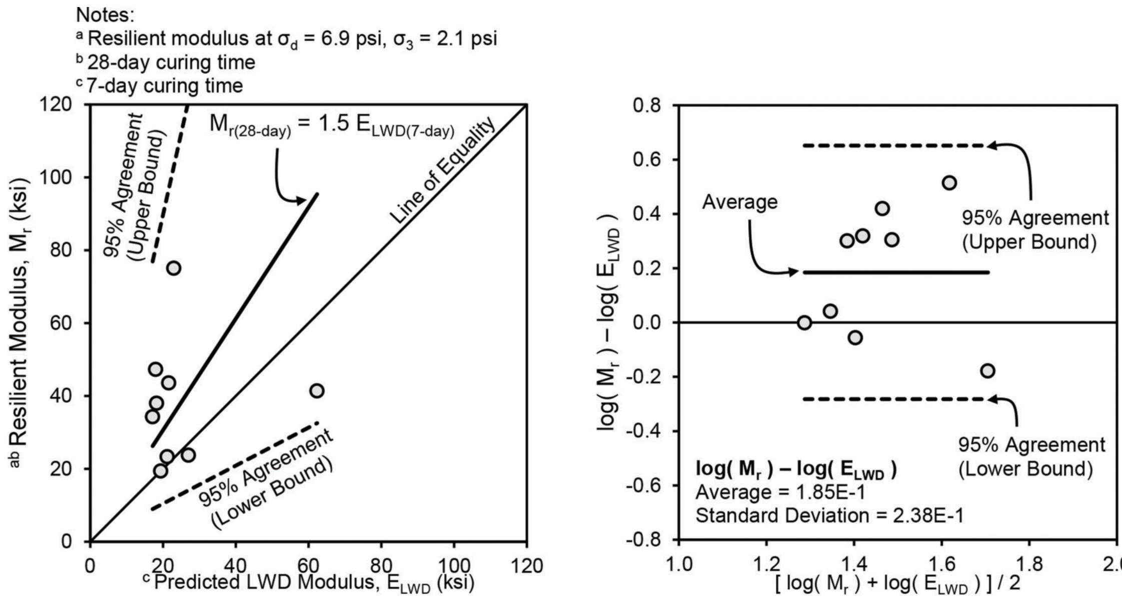
(a) (b)

Figure 3.14 Comparison of 28-day cure resilient modulus with 2-day cure predicted LWD elastic modulus: (a) conventional plot and (b) Bland-Altman plot.



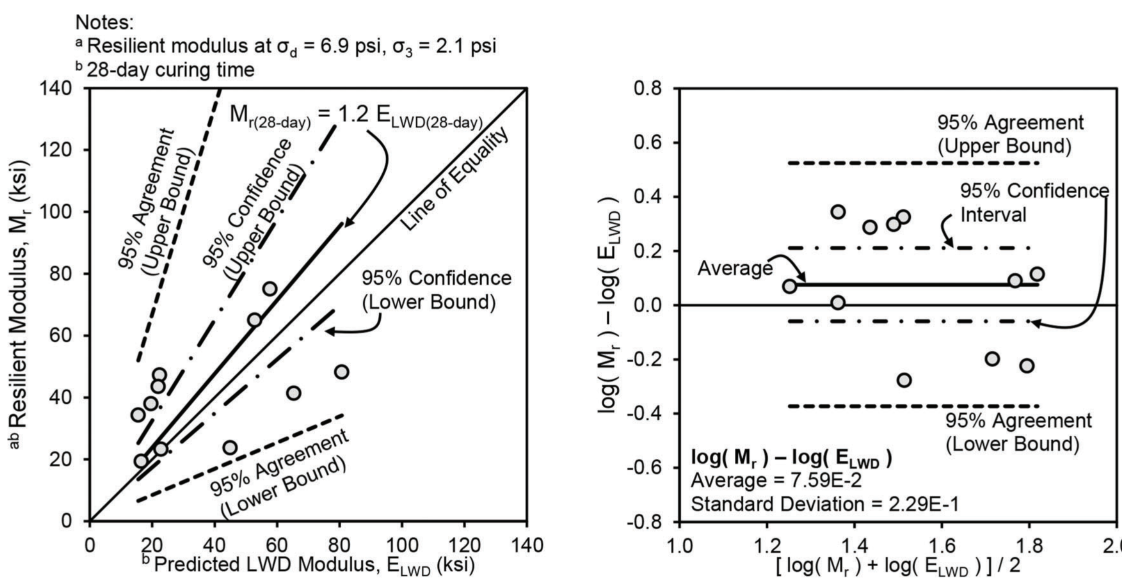
(a) (b)

Figure 3.15 Comparison of 28-day cure resilient modulus with 3-day cure predicted LWD elastic modulus: (a) conventional plot and (b) Bland-Altman plot.



(a) (b)

Figure 3.16 Comparison of 28-day cure resilient modulus with 7-day cure predicted LWD elastic modulus: (a) conventional plot and (b) Bland-Altman plot.



(a) (b)

Figure 3.17 Comparison of 28-day cure resilient modulus with 28-day cure predicted LWD elastic modulus: (a) conventional plot and (b) Bland-Altman plot.

standard error in the E_{LWD} to ΔUCS correlation, probabilistic models for predicting ΔUCS were generated (Figure 3.21). If measured LWD deflection equals 0.27 mm, as specified in the INDOT standard specifications; then there is an 86% probability that ΔUCS will meet or exceed 70 psi. For there to be a 90% probability that ΔUCS meets or exceeds 70 psi, measured LWD deflection should equal 0.21 mm.

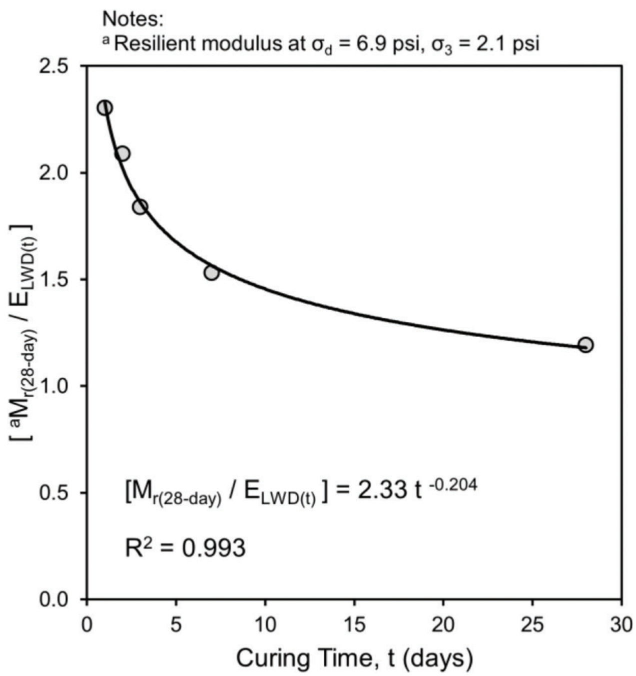


Figure 3.18 Relationship between $M_{r(28\text{-day})}$ / $E_{LWD(t)}$ (i.e., curing coefficient) and curing time.

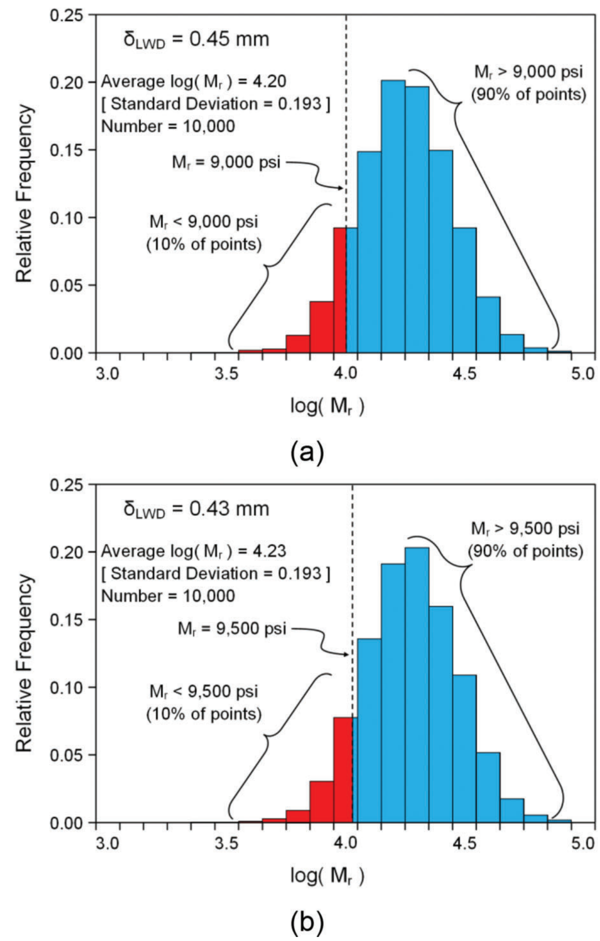


Figure 3.19 Probabilistic models for 28-day cure M_r determined from 1-day cure E_{LWD} with 90% of results meeting or exceeding: (a) 9,000 psi and (b) 9,500 psi.

TABLE 3.8
Unconfined compressive strength testing results for specimens 1-1 to 1-7 and 2-1 to 2-4

Specimen ID	Unconfined Compressive Strength (psi)[a]	Unconfined Compressive Strength Increase (psi)
1-1	142	125
1-2	127	109
1-3	147	130
1-4	128	110
1-5	113	96
1-6	92	74
1-7	128	110
2-1	192	168
2-2	161	136
2-3	367	342
2-4	195	171

[a]28-day curing time.

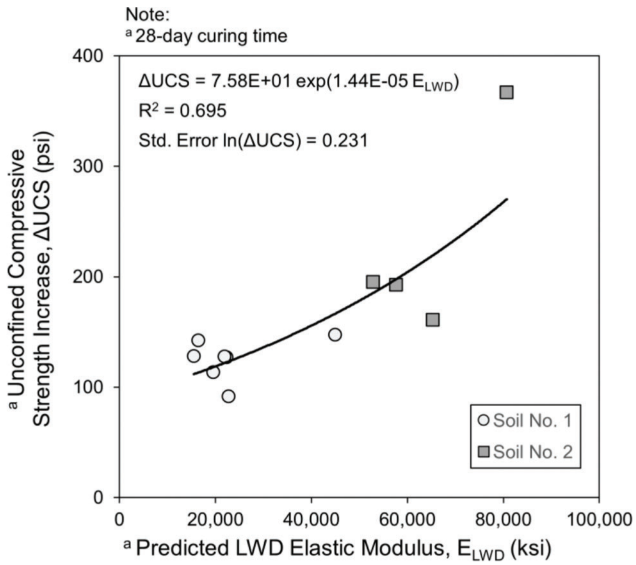


Figure 3.20 Comparison of E_{LWD} (28-day cure) with ΔUCS (28-day cure).

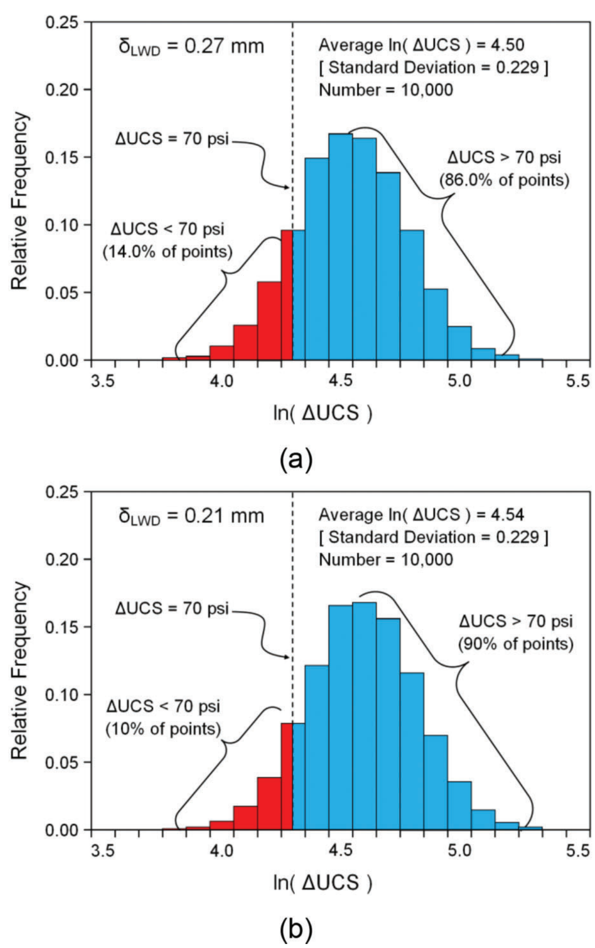


Figure 3.21 Probabilistic models for ΔUCS determined from E_{LWD}: (a) 0.27 mm LWD deflection and (b) 90% of results meeting or exceeding 70 psi.

4. FIELD TESTING PROGRAM

4.1 Field Testing Methods

4.1.1 Light Weight Deflectometer

Shown in Figure 4.1, light weight deflectometer testing (LWD) was conducted using a Zorn LWD setup. LWD testing involves dropping a 22 lb. drop weight from about 28.4 in. onto an 11.81-in. diameter loading plate resting on the ground surface. The impulse generated by the drop weight striking the loading plate induces vertical deflection at the ground surface that is inversely proportional to the ground stiffness. An accelerometer housed inside of the loading plate measures acceleration of the loading plate over time, and an external data acquisition device twice integrates the acceleration response with respect to time to compute deflection. The data acquisition device determines the maximum deflection reported in millimeters.

In addition to the mass of the drop weight and its drop height, the force applied by the LWD depends on the stiffness of the buffer located between the drop weight and the loading plate. The LWD used in this study had a buffer stiffness of about 2,000 lb./in. Peak force applied by the LWD is calculated from Equation 3.1.

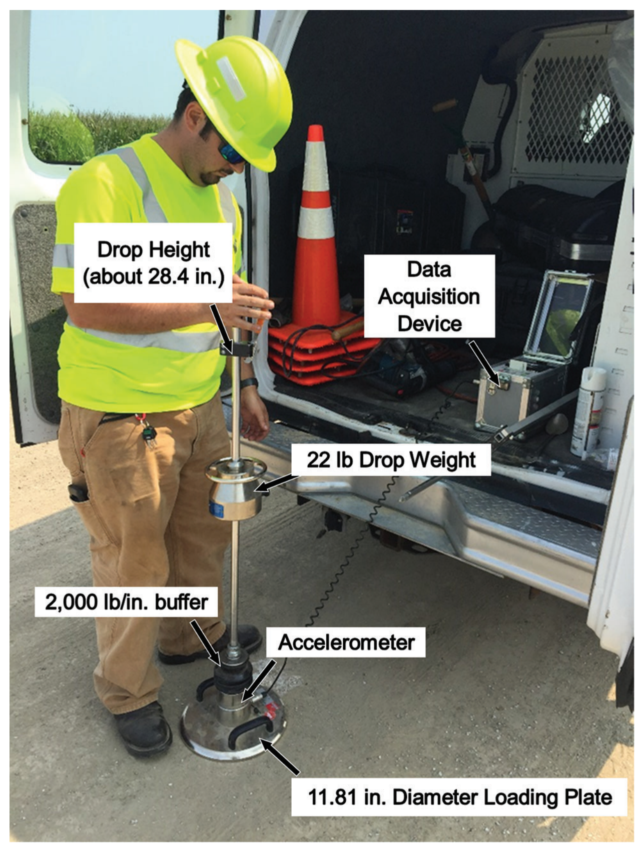


Figure 4.1 Zorn light weight deflectometer field test setup.

In accordance with ITM 508, the LWD used in this study was calibrated to apply a 1,590 lb. peak force over a pulse duration of 17 ms.

Measured LWD deflections were used to determine in situ elastic moduli (E_{LWD}) using Equation 4.1 that is derived from the Boussinesq solution for the distribution of stresses in an elastic solid.

$$E_{LWD} = \frac{F(1-v^2)f}{\pi r \delta_{LWD}} \qquad \text{(Eq. 4.1)}$$

Where,

E_{LWD} = LWD elastic modulus (psi),
F = peak applied force (lb.),
v = Poisson's ratio (assumed equal to 0.3),
f = contact stress distribution factor (equal to $\pi/2$)
r = loading plate radius (in.), and
δ_{LWD} = LWD measured deflection (in.).

The contact stress distribution factor (f) in Equation 4.1 characterizes the shape of contact stresses applied to the ground surface. Conventional thinking suggests that applied stresses ought to be uniformly distributed at the ground surface; however, this assumption requires that loaded areas also be flexible. Because LWD loading is applied to a steel plate with a stiffness far greater than that of the ground, we assumed that the loaded area is rigid. Therefore, the shape of LWD contact stresses were assumed to follow an inverse-parabolic distribution with f equal to $\pi/2$.

4.1.2 Falling Weight Deflectometer

Shown in Figure 4.2, falling weight deflectometer testing (FWD) was conducted using Dynatest FWD setups. The FWD setups used in this study all apply nominal loads of 7 kip, 9 kip, and 11 kip to an 11.81 in diameter loading plate resting on the pavement surface. An array of 9-geophones positioned at distances ranging from 0 in. to 60 in. from the center of the loading plate measure resulting surface deflections, and a load cell measures actual applied loading. FWD loadings and deflections were normalized to 9 kip, which is one-half of an 18k kip single axle loading.

Measured FWD deflections and loadings were used to determine subgrade resilient moduli and effective pavement structural numbers using the AASHTO 1993 *Pavement Design Guide* back-calculation procedure. Equation 4.2 was used to calculate subgrade resilient modulus.

$$M_r = \frac{0.24F}{\delta_\rho \rho} \qquad \text{(Eq. 4.2)}$$

Where,

M_r = subgrade resilient modulus (psi),
F = peak applied force (lb.),
δ_ρ = deflection at a distance ρ from the center of the load (in.), and
ρ = radial distance from center of loading plate.

AASHTO (1993) recommends that back-calculated M_r values be multiplied by a correction factor (0.33 typical) for use in pavement overlay design. However, recent research conducted by Park, Nantung, and Bobet (2018) as part of INDOT project No. SPR-3710 showed that uncorrected, FWD back-calculated subgrade resilient moduli values were approximately equal to resilient moduli obtained from laboratory testing in accordance with AASHTO T 307 (2017). Therefore, no correction factors were applied to FWD back-calculated M_r values in this study.

Stated in (AASHTO, 1993, pp. III–96), "the deflection used to back-calculate the subgrade modulus must be measured far enough away that it provides a good estimate of the subgrade modulus, independent of the effects of any layers above, but also close enough that it is not too small to measure accurately." Therefore, it is recommended that the value for r used in Equation 4.2 be no less than 0.7 times the radius of the stress bulb at the subgrade-pavement interface (ρ_e) that is determined from Equation 4.3.

$$\rho_e = \sqrt{r^2 + \left(h\sqrt[3]{\frac{E_p}{M_r}}\right)^2} \qquad \text{(Eq. 4.3)}$$

Figure 4.2 Dynatest falling weight deflectometer test setup.

Where,

ρ_e = radius of the stress bulb at the subgrade-pavement interface (in.),
r = loading plate radius (in.),
h = total thickness of pavement layers above the subgrade (in.),
E_p = effective modulus of all pavement layers above the subgrade (psi), and
M_r = subgrade resilient modulus (psi).

E_p values were determined using Equation 4.4 that uses the method of equivalent thickness (Odemark, 1949) for predicting stresses and displacements in layered elastic systems.

$$\delta_o = \frac{3F}{2\pi r}\left\{ \frac{1}{M_r\sqrt{1+\left[\left(\frac{h}{r}\right)\sqrt[3]{\frac{E_p}{M_r}}\right]^2}} + \frac{\left[1-\frac{1}{\sqrt{1+\left(\frac{h}{r}\right)^2}}\right]}{E_p} \right\} \quad \text{(Eq. 4.4)}$$

Where,

δ_o = deflection measured at the center of the loading plate (in.),
F = peak applied force (lb.),
r = loading plate radius (in.),
M_r = subgrade resilient modulus (psi),
h = total thickness of all pavement layers above the subgrade (in.), and
E_p = effective modulus of all pavement layers above the subgrade (psi).

Although AASHTO (1993) recommends that δ_o values be adjusted to a standard temperature of 68°F, no temperature adjustments were made to the deflections in this study. Indeed, the scope of this study does not involve the design values for bound pavement layers, but rather the stiffness properties of subgrade soils.

Values for effective structural numbers (SN_{eff}) of the pavement layers were determined using Equation 4.5.

$$SN_{eff} = 0.0045h\sqrt[3]{E_p} \quad \text{(Eq. 4.5)}$$

Where,

SN_{eff} = effective structural number,
h = total thickness of all pavement layers, and
E_p = effective modulus of pavement layers above the subgrade.

4.2 Field Testing Results

Field testing was conducted during the 2018 and 2019 construction seasons. Figure 4.3 shows the locations of field test sites over the state of Indiana that include the following:

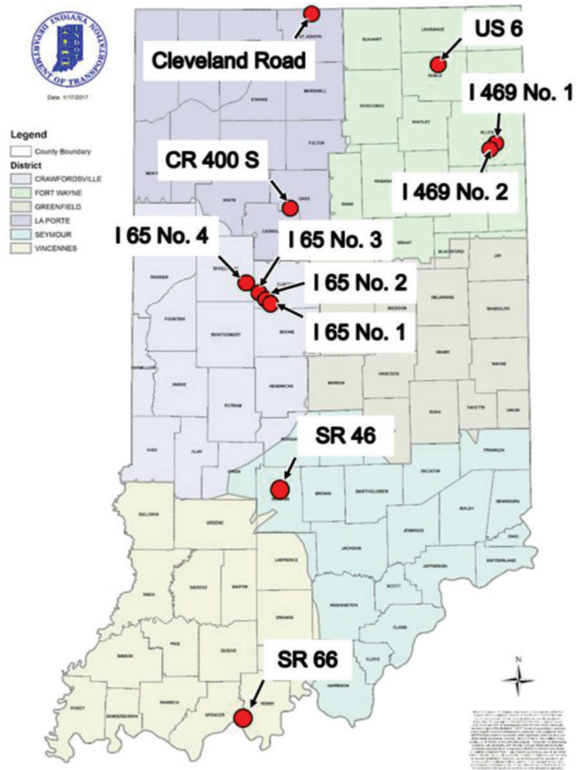


Figure 4.3 Locations of field test sections.

- US 6 (Fort Wayne District),
- I 469 No. 2 (Fort Wayne District),
- I Cleveland Road (La Porte District),
- I 65 No. 1 (Crawfordsville District),
- I 65 No. 2 (Crawfordsville District),
- I 65 No. 3 (Crawfordsville District),
- I 65 No. 4 (Crawfordsville District),
- SR 46 (Seymour District),
- SR 66 (Vincennes District), and
- CR 400 S (La Porte District).

In general, LWD tests on pavement subgrades were located along the right wheel path of driving lanes being constructed. Because INDOT standard specifications allow for LWD acceptance tests of subgrade Type IBC construction as soon as 1 day after chemical treatment, LWD tests in this study were generally conducted on the day following treatment. Table 4.1 summarizes average LWD deflections and LWD moduli for the field test sections.

After placement of concrete or hot-mix asphalt pavement layers, FWD testing was conducted on the test sections to assess structural performance of constructed pavement systems. FWD testing followed INDOT Division of Research & Development protocols that tests be located along the right wheel path of lanes being tested. Table 4.1 summarizes average effective structural numbers and back-calculated subgrade resilient moduli for the field test sections.

TABLE 4.1
Summary of LWD and FWD field testing results

	Results of LWD Testing During Construction				Results of FWD Testing After Construction			
	LWD Deflection (mm)		LWD Elastic Modulus (psi)		Pavement Effective Structural Number		Back-Calculated Subgrade Resilient Modulus (psi)	
Test Section	Average	COV[a] (%)	Average	COV[a] (%)	Average	COV[a] (%)	Average	COV[a] (%)
US 6	0.206	49.5	18,080	40.9	8.33	12.9	49,100	29.2
I 469 No. 1	0.318	37.6	10,980	32.4	6.44	2.7	42,390	46.1
I 469 No. 2	0.283	23.4	11,560	23.5	6.76	3.1	41,580	18.2
Cleveland Road	0.356	51.7	10,580	46.2	8.42	19.5	29,160	12.1
I 65 No. 1	0.235	22.1	13,930	26.1	6.60	5.1	33,380	10.4
I 65 No. 2	0.294	30.2	11,280	24.0	6.53	6.9	28,410	15.5
I 65 No. 3	0.174	24.0	18,380	18.6	6.64	4.0	36,820	13.1
I 65 No. 4	0.252	29.5	13,260	26.6	6.52	7.7	29,868	21.1
SR 46	0.303	35.9	11,220	26.8	8.61	20.9	58,000	24.1
SR 66	0.303	37.8	11,760	37.7	3.49	7.6	34,610	17.3
CR 400 S	0.249	23.7	13,150	22.0	3.45	5.5	47,430	21.6

[a]COV = coefficient of variation.

The following sections present detailed background information and testing results for the field test sections.

4.2.1 US 6 (Fort Wayne District)

Located near Brimfield in Fort Wayne District, the US 6 test section was part of DES No. 1296362 that was let out under Contract No. B-35097. The project involved the realignment of US 6 and the construction of a railroad overpass at reference post (RP) 117+67. The contract required construction of approximately 1.3 lane-miles of new concrete pavement, and Figure 4.4 shows the specified pavement cross section and nominal thicknesses. The contract was awarded February 2017 and then completed October 2019.

Subgrade soil for the new alignment was generally granular with no plasticity. Table D.1 summarizes the index properties, compaction characteristics, and strength properties for the subgrade. A subgrade treatment mix design performed on US 6 soil samples revealed that inclusion of 4% (by dry weight) Portland cement was required to satisfactorily improve subgrade soils in accordance with the *INDOT Design Procedures for Soil Modification or Stabilization.* Table D.2 summarizes the results of the subgrade treatment mix design for US 6 subgrade soil. Subgrade treatment operations took place on May 31, 2018, using dry Portland cement mixing.

LWD testing of the US 6 test section subgrade was conducted on June 1, 2018. Shown in Figure D.1, tests were located along the westbound driving lane west of the railroad overpass (STA 69+58 to STA 74+08) and along the eastbound driving lane east of the railroad overpass (STA 78+52 to STA 83+02). Average LWD deflection for the US 6 test section equaled 0.206 mm (Figure D.2a), and average LWD elastic modulus for the US test section equaled 18,080 psi (Figure D.2b). FWD testing of the US 6 test section was conducted on November 21, 2018 after the concrete surface had been placed and sufficiently cured. Average effective structural number for the US 6 test section equaled 8.33 (Figure D.3a), and average back-calculated FWD resilient modulus for the US 6 test section equaled 49,100 psi (Figure D.3b).

4.2.2 I 469 (Fort Wayne District)

Located near Fort Wayne in Fort Wayne District, the I 469 No. 1 and I 469 No. 2 test sections were part of DES No. 1296429that was let out under Contract No. R-35099. The project involved pavement replacement of I 469 from RP 12+42 to RP 16+73. The contract required construction of approximately 17.3 lane-miles of new hot-mix asphalt pavement, and Figure D.4 shows the specified pavement cross section and nominal thicknesses. The contract was awarded October 2016 and then completed February 2020.

Subgrade soil for the new alignment was generally fine-grained with high plasticity. Table D.3 summarizes the index properties, compaction characteristics, and strength properties for the subgrade. A subgrade treatment mix design performed on I 469 soil samples revealed that inclusion of 5% (by dry weight) Portland cement was required to satisfactorily improve subgrade soils in accordance with the *INDOT Design Procedures for Soil Modification or Stabilization.* Table D.4 summarizes the results of the subgrade treatment mix design for I 469 subgrade soil. Because of the large project scope, subgrade treatment operations took place off-and-on over the duration of project using dry Portland cement mixing. Subgrade treatment of the I 469 No. 1 test section occurred on May 29, 2018, and subgrade treatment of the I 469 No. 2 test section occurred on June 13, 2018.

LWD testing of the I 469 No.1 test section subgrade was conducted on May 30, 2018. Shown in Figure D.5, tests were located along the northbound driving lane from RP 15+10 to RP 15+20 (STA 848+00 to STA 852+50) and from RP 15+63 to RP 15+80 (STA 876+00

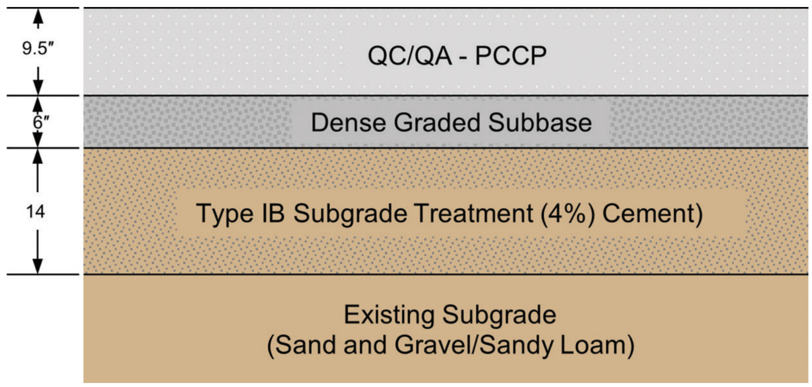


Figure 4.4 US 6 test section pavement cross section.

to STA 880+50). Average LWD deflection for the I 469 No. 1 test section equaled 0.318 mm (a), and average LWD elastic modulus for the I 469 No. 1 test section equaled 10,980 psi (Figure D.6b). FWD testing of the I 469 No. 1 test section was conducted on September 24, 2018 after the hot-mix asphalt surface course had been placed. Average effective structural number for the I 469 No. 1 test section equaled 6.44 (Figure D.7a), and average back-calculated FWD resilient modulus for the I 469 No. 1 test section equaled 42,390 psi (Figure D.7b).

LWD testing of the I 469 No. 2 test section subgrade was conducted on June 14, 2018. Shown in Figure D.5, tests were located along the northbound driving lane from RP 12+44 to RP 12+80 (STA 707+00 to STA 716+00). Average LWD deflection for the I 469 No. 1 test section equaled 0.283 mm (Figure D.8a), and average LWD elastic modulus for the I 469 No. 1 test section equaled 11,560 psi (Figure D.8b). FWD testing of the I 469 No. 2 test section was conducted on September 24, 2018, after the hot-mix asphalt surface course had been placed. Average effective structural number for the I 469 No. 2 test section equaled 6.76 (Figure D.9a), and average back-calculated FWD resilient modulus for the I 469 No. 1 test section equaled 41,580 psi (Figure D.9b).

Four test points between STA 876+50 and STA 878+50 along the I 469 No. 1 test section and one test point at STA 715+80 along the I 469 No. 2 test section yielded substantially higher back-calculated FWD resilient moduli on the order of 70,000 psi to 80,000 psi. Inspection of construction records revealed that these particular locations were subjected to foundation stabilization in which foundation soils were lime treated prior to cement treating the subgrade. The double treatment process consisted of the following general steps:

1. Removing the top 14 in. of subgrade soil to expose the foundation soil.
2. Treating the foundation soil either lime or lime-kiln dust.
3. Returning the subgrade soil removed in step 1.
4. Treating the subgrade soil as prescribed in the subgrade treatment mix design.

4.2.3 Cleveland Road (La Porte District)

Located near South Bend in La Porte District, the Cleveland Road test section was part of DES No. 1298578 that was let out under Contract No. R-40170. A local public agency (LPA) project, the project involved pavement replacement of Cleveland Road in South Bend from the St. Joseph River to SR 933, as well as the rehabilitation of a bridge spanning the St. Joseph River. The contract required construction of approximately 3.6 lane-miles of new concrete pavement, and Figure D.10 shows the specified pavement cross section and nominal thicknesses. The contract was awarded January 2018 and has yet to be completed at the time of report publication.

Subgrade soil for the new alignment was generally non-plastic, clean sand. Table D.5 summarizes the index properties, compaction characteristics, and strength properties for the subgrade. A subgrade treatment mix design performed on Cleveland Road soil samples revealed that inclusion of 4% (by dry weight) Portland cement was required to satisfactorily improve subgrade soils in accordance with the *INDOT Design Procedures for Soil Modification or Stabilization*. Table D.5 summarizes the results of the subgrade treatment mix design for Cleveland Road subgrade soil. Subgrade treatment operations took place on May 30, 2018 and May 31, 2018 using dry Portland cement mixing.

LWD testing of the Cleveland Road test section subgrade was conducted on May 31, 2018. Shown in Figure D.11, tests were located along the eastbound driving lane from about 100 ft east of the St. Joseph River bridge to 900 ft east of the St. Joseph River bridge (STA 64+70 to STA 72+70). Average LWD deflection for the Cleveland Road test section equaled 0.356 mm (Figure D.12a), and average LWD elastic modulus for the Cleveland Road test section equaled 10,580 psi (Figure D.12b). FWD testing of the Cleveland Road test section was conducted on August 9, 2018, after the concrete surface had been placed and sufficiently cured. Average effective structural number for the Cleveland Road test section equaled 8.42 (Figure D.13a), and average back-calculated FWD resilient modulus for the Cleveland Road test section equaled 29,160 psi (Figure D.13b).

4.2.4 I 65 (Crawfordsville District)

Located in Clinton and Tippecanoe Counties in Crawfordsville District, the I 65 No. 1, I 65 No. 2, I 65 No. 3, and I 65 No.4 test sections were part of DES No. 1382656 that was let out under Contract No. RS-36714. The project involved pavement resurfacing of I 65 from RP 152+30 to RP 165+00 and replacing decks on multiple bridges overpassing I 65. Five-hundred-foot-long sections of I 65 at CR 500 S, CR 600 W, SR 28, CR 900 E, and CR 800 E overpasses (approximately 1.9 lane-miles) required pavement replacement with new concrete pavement, and, and Figure D.14 shows the specified pavement cross section and nominal thicknesses. The contract was awarded March 2017 and has yet to be completed at the time of report publication.

Subgrade soil for the new alignment was generally sandy-loam with no plasticity. Samples of I65 subgrade were extracted at the CR 500 S overpass (I 65 No. 1 test section), the SR 28 overpass (I 65 No. 3 test section), and the CR 800 E overpass (I 65 No. 4), and Table D.7 summarizes the index properties, compaction characteristics, and strength properties for the subgrade soils. A subgrade treatment mix design performed on I 65 soil samples revealed that inclusion of 4% (by dry weight) Portland cement was required to satisfactorily improve subgrade soils in accordance with the *INDOT Design Procedures for Soil Modification or Stabilization*. Table D.8 summarizes the results of the subgrade treatment mix design for I 65 subgrade soil. Subgrade treatment of I 65 No. 1–4 took place on May 9, 2018, using dry Portland cement mixing.

LWD testing of the I 65 No. 1 test section subgrade was conducted on May 10, 2018. Shown in Figure D.15, tests were located along the northbound driving lane at the CR 500 S overpass from RP 153+20 to RP 153+29 (STA 730+25 to STA 735+25). Average LWD deflection for the I 65 No. 1 test section equaled 0.235 mm (Figure D.16a), and average LWD elastic modulus for the I 65 No. 1 test section equaled 13,930 psi (Figure D.16b). FWD testing of the I 65 No. 1 test section was conducted on November 5, 2018, after the concrete surface had been placed and cured sufficiently. Average effective structural number for the I 65 No. 1 test section equaled 6.60 (Figure D.17a), and average back-calculated FWD resilient modulus for the I 65 No. 1 test section equaled 33,380 psi (Figure D.17b).

LWD testing of the I 65 No. 2 test section subgrade was conducted on May 10, 2018. Shown in Figure D.15, tests were located along the northbound driving lane at the CR 600 W overpass from RP 154+13 to RP 154+22 (STA 822+25 to STA 827+30). Average LWD deflection for the I 65 No. 2 test section equaled 0.294 mm (Figure D.18a), and average LWD elastic modulus for the I 65 No. 2 test section equaled 11,280 psi (Figure D.18b). FWD testing of the I 65 No. 2 test section was conducted on November 5, 2018, after the concrete surface had been placed and cured sufficiently. Average effective structural number for the I 65 No. 2 test section equaled 6.53 (Figure D.19a), and average back-calculated FWD resilient modulus for the I 65 No. 2 test section equaled 28,410 psi (Figure D.19b).

LWD testing of the I 65 No. 3 test section subgrade was conducted on May 10, 2018. Shown in Figure D.15, tests were located along the northbound driving lane at the SR 28 overpass from RP 157+86 to RP 157+95 (STA 975+25 to STA 980+24). Average LWD deflection for the I 65 No. 3 test section equaled 0.174 mm (Figure D.20a), and average LWD elastic modulus for the I 65 No. 3 test section equaled 18,380 psi (Figure D.20b). FWD testing of the I 65 No. 3 test section was conducted on November 5, 2018 after the concrete surface had been placed and cured sufficiently. Average effective structural number for the I 65 No. 3 test section equaled 6.64 (Figure D.21a), and average back-calculated FWD resilient modulus for the I 65 No. 3 test section equaled 36,820 psi (Figure D.21b).

LWD testing of the I 65 No. 4 test section subgrade was conducted on May 10, 2018. Shown in Figure D.15, tests were located along the northbound driving lane at the CR 800 E overpass from RP 164+70 to RP 164+79 (STA 108+05 to STA 113+05). Average LWD deflection for the I 65 No. 4 test section equaled 0.252 mm (Figure D.22a), and average LWD elastic modulus for the I 65 No. 4 test section equaled 13,260 psi (Figure D.22b). FWD testing of the I 65 No. 4 test section was conducted on November 5, 2018, after the concrete surface had been placed and cured sufficiently. Average effective structural number for the I 65 No. 4 test section equaled 6.52 (Figure D.23a), and average back-calculated FWD resilient modulus for the I 65 No. 4 test section equaled 29,870 psi (Figure D.23b).

4.2.5 SR 46 (Seymour District)

Located near Bloomington in Seymour District, the SR 46 test section was part of DES No. 1801945 and 1801946 that was let out under Contract No. R-41679. The project involved pavement replacement and restoration on SR 45 and SR 46 at various locations. The contract required construction of approximately 1.6 lane-miles of new concrete pavement along SR 46, and Figure D.24 shows the specified pavement cross section and nominal thicknesses. The contract was awarded April 2019 and has yet to be completed at the time of report publication.

Subgrade soil for the new alignment was generally high plasticity clay. Table D.9 summarizes the index properties, compaction characteristics, and strength properties for the subgrade soils. A subgrade treatment mix design performed on SR 46 soil samples revealed that inclusion of 4% (by dry weight) lime kiln dust and 4% (by dry weight) Portland cement was required to satisfactorily improve subgrade soils in accordance with the *INDOT Design Procedures for Soil Modification or Stabilization*. Table D.10 summarizes the results of the subgrade treatment mix design for SR 46 subgrade soil. Subgrade treatment with lime kiln dust took place on September 14, 2019, and subgrade treatment with Portland cement (dry mixing) took place on September 15, 2019.

LWD testing of the SR 46 test section subgrade was conducted on September 16, 2019. Shown in Figure D.25, tests were located along the eastbound driving lane from RP 52+10 to RP 52+46 (STA 1+40 to STA 20+40). Average LWD deflection for the SR 46 test section equaled 0.303 mm (Figure D.26a), and average LWD elastic modulus for the SR 46 test section equaled 11,220 psi (Figure D.26b). FWD testing of the SR 46 test section was conducted on August 20, 2020, after the concrete surface had been placed and cured sufficiently. Average effective structural number for the SR 46 test section equaled 8.61 (Figure D.27a), and average back-calculated FWD resilient modulus for the SR 46 test section equaled 58,000 psi (Figure D.27b).

4.2.6 SR 66 (Vincennes District)

Located near Tell City in Vincennes District, the SR 66 test section was part of DES No. 1400830 that was let out under Contract No. R-37690. The project involved new road construction (Switzer Road) and the construction of an added travel lane for SR 66. The contract required construction of approximately 0.4 lane-miles of new hot-mix asphalt pavement along SR 66, and Figure D.28 shows the specified pavement cross section and nominal thicknesses. The contract was awarded December 2018 and has yet to be completed at the time of report publication.

Subgrade soil for the new alignment was generally non-plastic silt. Table D.11 summarizes the index properties, compaction characteristics, and strength properties for the subgrade soils. A subgrade treatment mix design performed on SR 66 soil samples revealed that inclusion of 5% (by dry weight) Portland cement was required to satisfactorily improve subgrade soils in accordance with the *INDOT Design Procedures for Soil Modification or Stabilization.* Table D.12 summarizes the results of the subgrade treatment mix design for SR 66 subgrade soil. Subgrade treatment of SR 66 took place on August 20, 2019, using dry Portland cement mixing.

LWD testing of the SR 66 test section subgrade was conducted on August 21, 2019. Shown in Figure D.29, tests were located along the westbound driving lane from RP 75+80 to RP 75+60 (STA 316+00 to STA 306+00). Average LWD deflection for the SR 66 test section equaled 0.303 mm (Figure D.30a), and average LWD elastic modulus for the SR 46 test section equaled 11,760 psi (Figure D.30b). FWD testing of the SR 66 test section was conducted on August 19, 2020, after the hot-mix asphalt surface course had been placed. Average effective structural number for the SR 66 test section equaled 3.49 (Figure D.31a), and average back-calculated FWD resilient modulus for the SR 66 test section equaled 34,610 psi (Figure D.31b).

4.2.7 CR 400 S (LaPorte District)

Located near Clymers in La Porte District, the CR 400 S test section was part of DES No. 1383352 that was let out under Contract No. R-37356. A local public agency (LPA) project, the project involved pavement replacement of CR 400 S in Cass County from 500 ft east of CR 400 W to 1,00 ft east of CR 300 W. The contract required construction of approximately 2.1 lane-miles of new hot-mix asphalt pavement, and Figure D.32 shows the specified pavement cross section and nominal thicknesses. The contract was awarded December 2017 and then completed March 2019.

Subgrade soil for the new alignment was generally silty lean-clay. Table D.13 summarizes the index properties, compaction characteristics, and strength properties for the subgrade. A subgrade treatment mix design performed on Cleveland Road soil samples revealed that inclusion of 5% (by dry weight) Portland cement was required to satisfactorily improve subgrade soils in accordance with the *INDOT Design Procedures for Soil Modification or Stabilization.*

Table D.14 summarizes the results of the subgrade treatment mix design for CR 400 S subgrade soil. Subgrade treatment operations took place on August 12, 2018, using dry Portland cement mixing.

LWD testing of the CR 400 S test section subgrade was conducted on August 14, 2018. Shown in Figure D.33, tests were located along the eastbound driving lane from about 570 ft east of CR 400 W to 2,970 ft east of CR 400 W (STA 37+50 to STA 61+50). Average LWD deflection for the CR 400 S test section equaled 0.249 mm (Figure D.34a), and average LWD elastic modulus for the CR 400 S test section equaled 13,150 psi (Figure D.34b). FWD testing of the CR 400 S test section was conducted on August 5, 2020 after the hot-mix asphalt surface course had been placed. Average effective structural number for the CR 400 S test section equaled 3.45 (Figure D.35a), and average back-calculated FWD resilient modulus for the CR 400 S test section equaled 47,430 psi (Figure D.35b).

5. ANALYSIS OF LABORATORY- AND FIELD-TESTING RESULTS

5.1 Efficacy of Predicting Resilient Modulus from LWD

Measured LWD deflections from all field test sections are compiled into Figure 5.1. Without transformation, the deflection data is skewed right. However, logarithmic (base 10) transformation of the data yields nearly normal distribution. Average log transformed LWD deflection equals -0.586 that equates to 0.259 mm, and log transformed standard deviation equals 0.158.

Figure 5.2 provides a comparison of resilient modulus determined from LWD testing (Equations 4.1 and 3.9) with resilient modulus determined from FWD testing (Equations 4.2). Results tend to be in agreement with the line of equality; however, FWD determined resilient moduli tend to be greater likely due to more favorable stress conditions (higher bulk stress and lower shear stress). Bland-Altman analysis of agreement (Figure 5.3) reveals that the vast majority of points (97.4%) fall between the 95% (i.e., $\alpha = 0.5$) limits of agreement. Therefore, resilient moduli predicted from LWD immediately following subgrade treatment

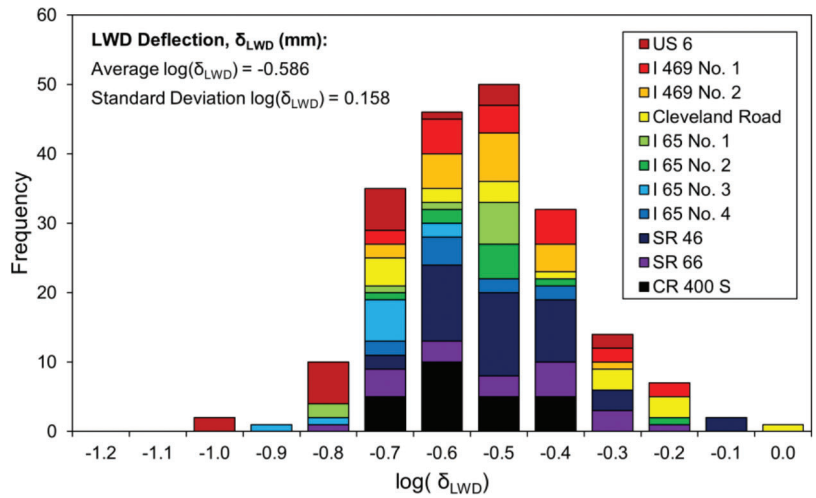


Figure 5.1 Distribution of measured LWD deflections from field test sections.

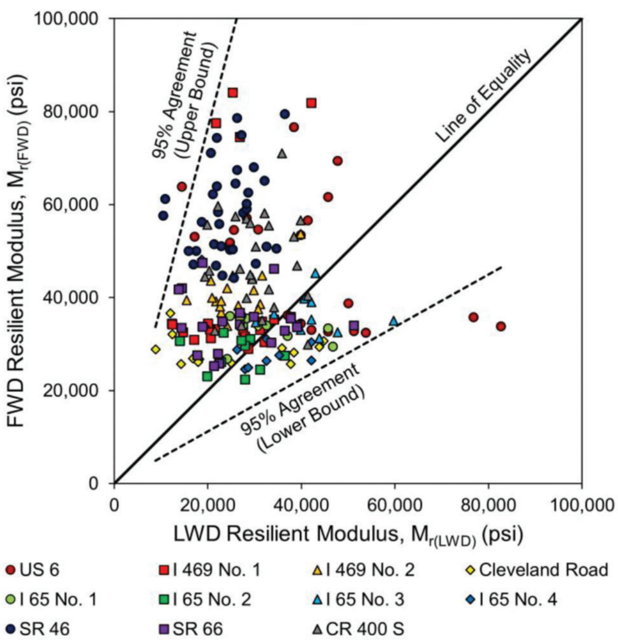


Figure 5.2 Comparison of FWD determined resilient modulus with LWD determined resilient modulus.

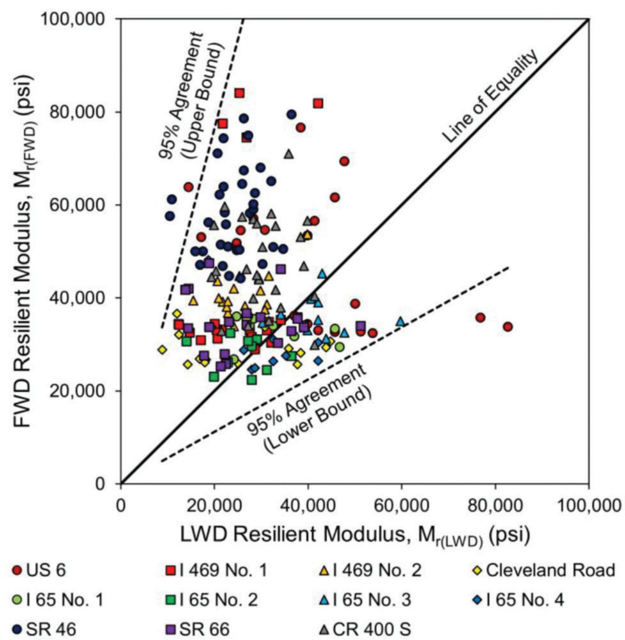


Figure 5.3 Bland-Altman comparison of FWD determined resilient modulus with LWD determined resilient modulus.

adequately agree with resilient moduli back-calculated from FWD measured on the pavement surface.

5.2 Resilient Modulus Design Inputs for Cement Treated Subgrade

A probabilistic model for LWD determined resilient modulus was generated (Figure 5.4) using LWD defection average and standard deviation values (Figure 5.1) and the standard error for predicting resilient modulus from LWD elastic modulus (Figure 3.13). The distribution of LWD determined M_r values is skewed right; however, logarithmic (base 10) transformation of the data yields a nearly normal distribution. Average log transformed LWD determined M_r equals 4.44 that equates to 27,500 psi, and log transformed standard deviation equals 0.251. As a rule of thumb in QA testing, INDOT should expect that 90% of construction acceptance tests yield passing test results (i.e., $p = 0.1$). The inverse normal at $p = 0.1$ for the log transformed LWD determined M_r equals 4.12 that equates to 13,200 psi. Therefore, based on actual LWD deflections measured on cement treated subgrade (subgrade type IBC) during new pavement construction along with the laboratory study documented in Section 3 of this report, INDOT can comfortably assign design resilient modulus values equal to 13,200 psi for subgrade treatment type IBC in pavement design.

Figure 5.5a provides a combined distribution of FWD back-calculated M_r values for the test sections documented in Section 4 of this report. The distribution of FWD

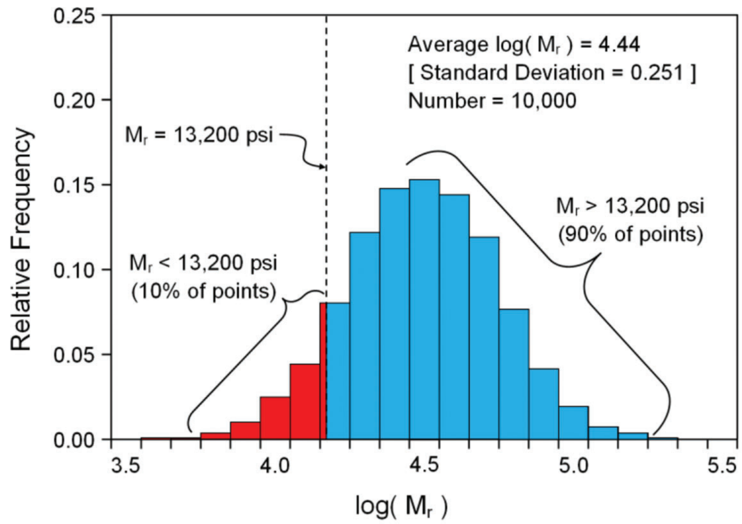


Figure 5.4 Probabilistic model for LWD determined resilient modulus using distribution of LWD deflections from field test sections.

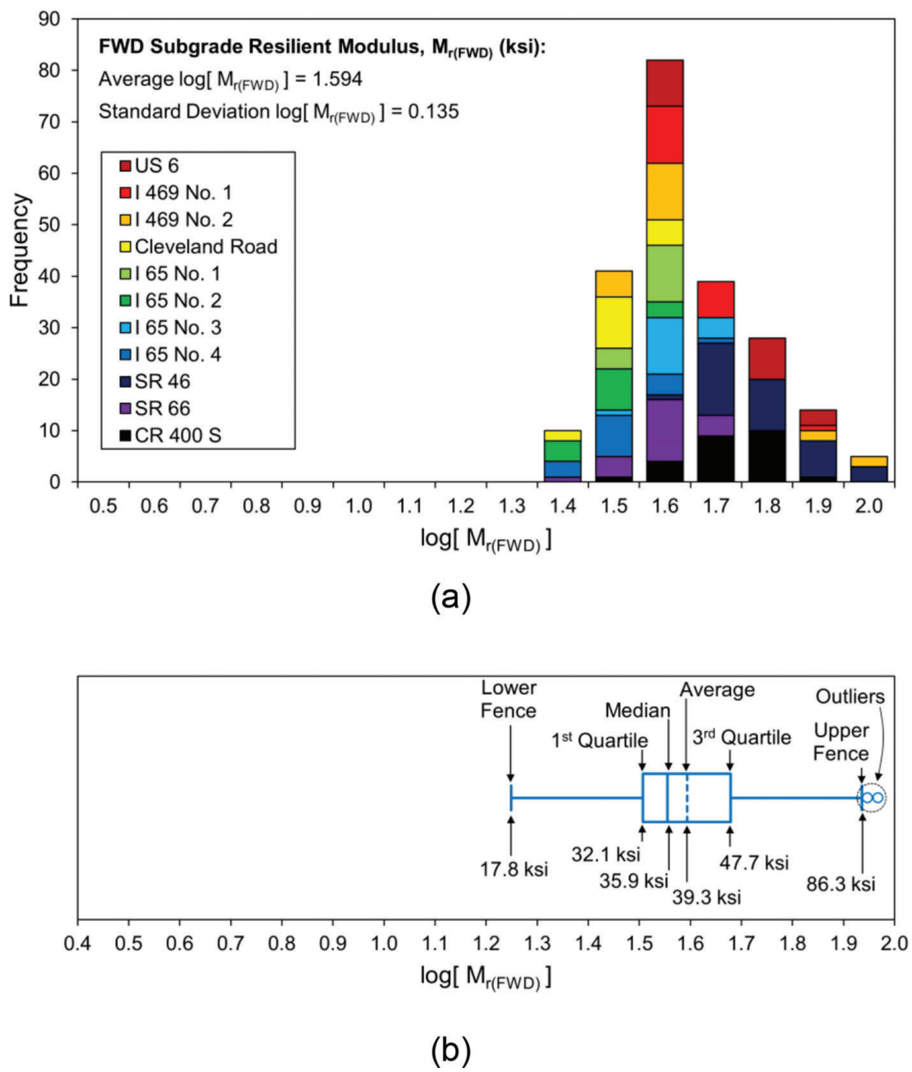


Figure 5.5 Distribution of FWD determined resilient modulus for field test sections reported as (a) histogram and (b) Tukey box plot.

back-calculated M_r values is skewed right, so values were logarithmically (base 10) transformed yielding a nearly normal distribution. Average log transformed FWD back-calculated M_r equals 4.594 that equates to 39,300 psi. Figure 5.5b presents the FWD back-calculated M_r values using a Tukey box plot. The box plot fences indicate practical limits for data distributions—values outside of the fences are outliers. The lower fence for the FWD back-calculated M_r distribution equals 17,800 psi. Therefore, based on FWD testing conducted on newly constructed pavements containing cement treated subgrade (subgrade treatment type IBC), INDOT can comfortably assign design resilient modulus values equal to 17,800 psi for subgrade treatment Type IBC in pavement design. The FWD based recommended M_r design values is 35% higher than that for the LWD based design value, which is likely due to the differing stress conditions. Because FWD tests were conducted atop pavement layers, subgrade soils experienced higher confinement (i.e., higher bulk stress) and lower applied stresses (i.e., lower octahedral shear stress).

6. RECOMMENDATIONS FOR IMPLEMENTATION

6.1 Maximum Allowable LWD Deflection for Cement Modified Soil

INDOT standard specifications require that LWD deflection measured on cement modified subgrade (typically measured after 1-day curing) equal no greater than 0.27 mm on average. Findings from the laboratory portion of this study suggests that 0.27 mm LWD deflection corresponds to 26,500 psi 28-day cure resilient modulus that is much greater than the 8,000 psi to 9,000 psi resilient modulus used in new pavement design. Therefore, the current maximum deflection criterion adequately assures that constructed cement modified subgrades meet design assumptions.

Besides meeting design resilient moduli, cement modified subgrades must be able to function as construction working platforms. INDOT design procedures for chemical modification and stabilization of soils require that cement modification increase laboratory unconfined compressive strength by 100 psi (70 psi in the field, see Section 3.1.3). Findings from the laboratory study suggest that 0.27 mm LWD deflection corresponds to 89 psi unconfined compressive strength increase. Therefore, the current maximum deflection criterion adequately assures that constructed cement modified subgrades function appropriately well as construction working platforms.

LWD field testing conducted at INDOT new pavement construction projects showed that LWD deflection equals 0.26 mm on average. So, actual LWD deflections are consistent with the 0.27 mm required by INDOT standard specifications. Moreover, resilient moduli predicted from LWD measurements conducted during construction are in agreement with resilient moduli determined from FWD testing measured atop pavement layers.

Because the current maximum LWD deflection criterion meets design resilient modulus assumptions, meets unconfined compressive strength increase requirements, and is consistent with actual measurements taken during construction; INDOT should continue specifying 0.27 mm maximum deflection for cement modified subgrade construction acceptance.

6.2 Cement Modified Soil Design Resilient Modulus Implementation Study

A key finding from this study involved typical resilient modulus values for cement modified subgrade. Conservative estimates for cement modified subgrade resilient modulus equaled 13,200 psi based on LWD testing and 17,800 psi based on FWD testing, which are both significantly greater than the 8,000 psi to 9,000 psi resilient moduli used in new pavement design. However, neither the LWD- nor the FWD-based methods directly measure resilient modulus. Therefore, there is no assurance that either method truly predict resilient modulus. Rather, it is recommended that additional testing be conducted to explore this finding further. The following sections provide an overview of the proposed implementation study to investigate in situ resilient modulus of cement treated subgrade.

6.2.1 Automated Plate Load Test (APLT)

The automated plate load test (APLT) system is a trailer-mounted rig (Figure 6.1) capable of performing static plate load tests (i.e., modulus of subgrade reaction) and repetitive/cyclic plate load tests (i.e., resilient modulus). A computer is integrated into the APLT rig that operates as a test controller and data acquisition system, so APLT operation is fully automated. Shown in Figure 6.2, a vertical actuator (7 ton capacity without anchoring) applies prescribed loads to a loading plate (8-in., 12-in., 18-in., or 30-in. diameter) while a force transducer measures actual loading and 3-laser displacement sensors measure vertical displacement. An 18-in.

Figure 6.1 Overview of automated plate load test (APLT).

diameter loading plate is commonly used when testing directly atop pavement subgrades. Table 6.1 provides the cyclic loading schedule for measuring subgrade resilient modulus. Testing parameters (e.g., applied cyclic axial stress) and results (resilient modulus and accumulated permanent deformation) may be viewed in real time (Figure 6.3). Post-processing of APLT measurements yields a PE stamped report (Figure 6.4) with recommendations for pavement design, quality assurance, etc. When measuring subgrade resilient modulus, the APLT report provides a stress-dependent resilient modulus relationship in addition to a recommended resilient modulus value for a particular stress condition.

6.2.2 S-BRITE Test Strip Field Study

As part of SPR-4327 (*Development of Compaction Control Guidelines for Aggregate Drainage Layers and Evaluation of In Situ Permeability Testing Methods for Aggregates*), researchers will be constructing two 20-ft by 60-ft pavement test strips at the S-BRITE facility at Purdue University in West Lafayette (Figure 6.5). Both test strips will be constructed with nominal 6 in. of No. 53 aggregate; however, one test strip will be constructed with cement modified subgrade (i.e., subgrade treatment type IBC), while the other test strip will have natural subgrade (i.e., control). Subgrade LWD testing will be conducted 1-day after cement treatment, and subgrade resilient modulus APLT testing will be conducted at least 28 days after cement treatment. APLT testing results will provide additional verification of the LWD based method for predicting resilient modulus. Moreover, APLT testing results will provide reliable measurements of cement modified subgrade resilient modulus for use in pavement design practice.

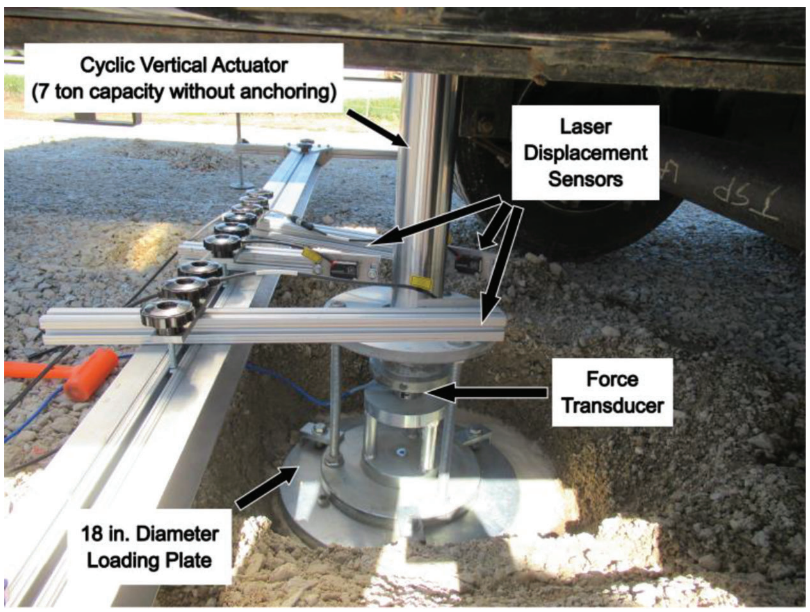


Figure 6.2 Automated plated load test (APLT) setup for measuring subgrade resilient modulus.

TABLE 6.1
Cyclic loading schedule for measuring in situ subgrade resilient modulus

Sequence	Maximum Applied Stress (psi)	Cyclic Axial Stress (psi)	Constant Axial Stress (psi)	Number of Cycles
0	15.0	13.0	2.0	500
1	6.0	4.0	2.0	100
2	10.0	8.0	2.0	100
3	15.0	13.0	2.0	100
4	20.0	18.0	2.0	150
5	30.0	28.0	2.0	200
6	40.0	38.0	2.0	150

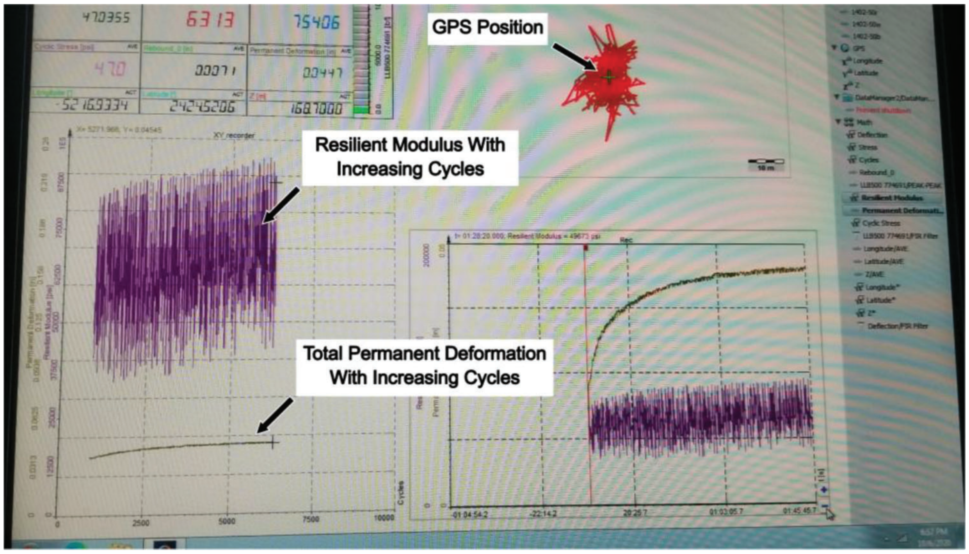
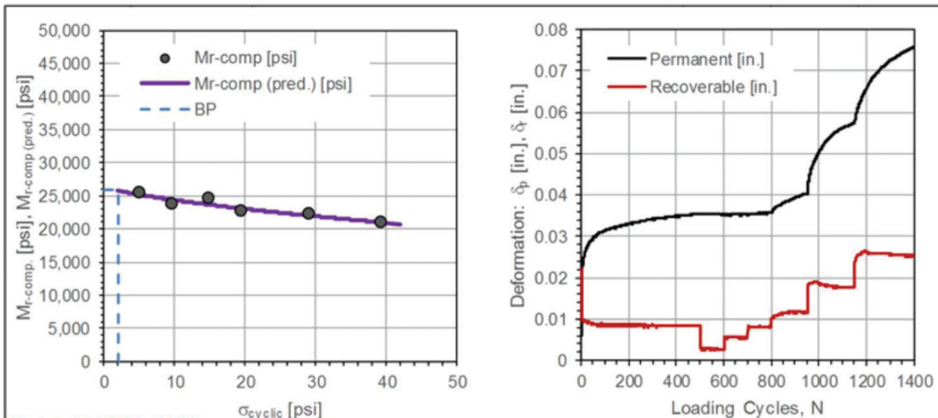


Figure 6.3 Sample real time automated plate load test (APLT) testing results.



Model: AASHTO (2015)

$$M_{r-comp} = k_1^* P_a \left(\frac{\theta}{P_a}\right)^{k_2^*} \left(1 + \frac{\tau_{oct}}{P_a}\right)^{k_3^*}$$

Parameter	Value	P-Value
k^*_1	1,759.7	2.29E-07
k^*_2	-0.008	9.21E-01
k^*_3	-0.551	3.66E-01
Adj. R^2	0.835	
Std. Error [psi]	626	

$M_{r\text{-comp (pred.)-BP}}$ [psi]		25,812
	$\sigma_{cyclic\text{-}BP}$ [psi]	2.0

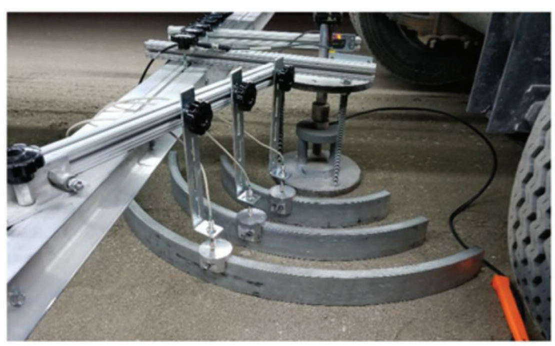


Figure 6.4 Sample automated plate load test (APLT) report findings.

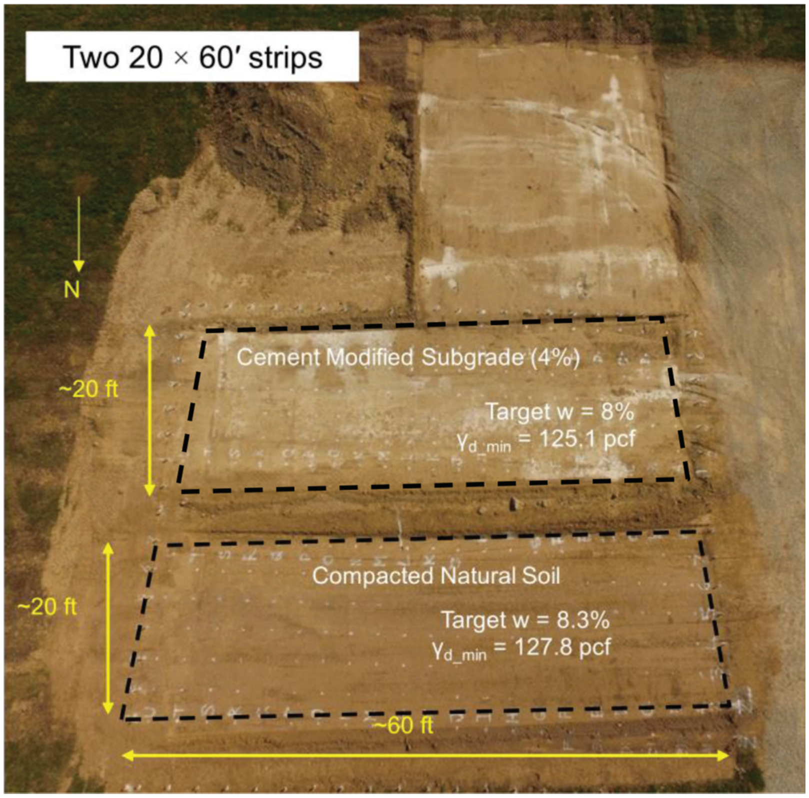


Figure 6.5 Layout of S-BRITE cement modified subgrade and control subgrade test sections.

7. SUMMARY AND CONCLUSIONS

This report documents the findings from SPR-4230. The main objective of SPR-4230 involves establishing performance-related quality assurance (QA) test methods for pavement subgrade construction. Because INDOT generally prefers specifying subgrade treatment type IBC (i.e., 14-in. chemically modified subgrade), this study focused on performance-based QA test methods for constructing cement modified subgrade. Moreover, INDOT prefers using light weight deflectometer (LWD) for chemically modified subgrade construction acceptance, so this study aimed to use LWD deflection measurements as performance-related construction acceptance criteria. A laboratory study was performed to relate LWD deflections with resilient modulus that is the key subgrade performance-related parameter in pavement design. In addition, LWD deflections were related with unconfined compressive strength increase that is the key parameter in chemical soil modification mix design. A rigorous field study consisting of LWD testing and falling weight deflectometer (FWD) testing at INDOT new pavement construction sites was conducted to verify the laboratory developed relationship. Recommendations for implementing results of this study into cement modified subgrade construction acceptance is provided, as are recommendations for future research.

The key findings from this study are as follows:

- Unconfined laboratory LWD elastic moduli for cement treated soil increases with increasing applied axial stress following an exponential growth relationship. Using the generalized form of Hooke's law, the laboratory LWD elastic moduli can be used in three-dimensional applications (e.g., in situ LWD testing). Combining the generalized laboratory LWD relationship with Bousinesq's solutions for distribution of vertical and radial stresses within a semi-infinite homogenous elastic solid then integrating calculated vertical strains allows for the prediction of in situ LWD deflection and in situ LWD elastic modulus (Section 3.3.1).
- At equivalent stress conditions (bulk stress and octahedral shear stress) and equal curing times, LWD elastic modulus is approximately equal to resilient modulus for cement modified soil. However, LWD testing for construction acceptance is typically conducted after only 1-day curing, well before fully developing strength/stiffness (>28 days). Therefore, as-constructed cement modified LWD elastic moduli can be multiplied by a curing coefficient for direct comparison with long-term resilient moduli (Section 3.3.2).
- INDOT requires cement modified subgrade resilient modulus pavement design inputs equaling 9,000 psi for clayey soils and 9,500 psi for sandy soils. Using a probabilistic model with LWD deflection equaling 0.45 mm, there is a 90% probability that resilient modulus

meets or exceeds 9,000 psi. Likewise, with LWD deflection equaling 0.43 mm, there is a 90% probability that resilient modulus meets or exceeds 9,500 psi (Section 3.3.2).

- INDOT requires that cement modification increase subgrade soil unconfined compressive strength (UCS) by no less than 100 psi. However, field UCS values tend to equal approximately 70% laboratory UCS values, so LWD values should demonstrate 70 psi increases in UCS. Predicted LWD elastic modulus correlates well ($R^2 = 0.695$) with UCS increases, using an exponential growth model. If measured LWD deflection equals 0.27 mm, as specified in the INDOT standard specifications; then there is an 86% probability that ΔUCS will meet or exceed 70 psi. For there to be a 90% probability that ΔUCS meets or exceeds 70 psi, measured LWD deflection should equal 0.21 mm (Section 3.3.3).
- Detailed case histories for new pavement construction projects incorporating cement modified subgrade have been developed—US 6, I 469, Cleveland Road, I 65, SR 46, SR 66, and CR 400 S. Case histories consist of laboratory mix designs, LWD elastic moduli during construction, and FWD derived resilient moduli after pavement placement have been generated (Section 4.2).
- LWD deflections from all field test sites combine into a skewed right distribution; however, logarithmic (base 10) transformation yields a nearly normal distribution with -0.586 average (0.259 mm) and 0.158 standard deviation (Section 5.1).
- Bland-Altman comparison between LWD predicted resilient modulus and FWD back-calculated resilient modulus reveals that the vast majority of points (97.4%) fall between the 95% (i.e., $\alpha = 0.5$) limits of agreement. Therefore, resilient moduli predicted from LWD immediately following subgrade treatment adequately agree with resilient moduli back-calculated from FWD measured on the pavement surface (Section 5.1).
- A probabilistic model for LWD predicted resilient modulus was generated using statistics from LWD field results combined with the standard error for predicting resilient modulus from LWD elastic modulus. Predicted resilient modulus equals 13,200 psi at $p = 0.1$ that corresponds to 90% of construction acceptance tests yielding passing results. Therefore, INDOT can comfortably assign design resilient modulus values equal to 13,200 psi for subgrade treatment type IBC in pavement design based on results from LWD test measurements (Section 5.2).
- A probabilistic model for FWD back-calculated resilient modulus was generated using statistics from FWD field tests. FWD back-calculated resilient modulus equals 17,800 psi at $p = 0.1$ that corresponds to 90% of construction acceptance tests yielding passing results. Therefore, based on results from FWD test measurements, INDOT can comfortably assign design resilient modulus values equal to 17,800 psi for subgrade treatment type IBC in pavement design (Section 5.2).
- Because the current maximum LWD deflection criterion meets design resilient modulus assumptions, meets unconfined compressive strength increase requirements, and is consistent with actual measurements taken during construction; INDOT should continue specifying 0.27 mm maximum deflection for cement modified subgrade construction acceptance (Section 6.1).
- Conservative estimates for cement modified subgrade resilient modulus equaled 13,200 psi based on LWD testing and 17,800 psi based on FWD testing, which are both significantly greater than the 8,000 psi to 9,000 psi resilient moduli used in new pavement design. Therefore, it is recommended that additional testing (Automated Plate Load Testing) be conducted to explore this finding further (Section 6.2).

REFERENCES

AASHTO. (1993). *AASHTO guide for design of pavement structures*. American Association of State Highway and Transportation Officials.

AASHTO. (2015). *Standard method of test for moisture–density relations of soils using a 2.5-kg (5.5-lb) rammer and a 305-mm (12-in.) drop* (AASHTO T 99-15). American Association of State and Highway Transportation Officials.

AASHTO. (2017). *Standard method of test for determining the resilient modulus of soils and aggregate materials* (AASHTO T 307-99). American Association of State and Highway Transportation Officials.

AASHTO. (2019). *Standard method of test for unconfined compressive strength of cohesive soil* (AASHTO T 208-15). American Association of State and Highway Transportation Officials.

FHWA. (2020, April 6). *Major types of transportation construction specifications: A guideline to understanding their evolution and application* [Webpage]. US Department of Transportation Federal Highway Administration. Retrieved October 26, 2020, from https://www.fhwa.dot.gov/construction/specs.cfm

INDOT. (2015, January 13). *Design procedures for soil modification or stabilization.* Indiana Department of Transportation.

Odemark, N. (1949). *Undersökning av elasticitetsegenskaperna hos olika jordarter samt teori för beräkning av beläggningar enligt elasticitetsteorin*. Statens Vaeginstitute.

Park, S., Nantung, T., & Bobet, A. (2018). *Correlation between resilient modulus (M_R) of soil, light weight deflectometer (LWD), and falling weight deflectometer (FWD)* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/08). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316651

White, D. J., Becker, P., Vennapusa, P. K. R., Mark, J. D., & White, C. I. (2013). Assessing soil stiffness of stabilized pavement foundations. *Transportation Research Record*, *2335*(1), 99–109. https://doi.org/10.3141/2335-11

APPENDICES

Appendix A. Results of LLWD Testing

Appendix B. Resilient Modulus Testing Results

Appendix C. Unconfined Compressive Strength Testing Results

Appendix D. Overview of Field Test Sites

APPENDIX A. RESULTS OF LLWD TESTING

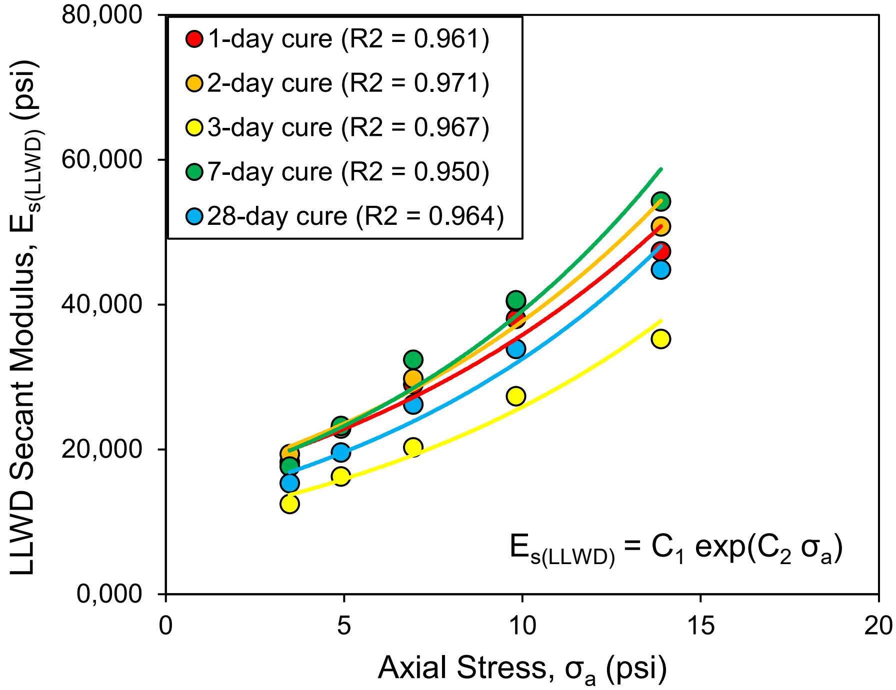


Figure A.1 Specimen 1–1 correlations for LLWD secant modulus from axial stress.

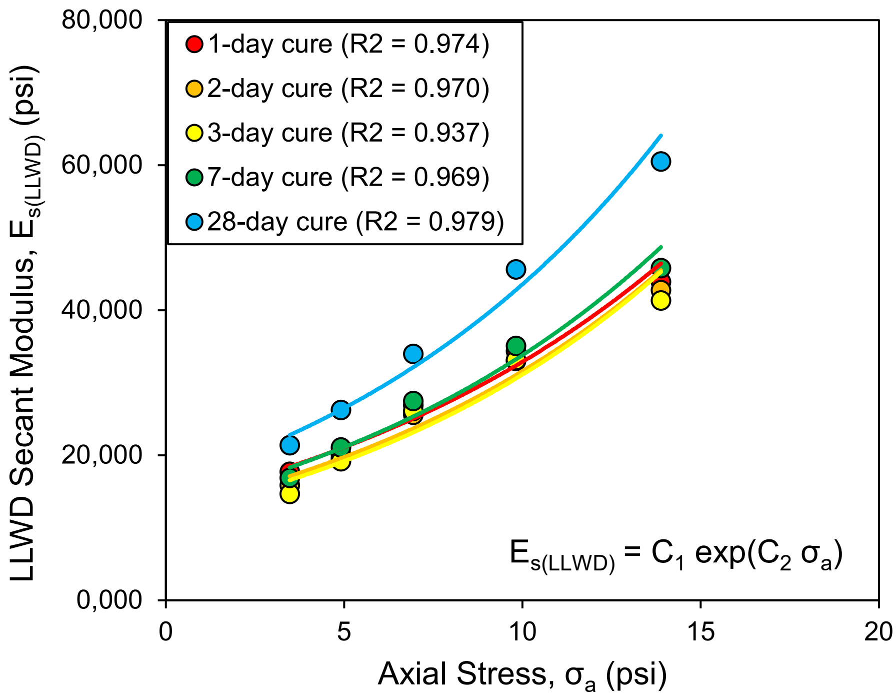


Figure A.2 Specimen 1–2 correlations for LLWD secant modulus from axial stress.

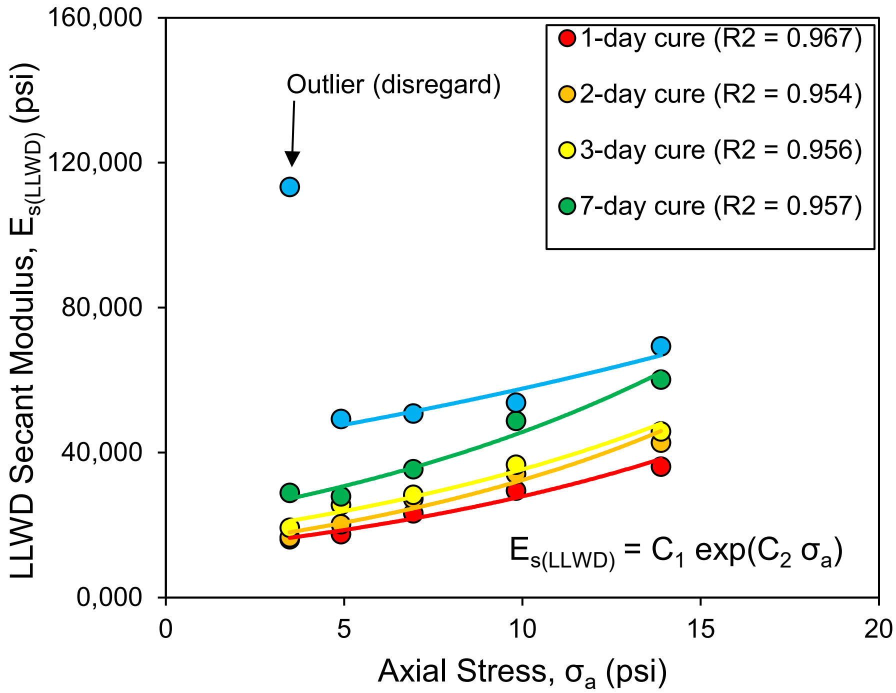


Figure A.3 Specimen 1–3 correlations for LLWD secant modulus from axial stress.

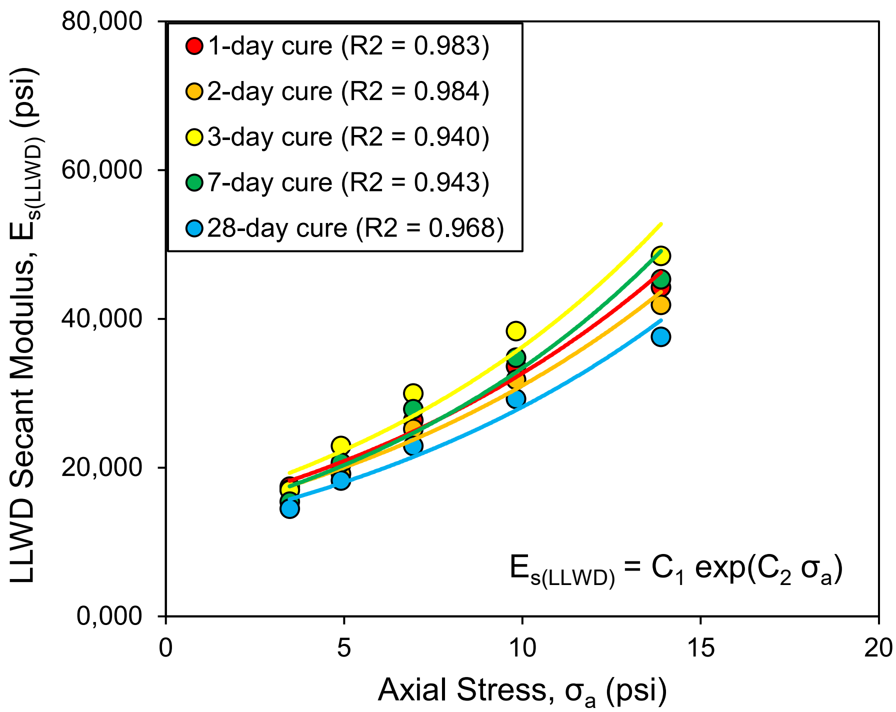


Figure A.4 Specimen 1–4 correlations for LLWD secant modulus from axial stress.

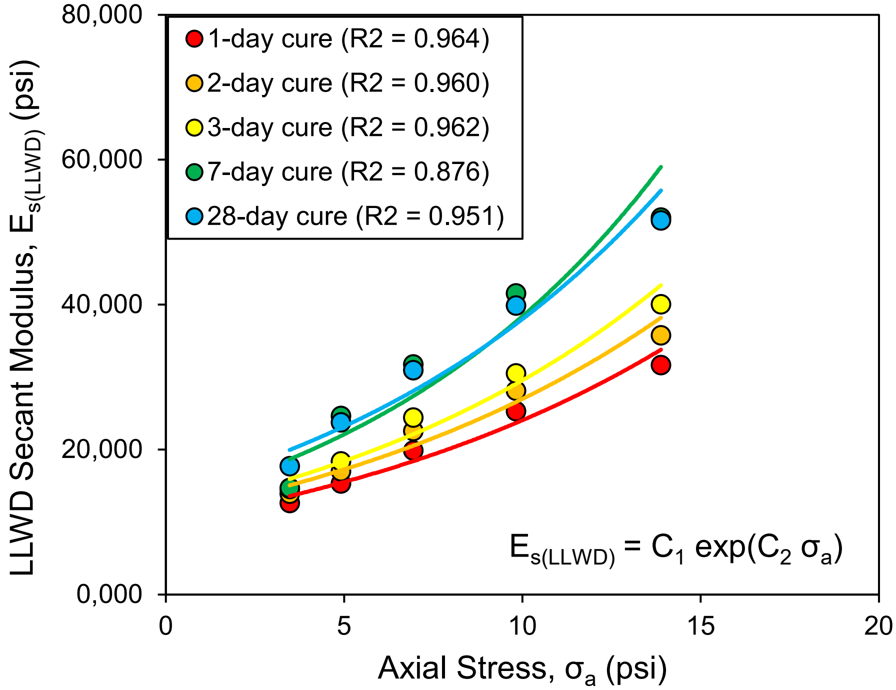


Figure A.5 Specimen 1–5 correlations for LLWD secant modulus from axial stress.

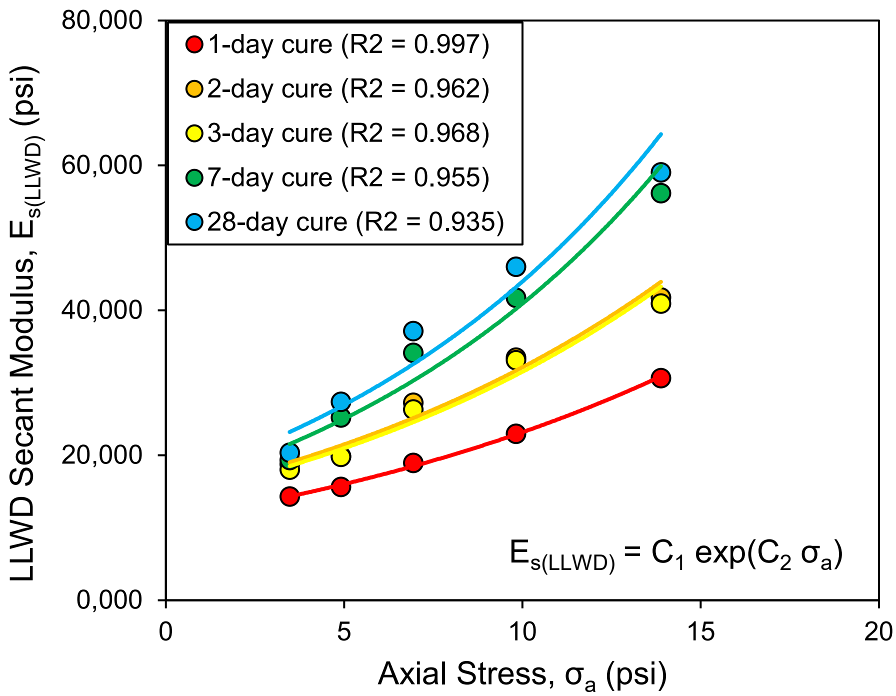


Figure A.6 Specimen 1–6 correlations for LLWD secant modulus from axial stress.

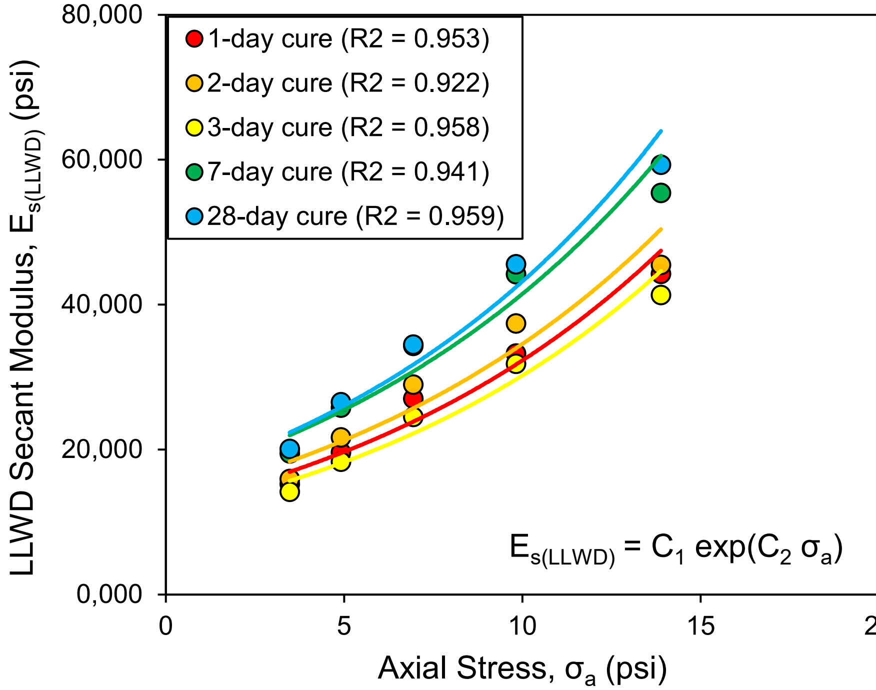


Figure A.7 Specimen 1–7 correlations for LLWD secant modulus from axial stress.

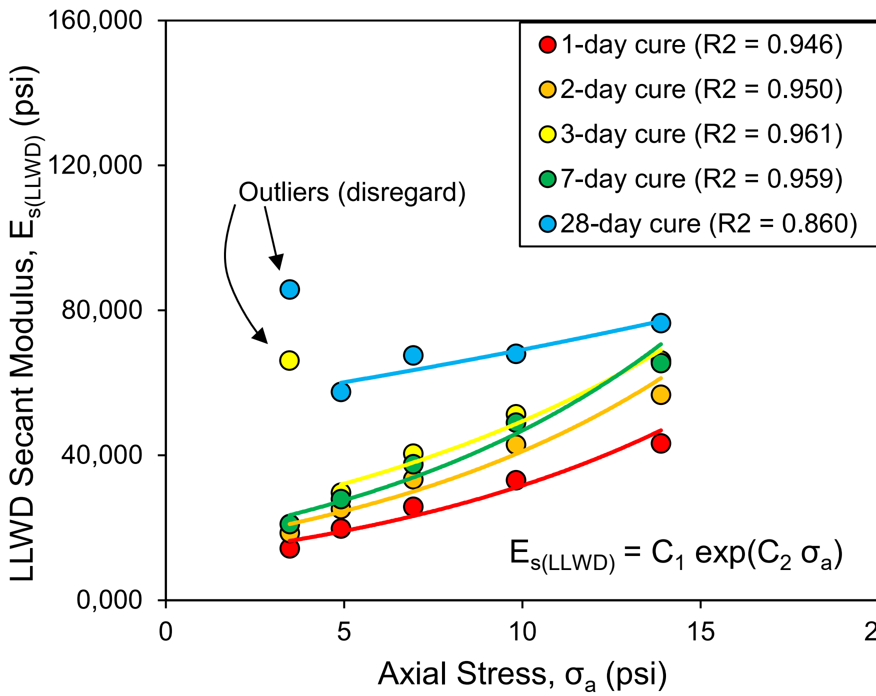


Figure A.8 Specimen 2–1 correlations for LLWD secant modulus from axial stress.

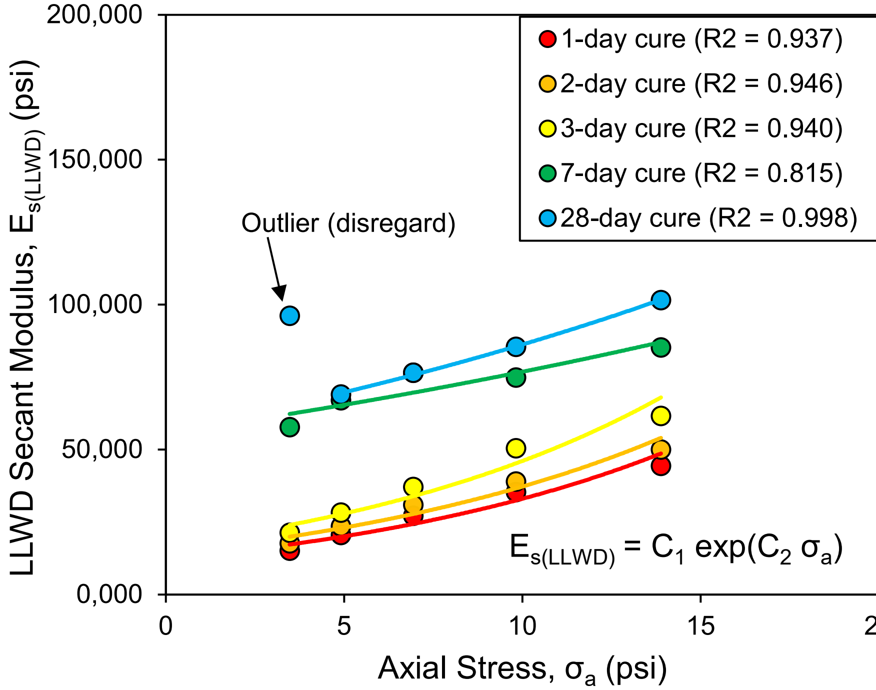


Figure A.9 Specimen 2–2 correlations for LLWD secant modulus from axial stress.

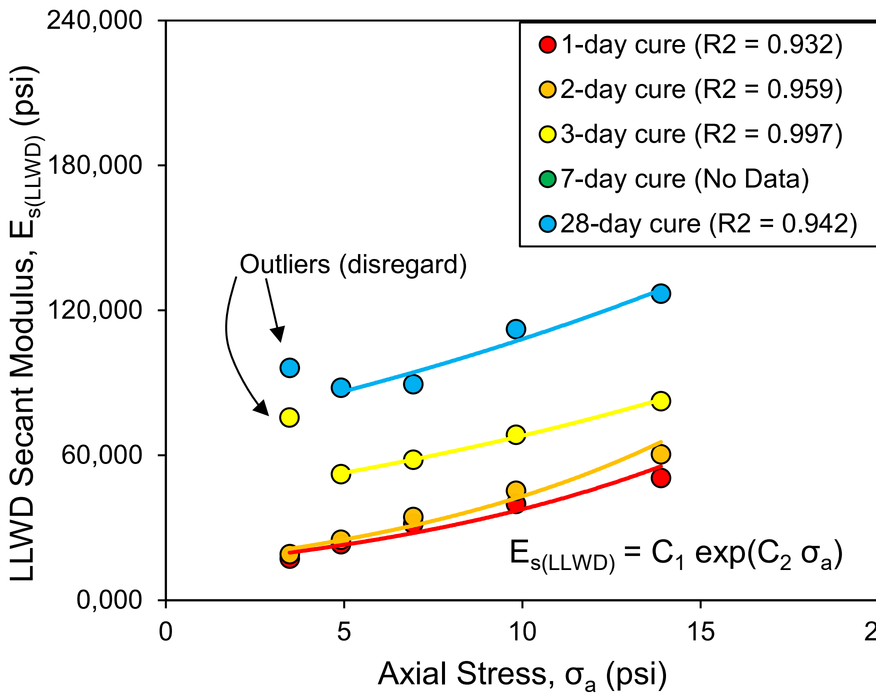


Figure A.10 Specimen 2–3 correlations for LLWD secant modulus from axial stress.

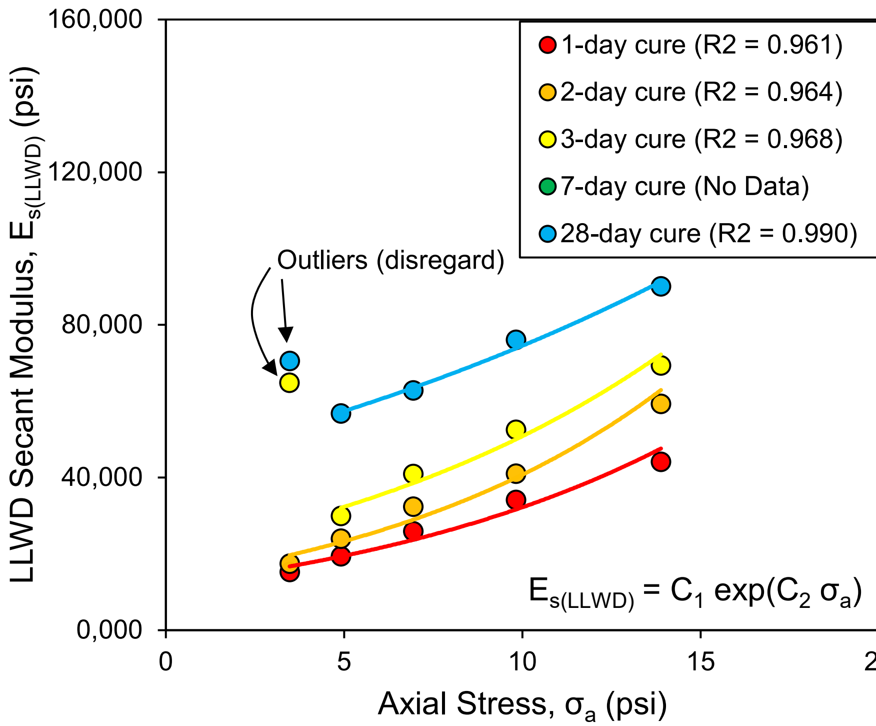


Figure A.11 Specimen 2–4 correlations for LLWD secant modulus from axial stress.

APPENDIX B. RESILIENT MODULUS TESTING RESULTS

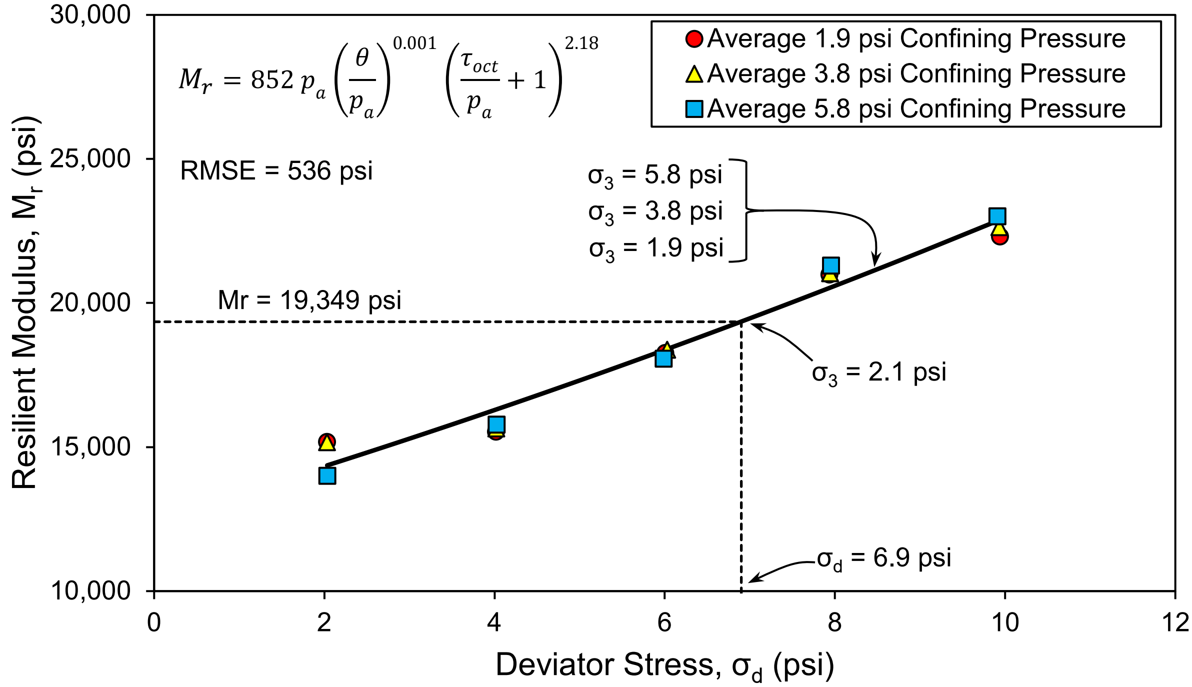


Figure B.1 Resilient modulus testing results for Specimen 1–1.

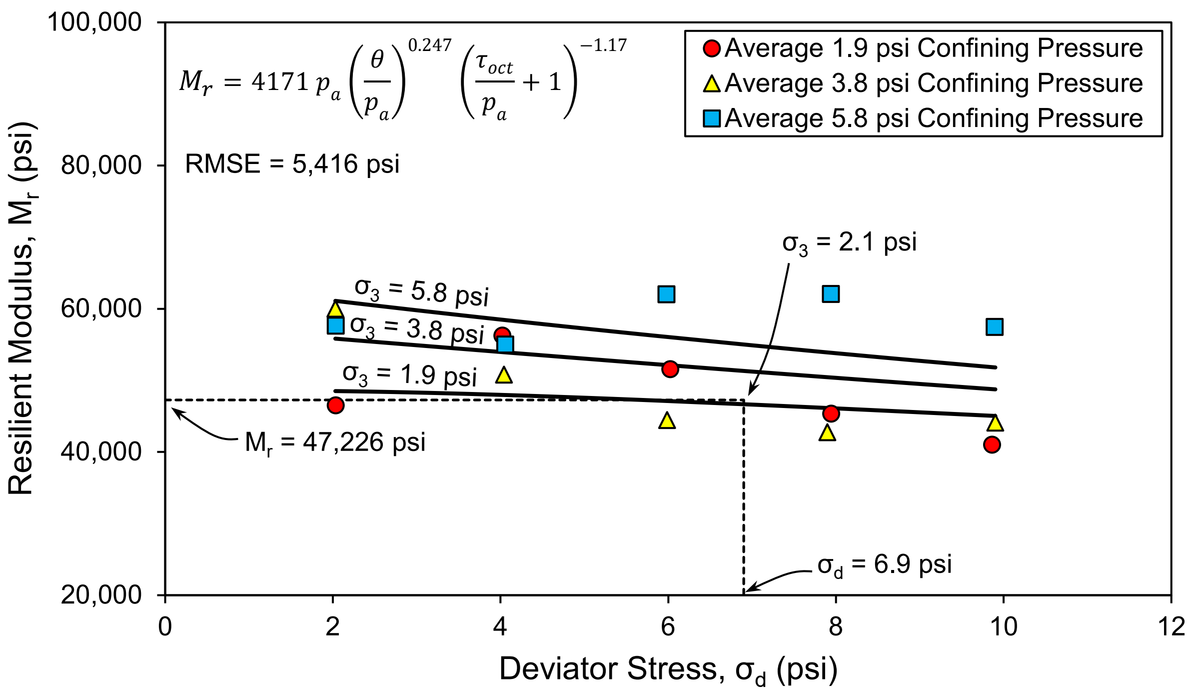


Figure B.2 Resilient modulus testing results for Specimen 1–2.

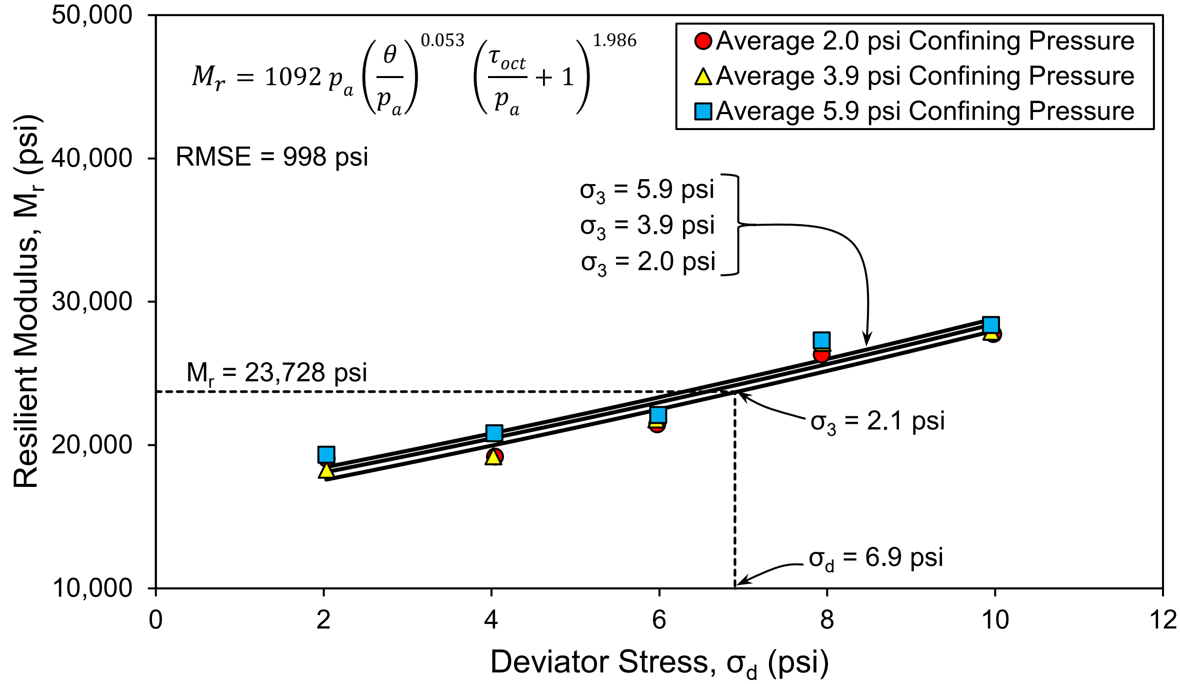


Figure B.3 Resilient modulus testing results for Specimen 1–3.

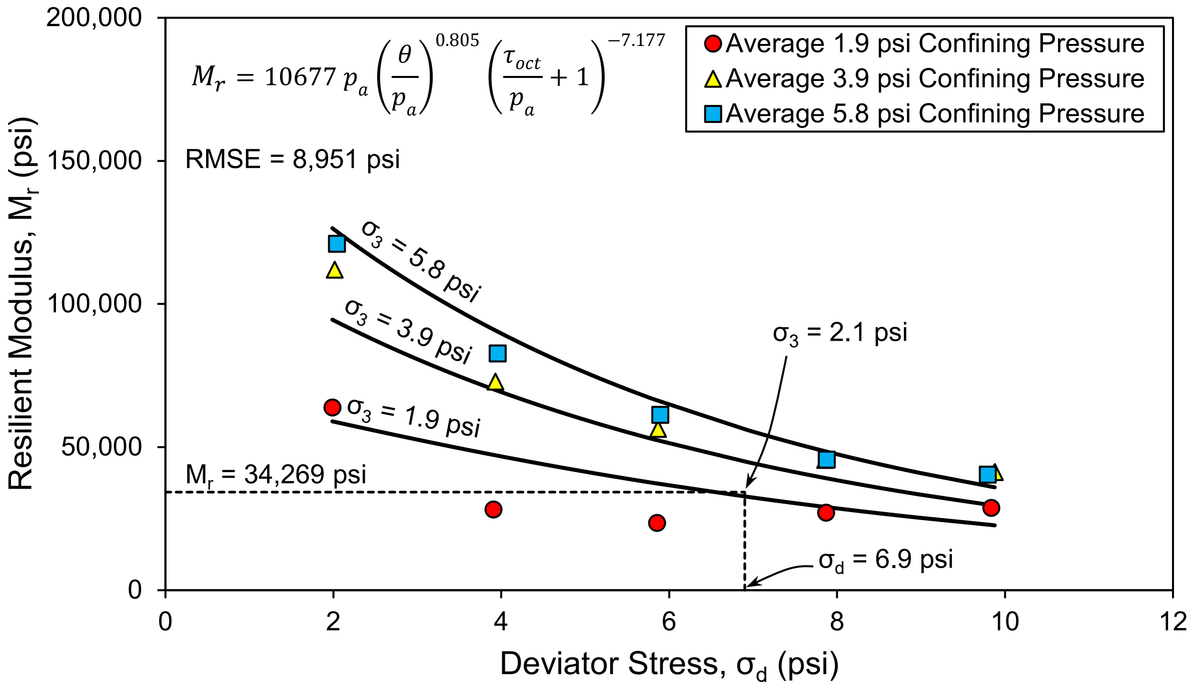


Figure B.4 Resilient modulus testing results for Specimen 1–4.

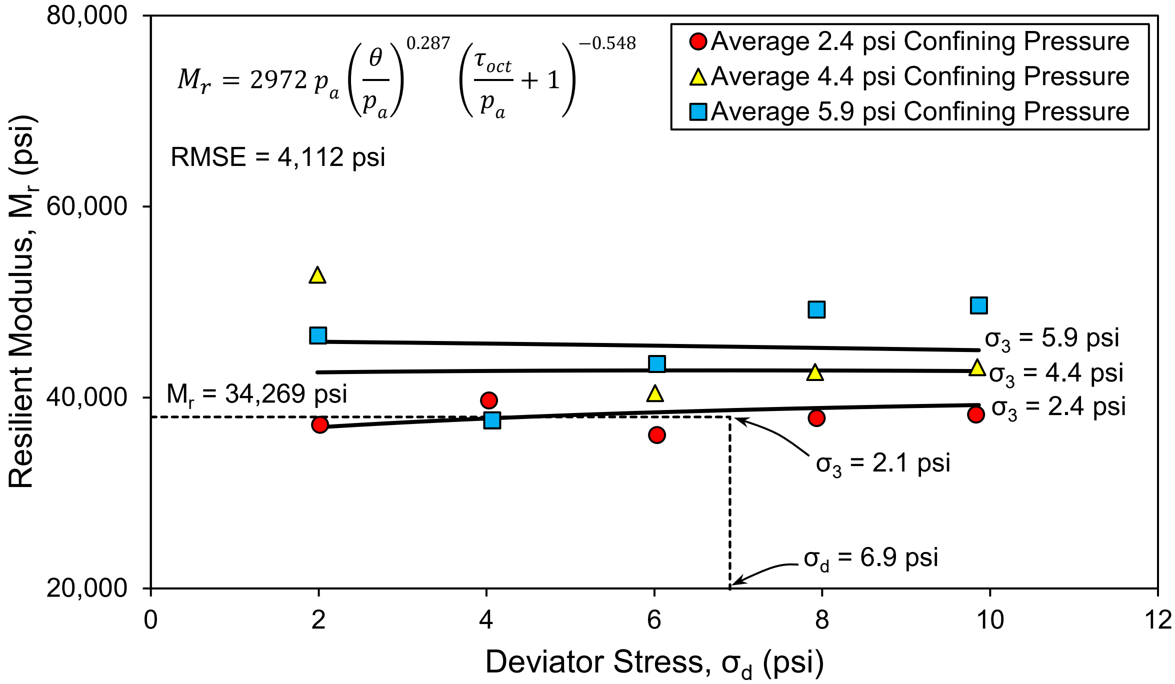


Figure B.5 Resilient modulus testing results for Specimen 1–5.

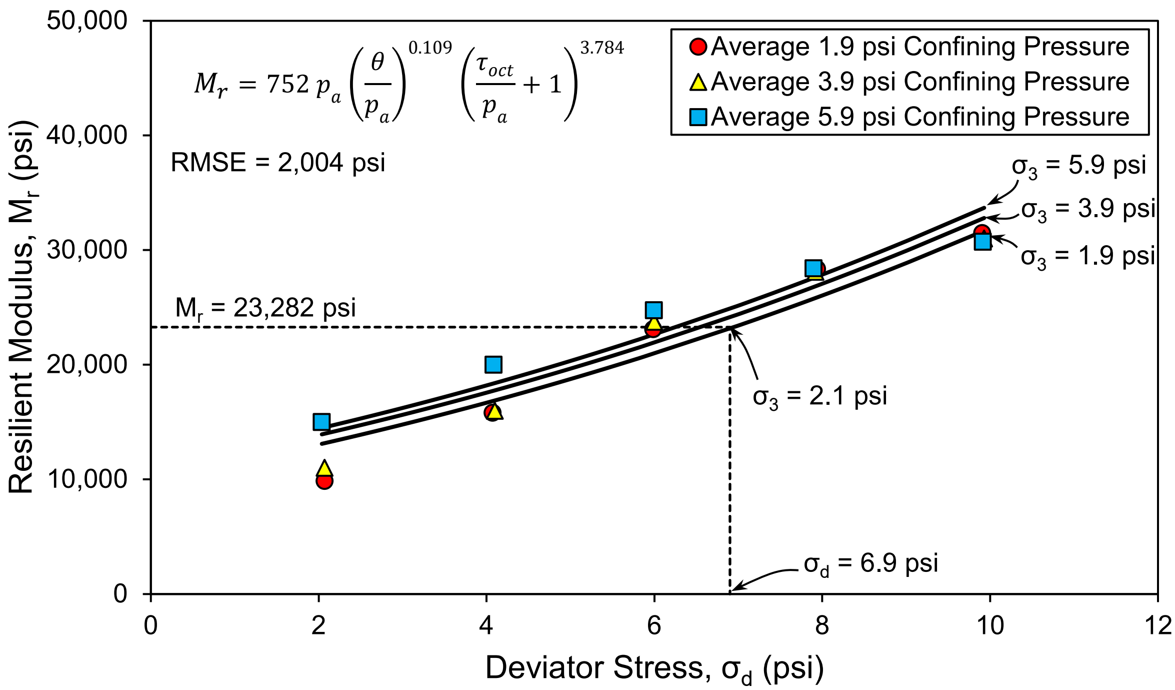


Figure B.6 Resilient modulus testing results for Specimen 1–6.

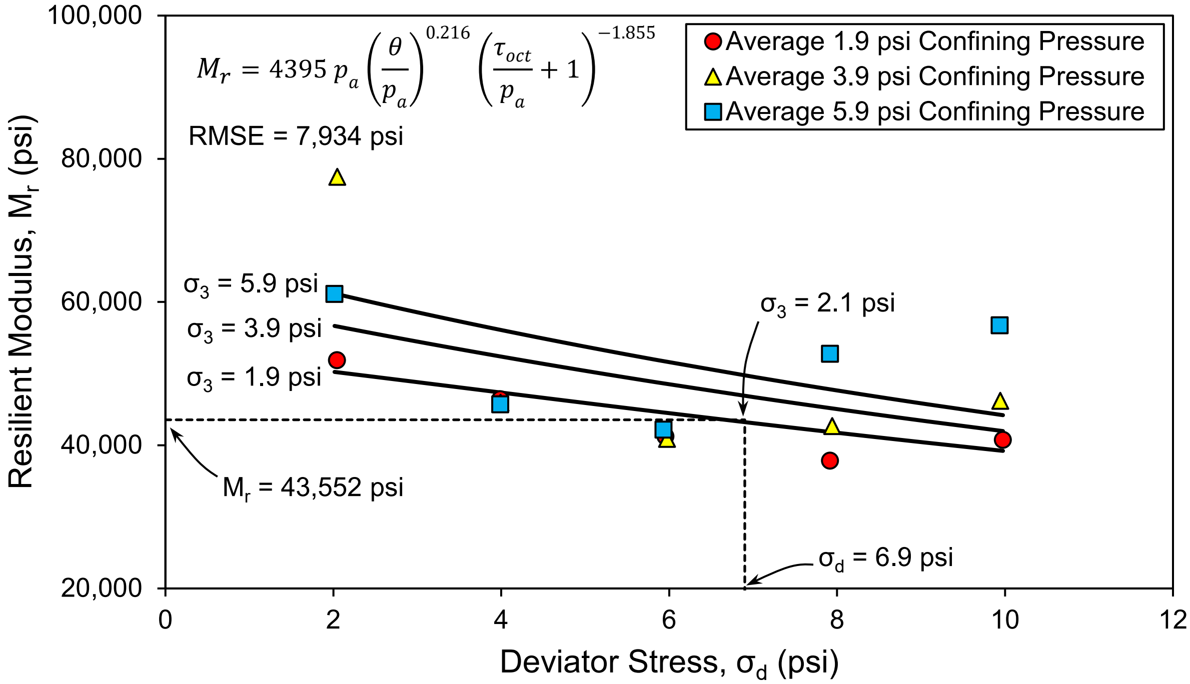


Figure B.7 Resilient modulus testing results for Specimen 1–7.

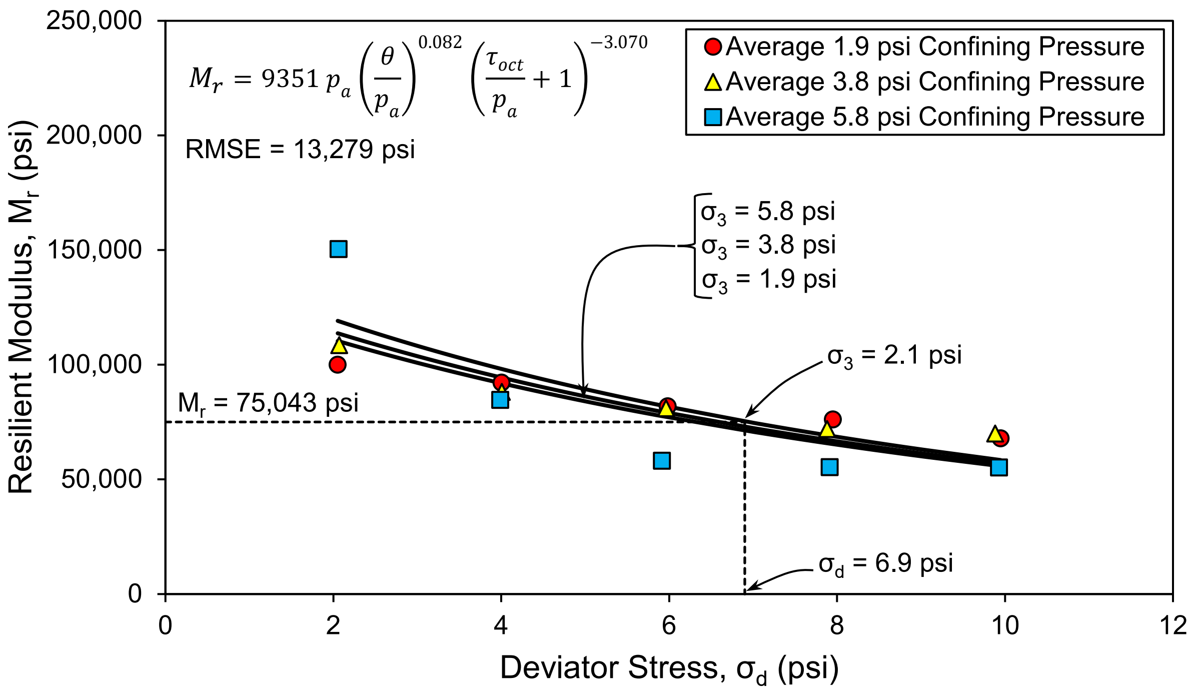


Figure B.8 Resilient modulus testing results for Specimen 2–1.

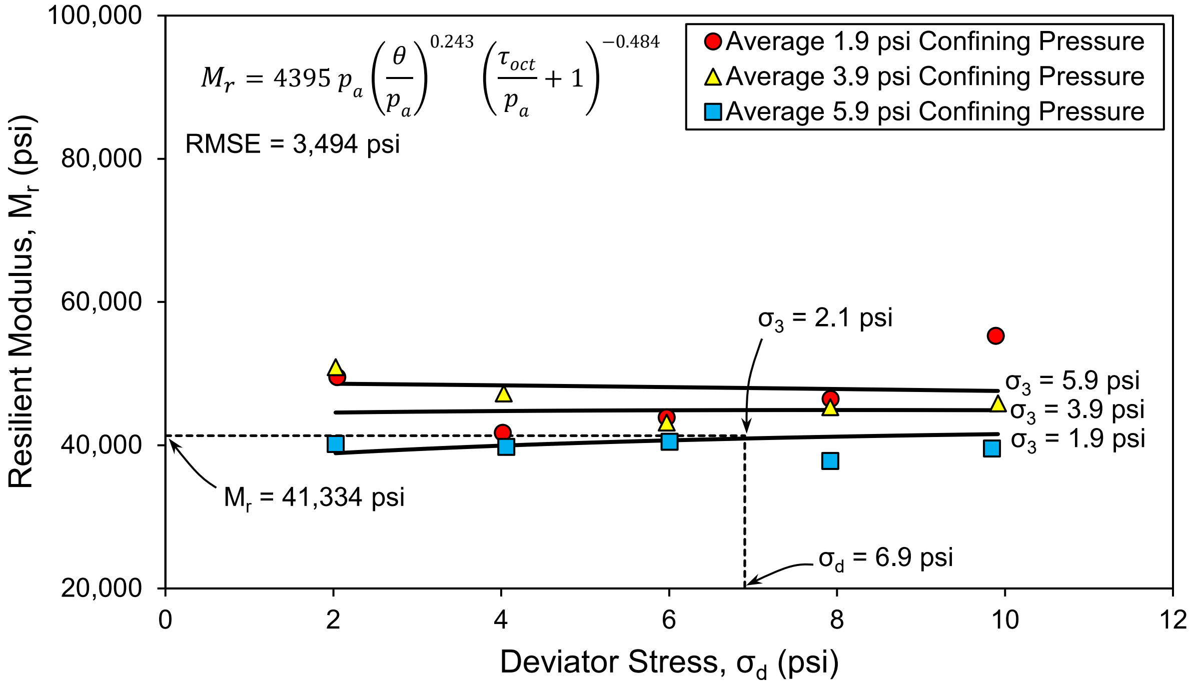


Figure B.9 Resilient modulus testing results for Specimen 2–2.

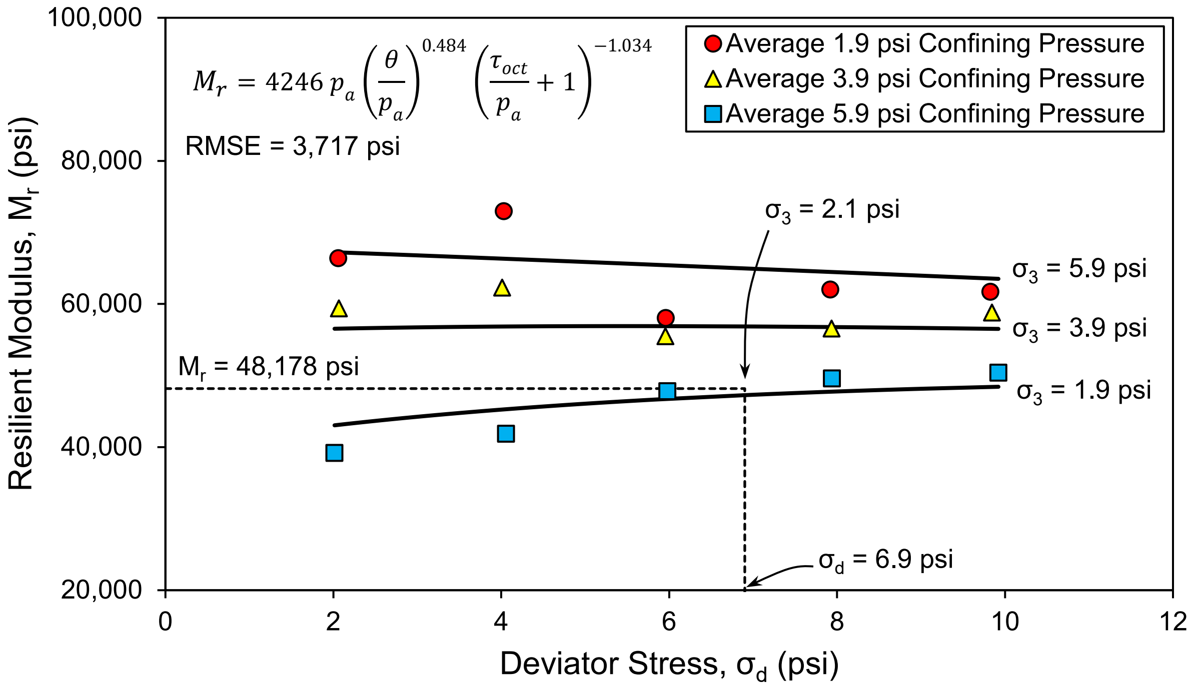


Figure B.10 Resilient modulus testing results for Specimen 2–3.

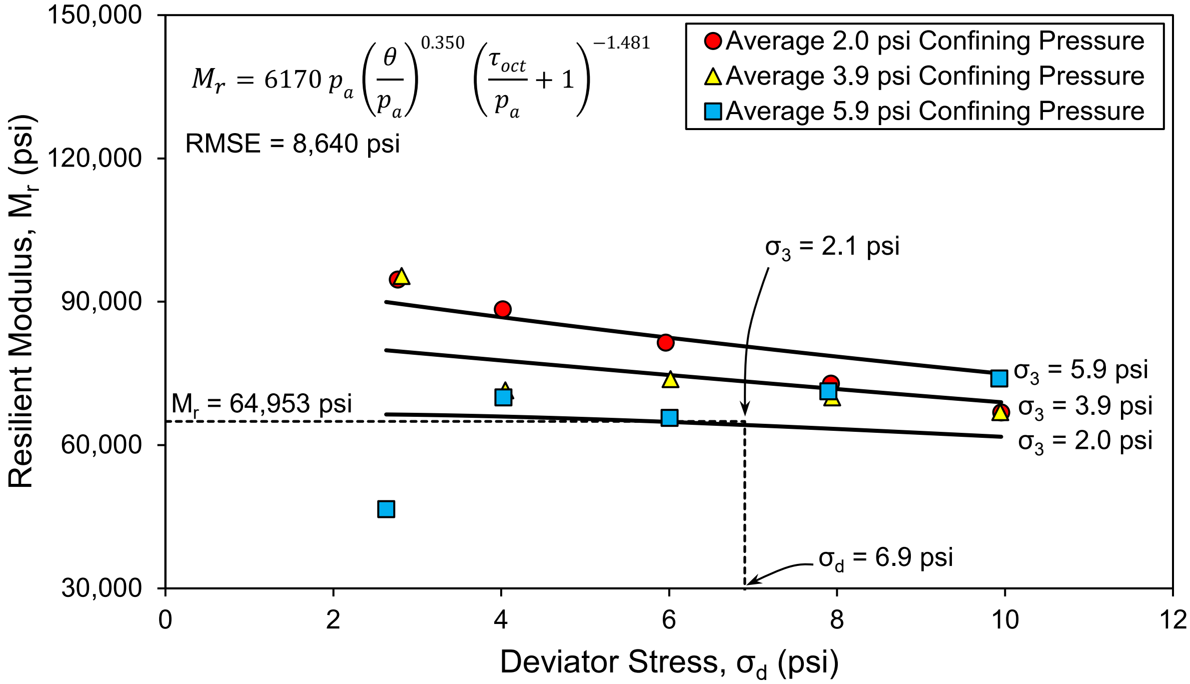


Figure B.11 Resilient modulus testing results for Specimen 2–4.

APPENDIX C. UNCONFINED COMPRESSIVE STRENGTH TESTING RESULTS

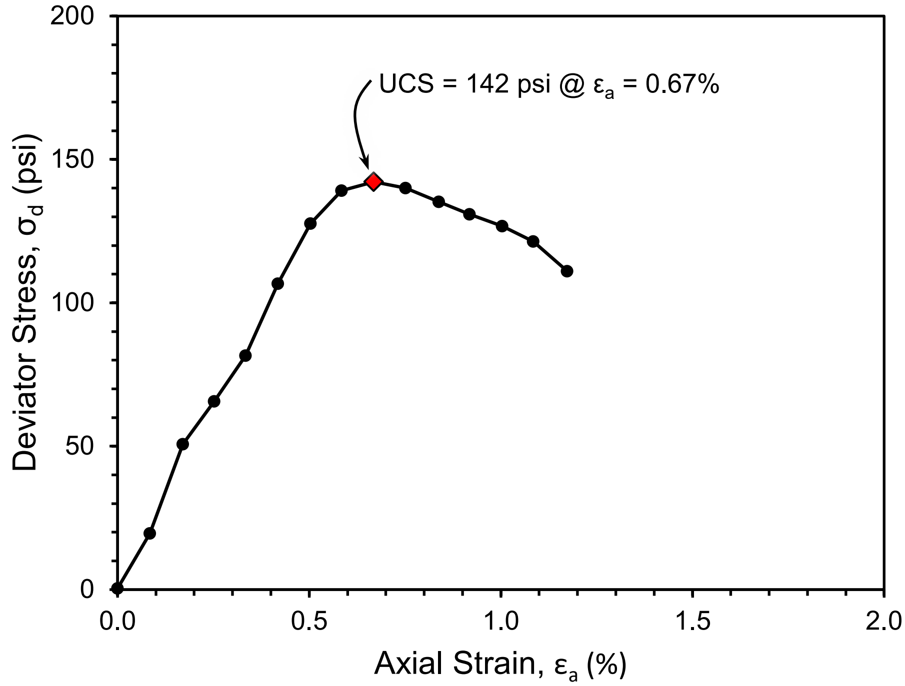


Figure C.1 Unconfined compressive strength test results for Specimen 1–1.

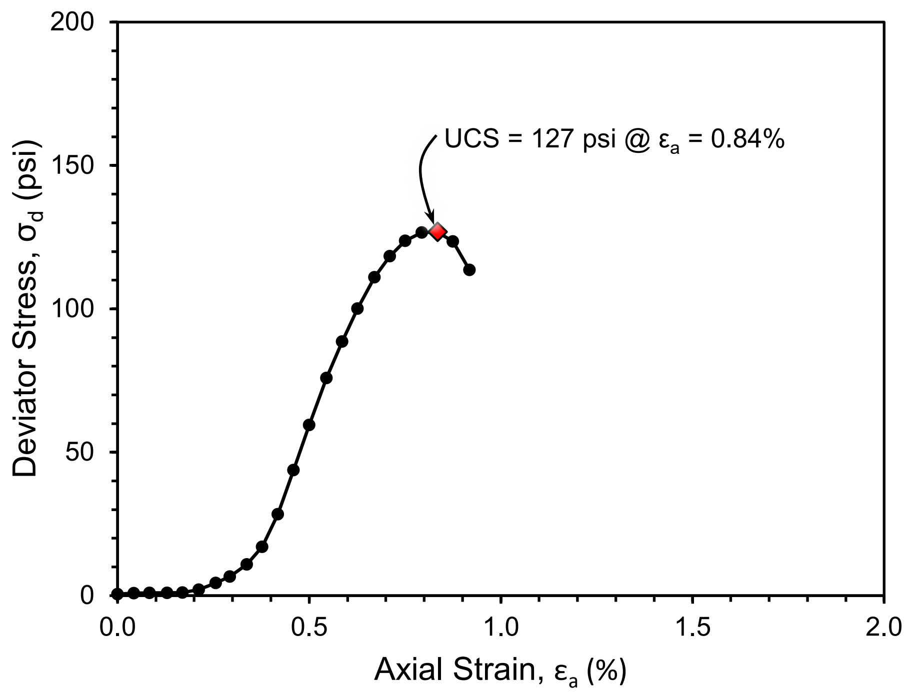


Figure C.2 Unconfined compressive strength test results for Specimen 1–2.

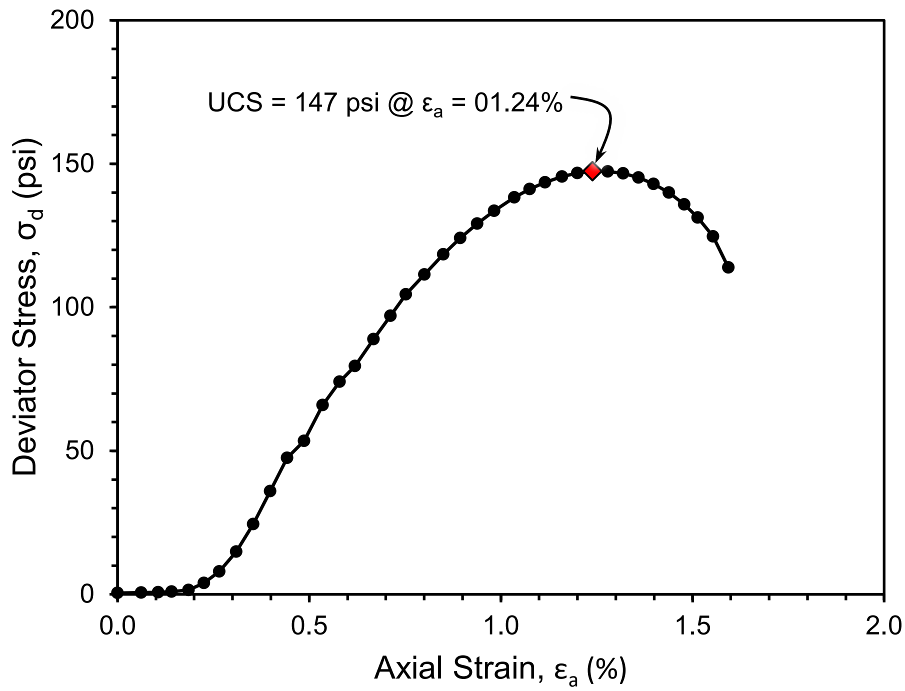


Figure C.3 Unconfined compressive strength test results for Specimen 1–3.

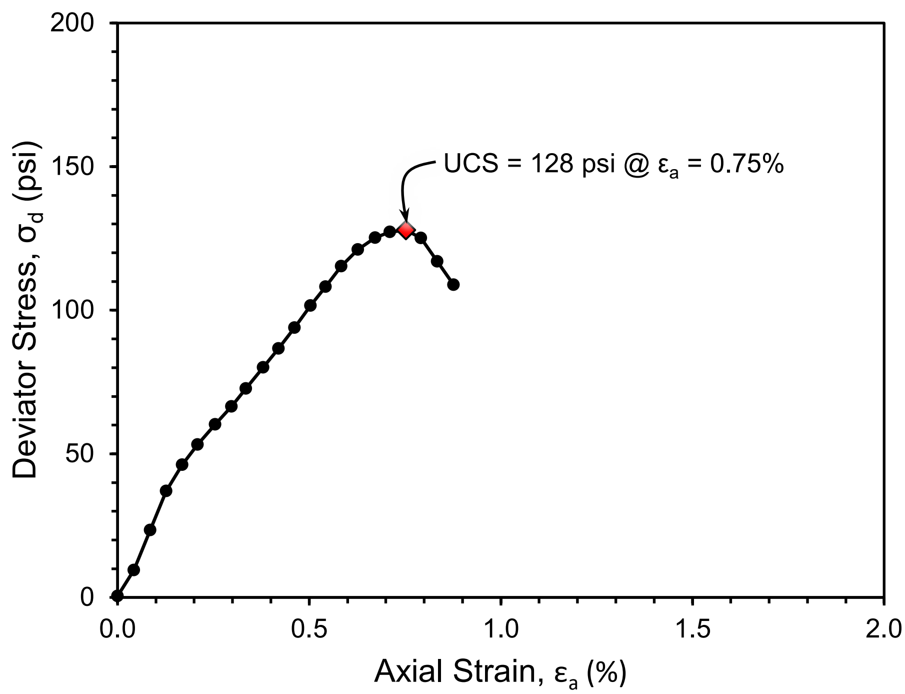


Figure C.4 Unconfined compressive strength test results for Specimen 1–4.

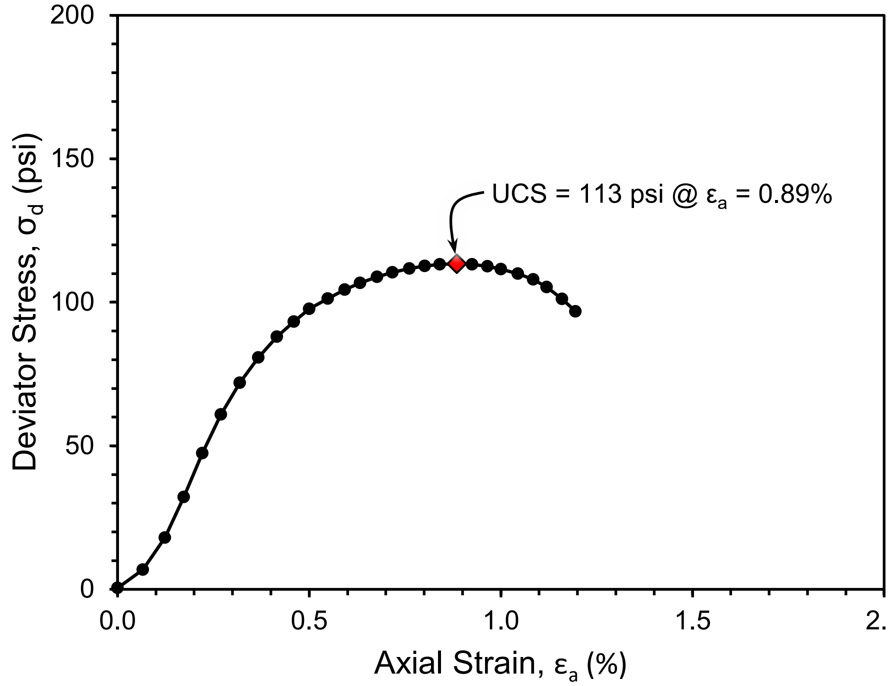


Figure C.5 Unconfined compressive strength test results for Specimen 1–5.

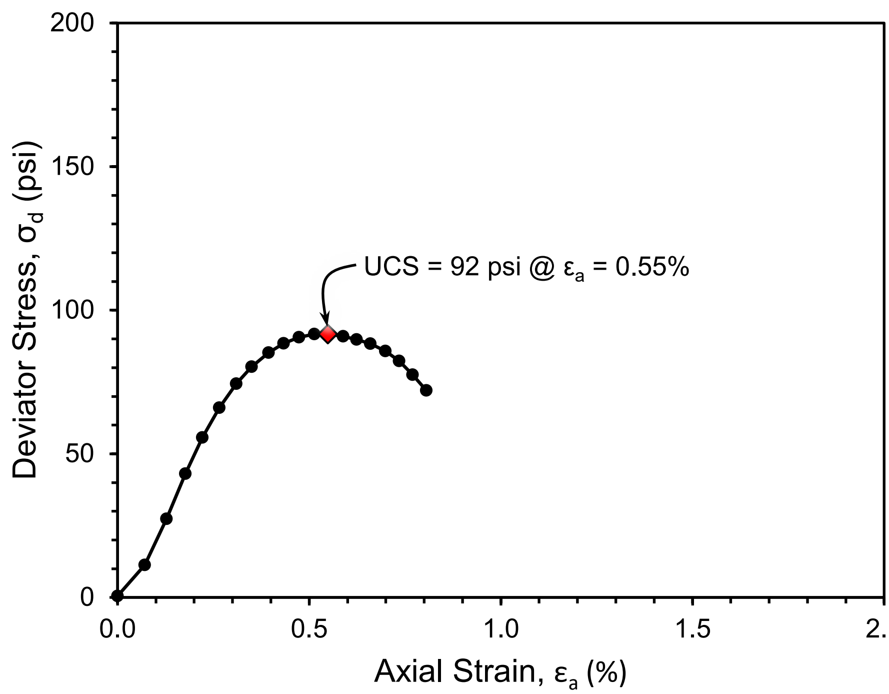


Figure C.6 Unconfined compressive strength test results for Specimen 1–6.

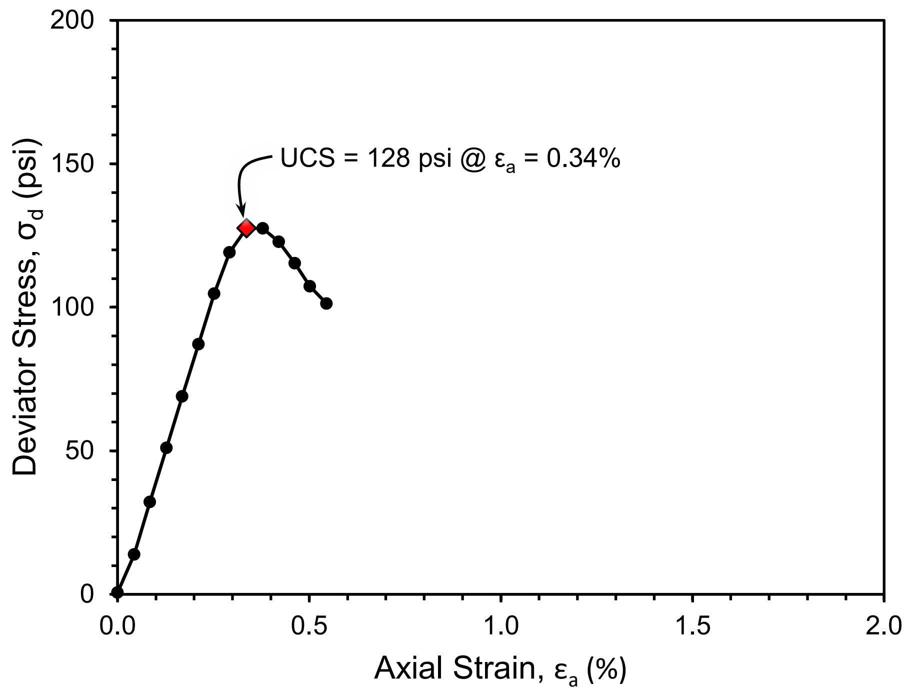


Figure C.7 Unconfined compressive strength test results for Specimen 1–7.

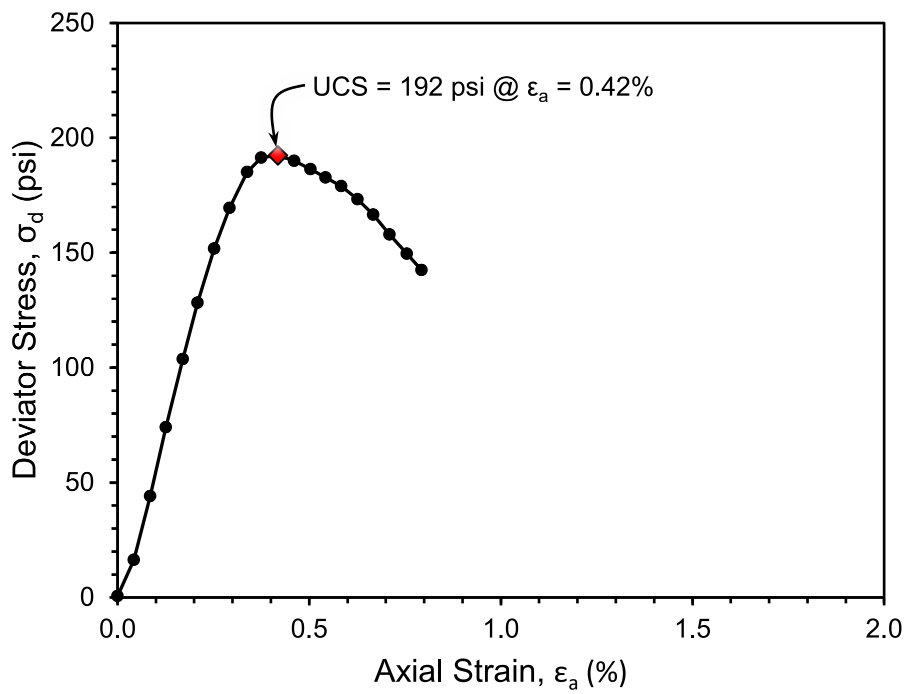


Figure C.8 Unconfined compressive strength test results for Specimen 2–1.

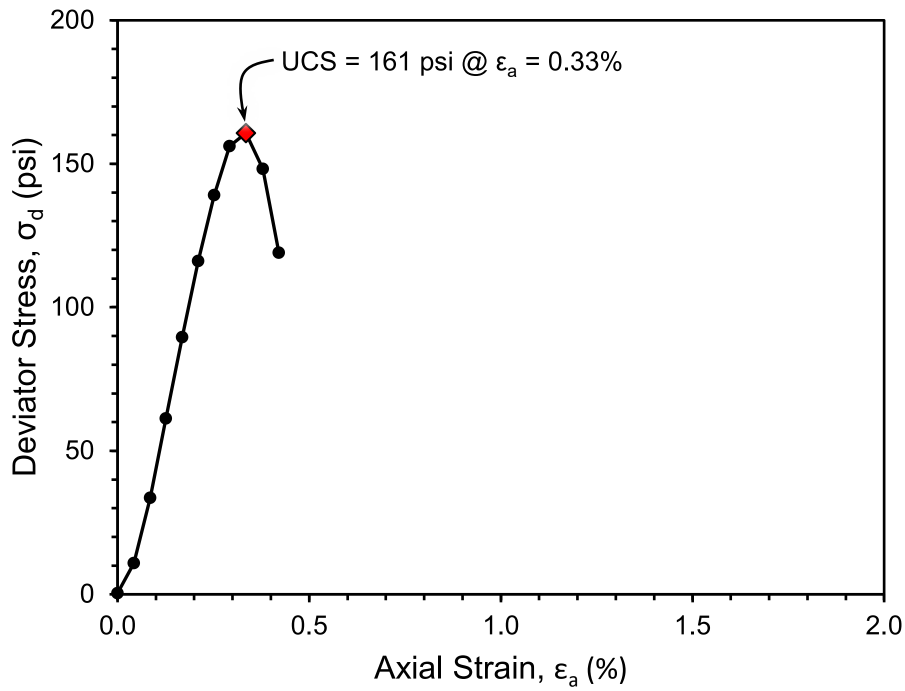


Figure C.9 Unconfined compressive strength test results for Specimen 2–2.

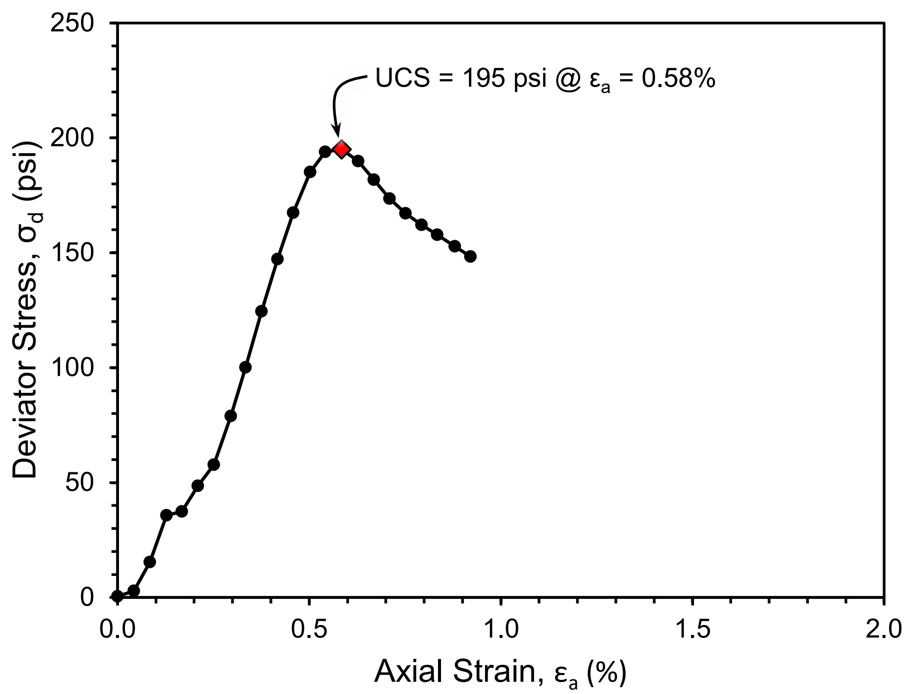


Figure C.10 Unconfined compressive strength test results for Specimen 2–4.

APPENDIX D. OVERVIEW OF FIELD TEST SITES

Table D.1 US 6 test section subgrade soil index properties and engineering properties

Property	US 6 Westbound Direction Specimen	US 6 Eastbound Direction Specimen
Particle Size Distribution		
Percent Gravel	42.5%	16.0%
Percent Sand	39.3%	39.0%
Percent Silt	10.0%	29.6%
Percent Clay	8.2%	15.4%
Plasticity		
Liquid Limit	NP[a]	NP[a]
Plasticity Index	NP[a]	NP[a]
Soil Classification		
AASHTO	A-1-b (0)	A-4 (0)
Textural	Sand and Gravel	Sandy Loam
Compaction Characteristics		
Maximum Dry Unit Weight	132.9 pcf	132.4 pcf
Optimum Moisture Content	7.9%	8.1%
Strength Properties		
[b]Unconfined Compressive Strength (UCS)	10 psi	22 psi

Note:
[a]NP = non-plastic
[b]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content

Table D.2 US 6 test section subgrade cement treatment mix design properties

Property	US 6 Westbound Direction Specimen	US 6 Eastbound Direction Specimen
Compaction Characteristics		
Maximum Dry Unit Weight	131.0 pcf	130.8 pcf
Optimum Moisture Content	8.8%	9.0%
Strength Properties		
[ab]Unconfined Compressive Strength (UCS)	285 psi	285 psi
Increase in UCS	275 psi	263 psi

Note:

[a]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content

[b]Samples cured for 48-hours in accordance with INDOT Design Procedures for Soil Modification or Stabilization

Table D.3 I 469 test sections subgrade soil index properties and engineering properties

Property	
Particle Size Distribution	
Percent Gravel	10.2%
Percent Sand	14.5%
Percent Silt	37.8%
Percent Clay	37.4%
Plasticity	
Liquid Limit	36
Plasticity Index	18
Soil Classification	
AASHTO	A-6 (12)
Textural	Clay
Compaction Characteristics	
Maximum Dry Unit Weight	114.5 pcf
Optimum Moisture Content	15.1%
Strength Properties	
[a]Unconfined Compressive Strength (UCS)	32 psi

Note:
[a]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content

Table D.4 I 469 test sections subgrade cement treatment mix design properties

Property	
Compaction Characteristics	
Maximum Dry Unit Weight	112.2 pcf
Optimum Moisture Content	16.5%
Strength Properties	
[a]Unconfined Compressive Strength (UCS)	158 psi
Increase in UCS	136 psi

Note:
[a]Samples cured for 48-hours in accordance with INDOT Design Procedures for Soil Modification or Stabilization

Table D.6 Cleveland Road test section subgrade soil index properties and engineering properties

Property	
Particle Size Distribution	
Percent Gravel	25.0%
Percent Sand	70.3%
Percent Fines	4.7%
Plasticity	
Liquid Limit	NP
Plasticity Index	NP
Soil Classification	
AASHTO	A-1-b (0)
Textural	Gravelly Sand
Compaction Characteristics	
Maximum Dry Unit Weight	117.6 pcf
Optimum Moisture Content	8.9%
Strength Properties	
[a]Unconfined Compressive Strength (UCS)	0 psi[b]

Note:
[a]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content
[b]Cohesionless soil incapable of maintaining form for UCS testing

Table D.7 Cleveland Road test section subgrade cement treatment mix design properties

Property	
Compaction Characteristics	
Maximum Dry Unit Weight	119.2 pcf
Optimum Moisture Content	10.0%
Strength Properties	
[ab]Unconfined Compressive Strength (UCS)	130 psi
Increase in UCS	130 psi

Note:
[a]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content
[b]Samples cured for 48-hours in accordance with INDOT Design Procedures for Soil Modification or Stabilization

Table D.8 I 65 test sections subgrade soil index properties and engineering properties

Property	I 65 No. 1	I 65 No 3	I 65 No. 4
Particle Size Distribution			
Percent Gravel	19.8%	33.7%	31.6%
Percent Sand	41.5%	40.7%	39.5%
Percent Silt	20.5%	13.4%	14.9%
Percent Clay	18.2%	12.2%	14.0%
Plasticity			
Liquid Limit	NP[a]	NP[a]	NP[a]
Plasticity Index	NP[a]	NP[a]	NP[a]
Soil Classification			
AASHTO	A-4 (0)	A-2-4 (0)	A-2-4 (0)
Textural	Sandy Loam	Sandy Loam	Sandy Loam
Compaction Characteristics			
Maximum Dry Unit Weight	129.2 pcf	130.1 pcf	126.4 pcf
Optimum Moisture Content	8.6%	7.0%	9.3%
Strength Properties			
[b]Unconfined Compressive Strength (UCS)	18 psi	15 psi	16

Note:
[a]NP = non-plastic
[b]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content

Table D.1 I 65 test sections subgrade cement treatment mix design properties

Property	I 65 No. 1	I 65 No 3	I 65 No. 4
Compaction Characteristics			
Maximum Dry Unit Weight	127.2 pcf	128.1 pcf	124.1 pcf
Optimum Moisture Content	9.5%	8.8%	10.2%
Strength Properties			
[ab]Unconfined Compressive Strength (UCS)	230 psi	196 psi	199 psi
Increase in UCS	212 psi	181 psi	183 psi

Note:
[a]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content
[b]Samples cured for 48-hours in accordance with INDOT Design Procedures for Soil Modification or Stabilization

Table D.2 SR 46 test section subgrade soil index properties and engineering properties

Property	
Particle Size Distribution	
Percent Gravel	2.8%
Percent Sand	7.7%
Percent Silt	44.1%
Percent Clay	45.4%
Plasticity	
Liquid Limit	60
Plasticity Index	31
Soil Classification	
AASHTO	A-7-6 (32)
Textural	Clay
Compaction Characteristics	
Maximum Dry Unit Weight	90.8 pcf
Optimum Moisture Content	27.5%
Strength Properties	
[a]Unconfined Compressive Strength (UCS)	36 psi

Note:
[a]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content

Table D.3 SR 46 test section subgrade cement treatment mix design properties

Property	
Compaction Characteristics	
Maximum Dry Unit Weight	86.2 pcf
Optimum Moisture Content	30.4%
Strength Properties	
[ab]Unconfined Compressive Strength (UCS)	147 psi
Increase in UCS	111 psi

Note:
[a]Samples cured for 48-hours in accordance with INDOT Design Procedures for Soil Modification or Stabilization
[a]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content

Table D.4 SR 66 test section subgrade soil index properties and engineering properties

Property	
Particle Size Distribution	
Percent Gravel	0.0%
Percent Sand	0.6%
Percent Silt	81.3%
Percent Clay	18.2%
Plasticity	
Liquid Limit	NP[a]
Plasticity Index	NP[a]
Soil Classification	
AASHTO	A-4 (0)
Textural	Silt
Compaction Characteristics	
Maximum Dry Unit Weight	107.5 pcf
Optimum Moisture Content	18.0%
Strength Properties	
[b]Unconfined Compressive Strength (UCS)	30 psi

Note:
[a]NP = non-plastic
[b]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content

Table D.5 SR 66 test section subgrade cement treatment mix design properties

Property	
Compaction Characteristics	
Maximum Dry Unit Weight	104.2 pcf
Optimum Moisture Content	19.1%
Strength Properties	
[ab]Unconfined Compressive Strength (UCS)	149 psi
Increase in UCS	119 psi

Note:
[a]Samples cured for 48-hours in accordance with INDOT Design Procedures for Soil Modification or Stabilization
[a]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content

Table D.6 CR 400 Stest section subgrade soil index properties and engineering properties

Property	
Particle Size Distribution	
Percent Gravel	0.4%
Percent Sand	3.8%
Percent Silt	61.3%
Percent Clay	34.5%
Plasticity	
Liquid Limit	47
Plasticity Index	26
Soil Classification	
AASHTO	A-7-6 (27)
Textural	Silty Clay
Compaction Characteristics	
Maximum Dry Unit Weight	106.8 pcf
Optimum Moisture Content	17.9%
Strength Properties	
[a]Unconfined Compressive Strength (UCS)	30 psi

Note:
[a]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content

Table D.7 CR 400 S test section subgrade cement treatment mix design properties

Property	
Compaction Characteristics	
Maximum Dry Unit Weight	104.2 pcf
Optimum Moisture Content	19.1%
Strength Properties	
[ab]Unconfined Compressive Strength (UCS)	152 psi
Increase in UCS	122 psi

Note:
[a]Samples cured for 48-hours in accordance with INDOT Design Procedures for Soil Modification or Stabilization
[a]Average of two reconstituted samples compacted to 95% relative compaction at optimum moisture content

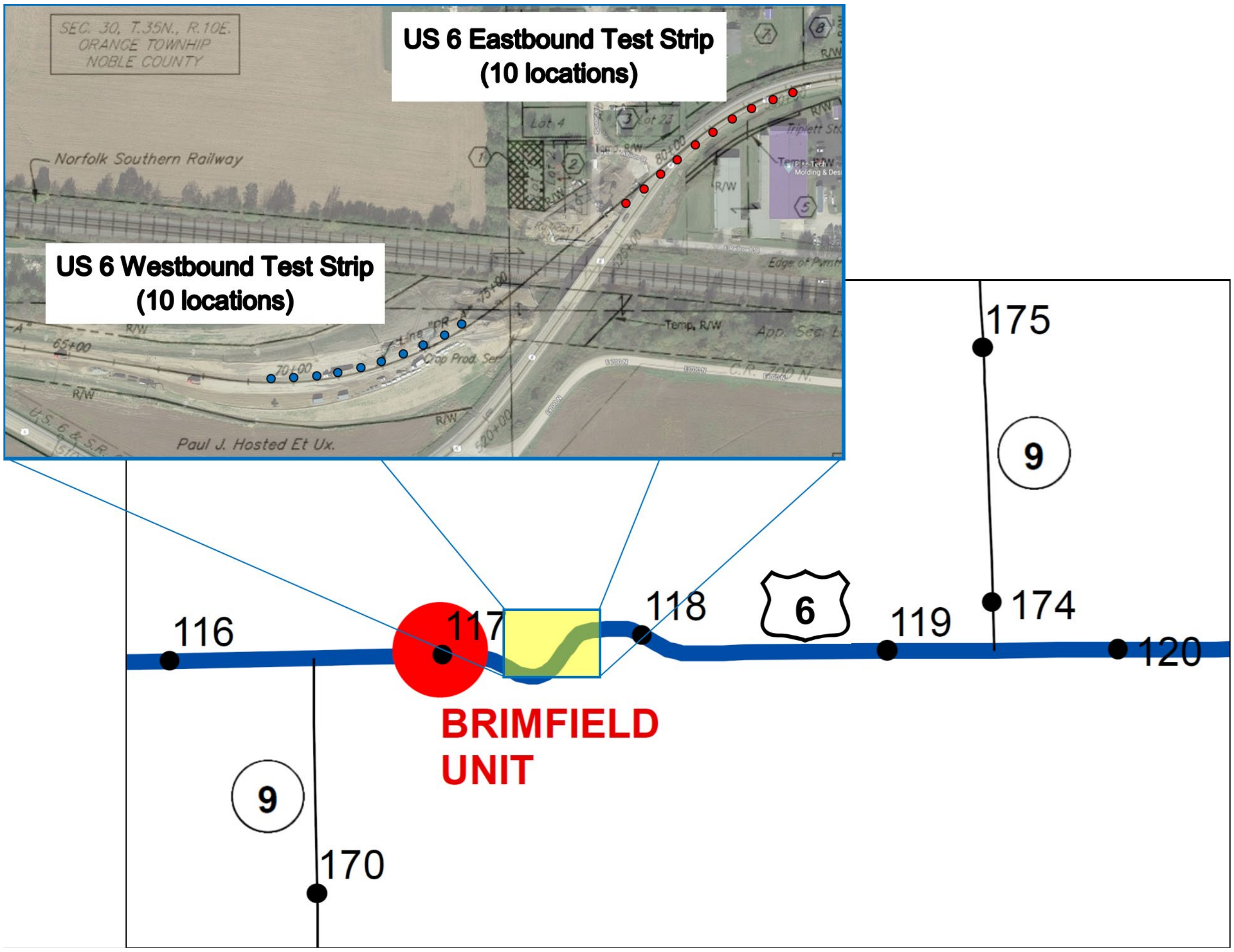
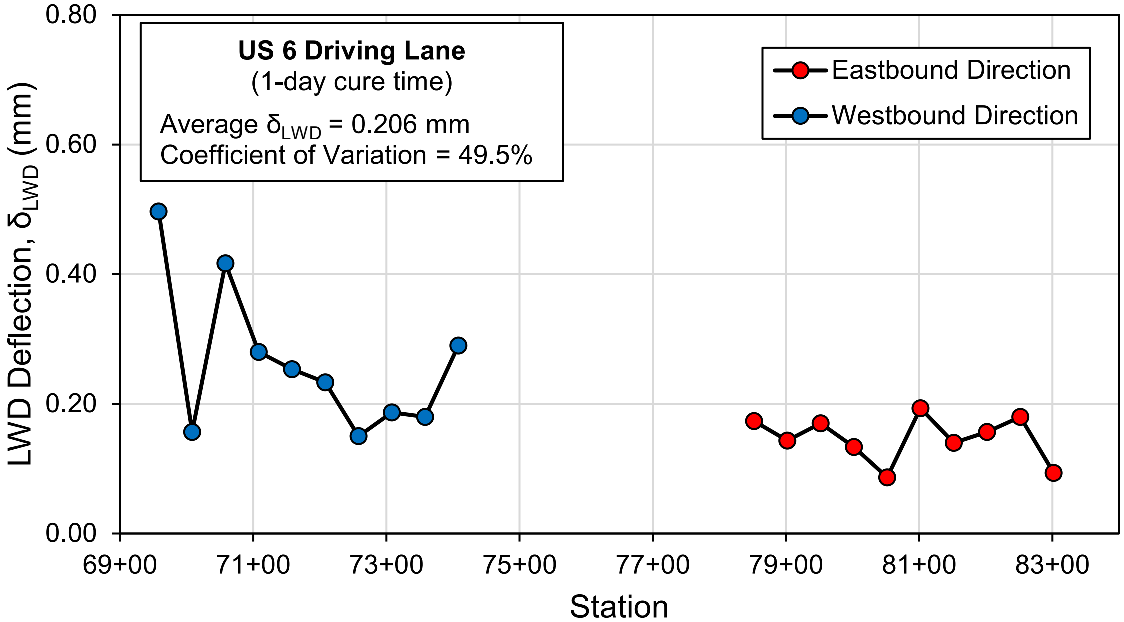
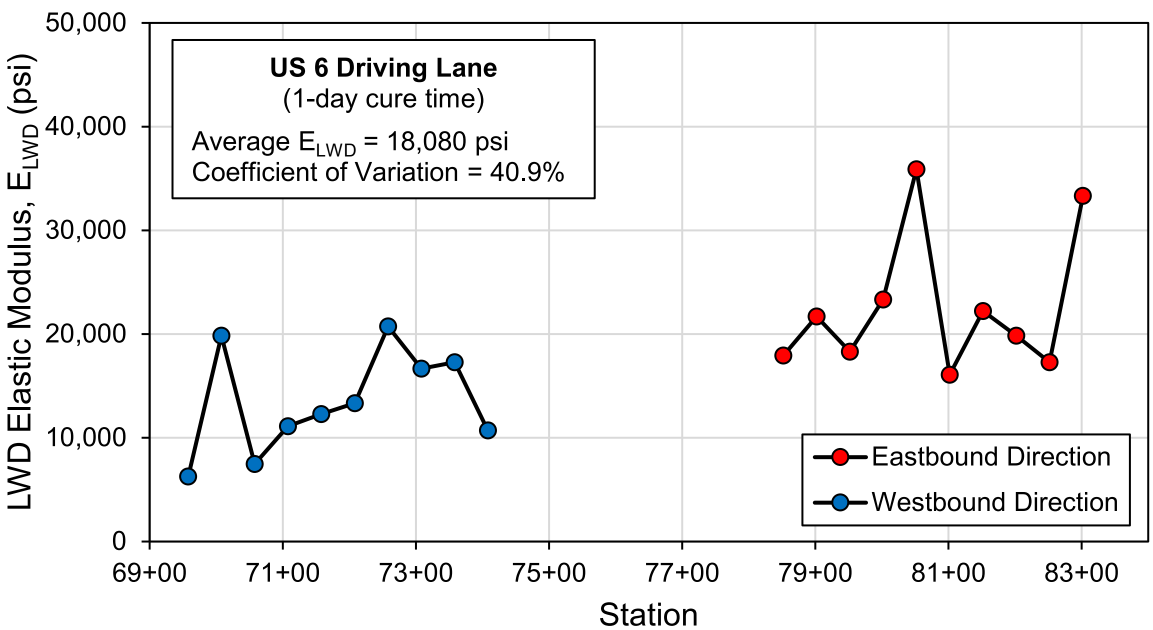


Figure D.1 US 6 test section layout of testing locations.

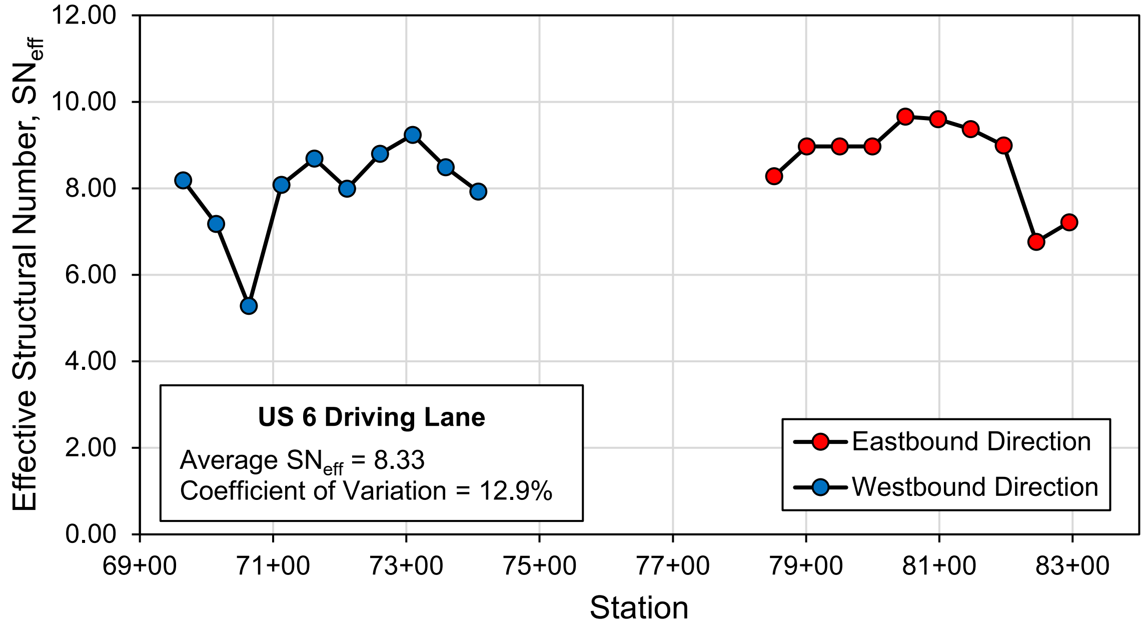


(a)

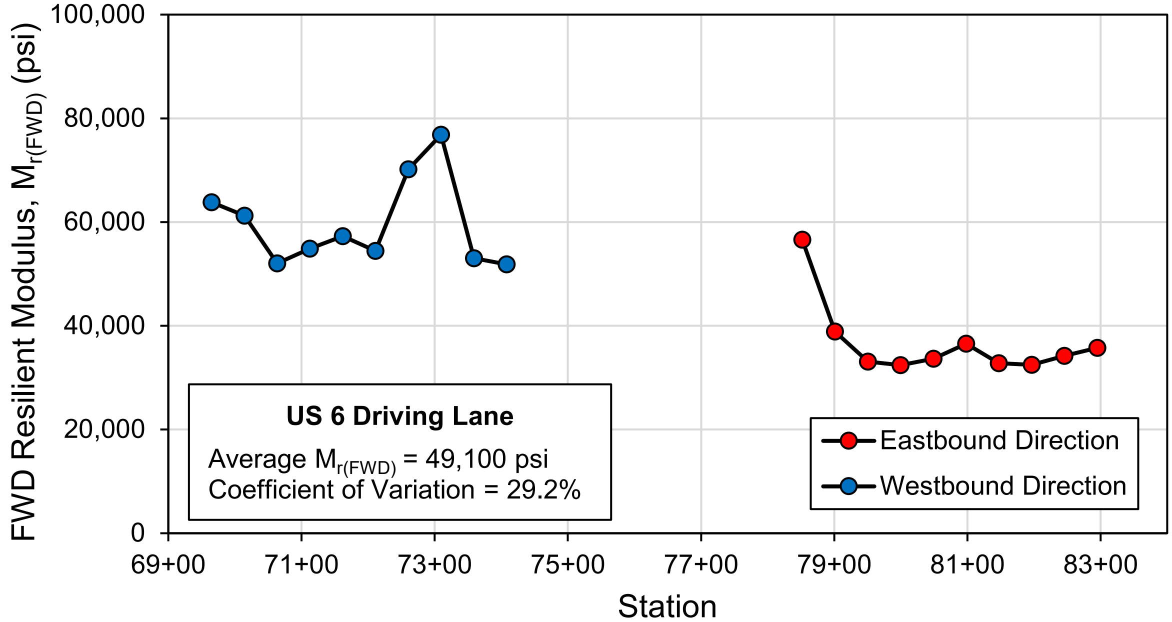


(b)

Figure D.2 US 6 test section LWD testing results—(a) measured LWD deflections, (b) LWD elastic moduli.



(a)



(b)

Figure D.3 US 6 test section FWD testing results—(a) pavement effective structural numbers, (b) FWD backcalcualted resilient moduli.

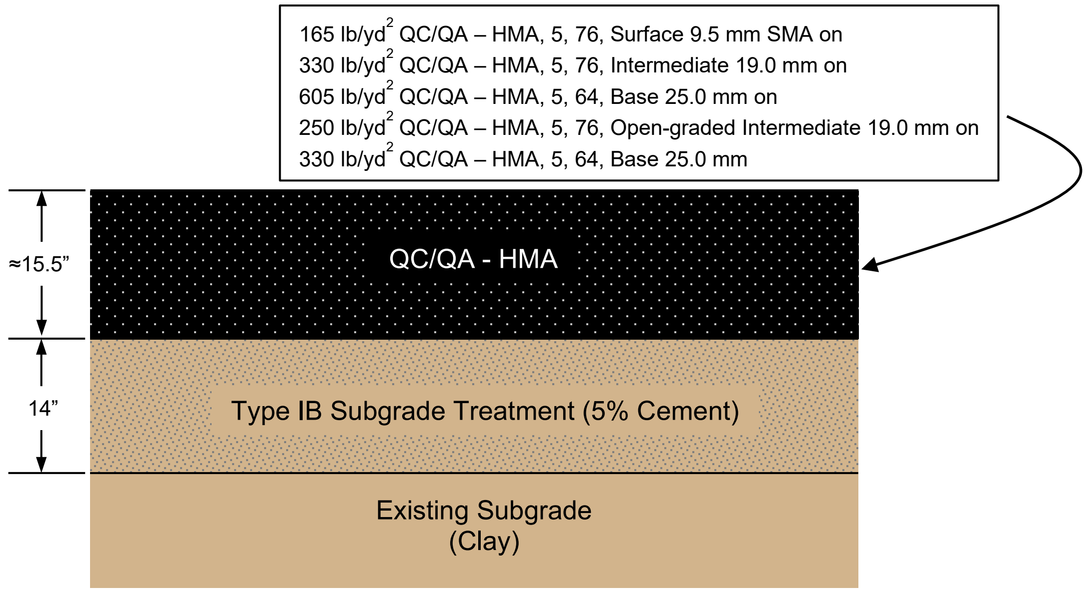


Figure D.4 I 469 test sections No. 1 and 2 pavement cross section.

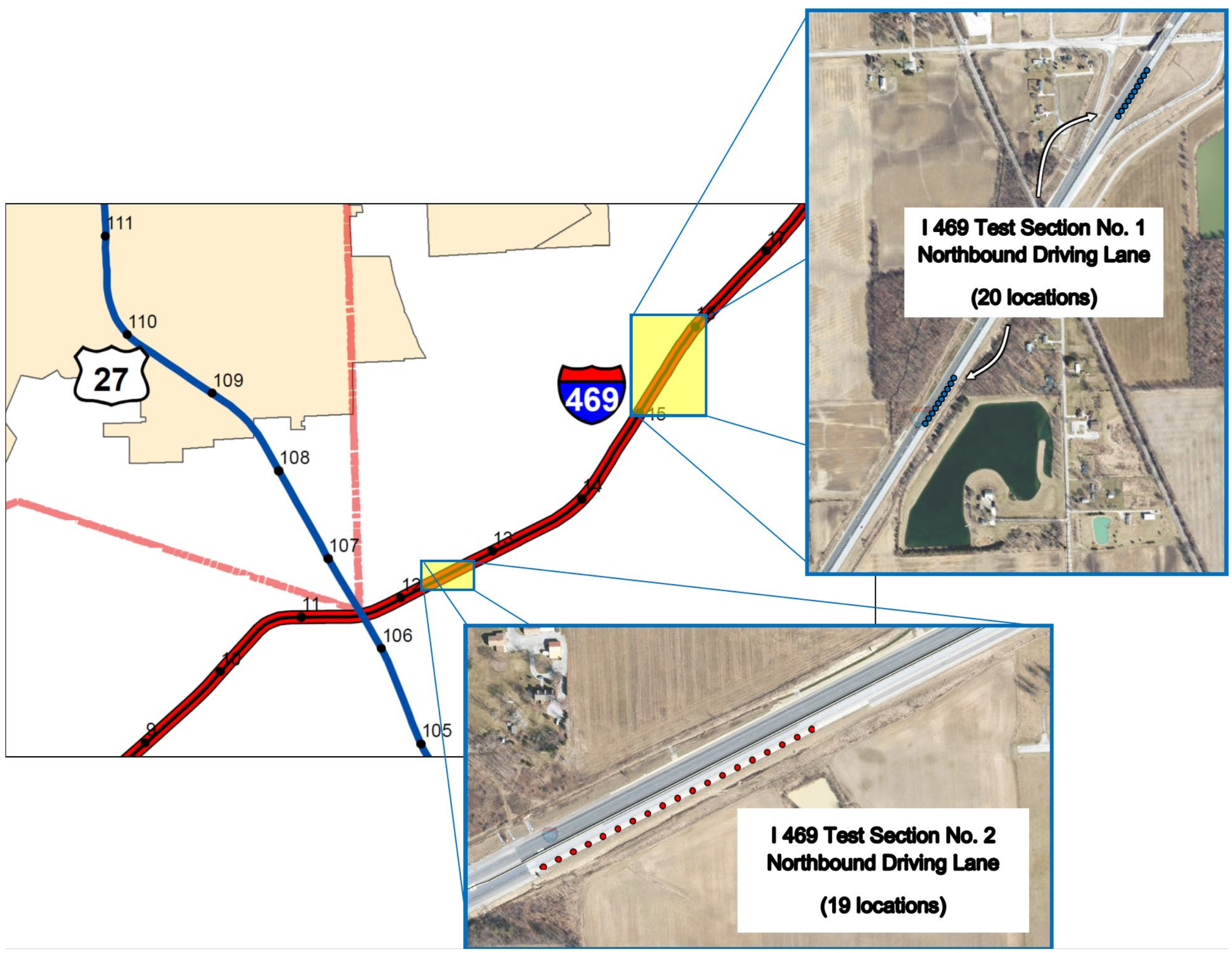


Figure D.5 I 469 test sections No. 1 and 2 layout of testing locations.

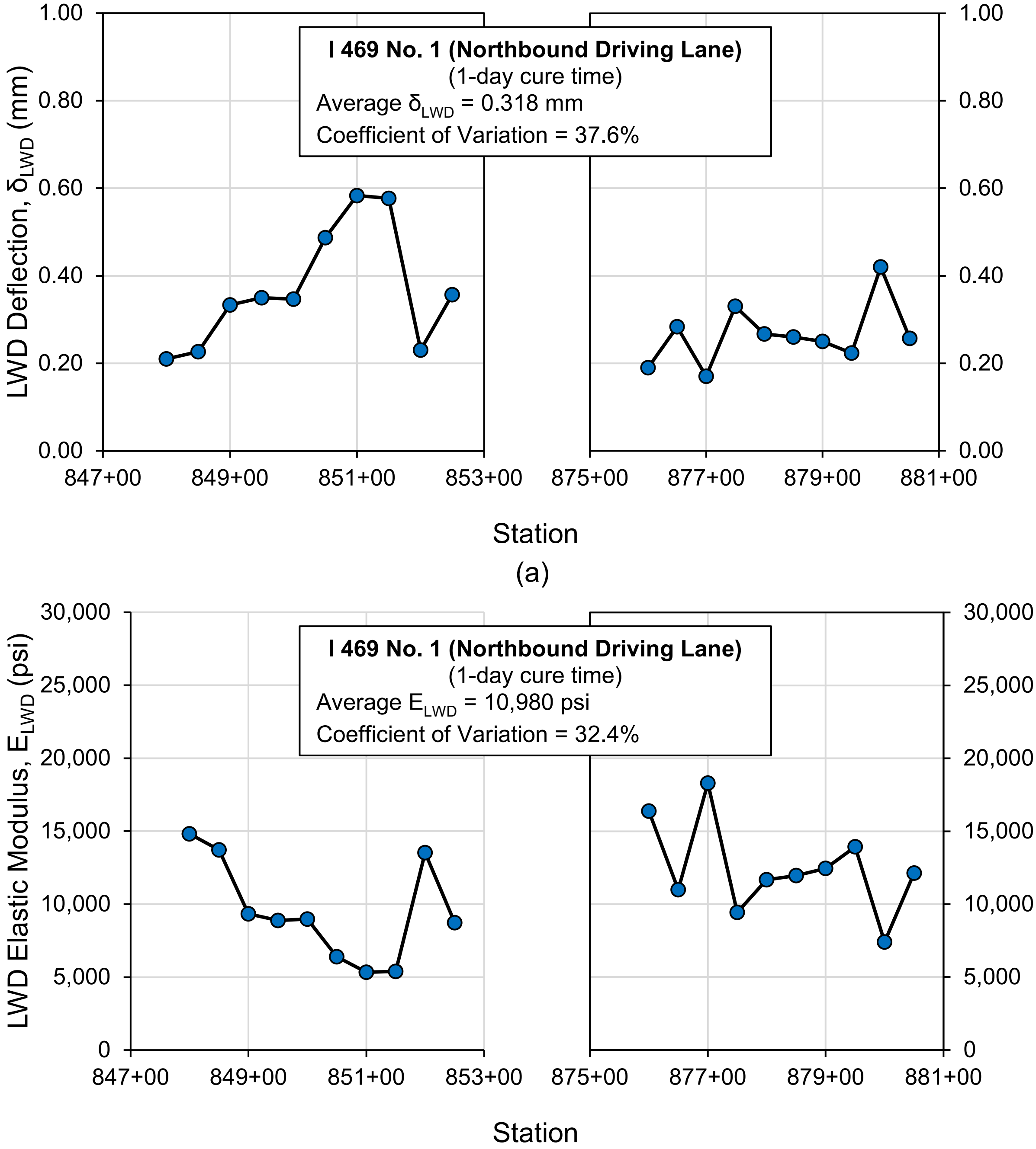


Figure D.6 I 469 No. 1 test section LWD testing results—(a) measured LWD deflections, (b) LWD elastic moduli.

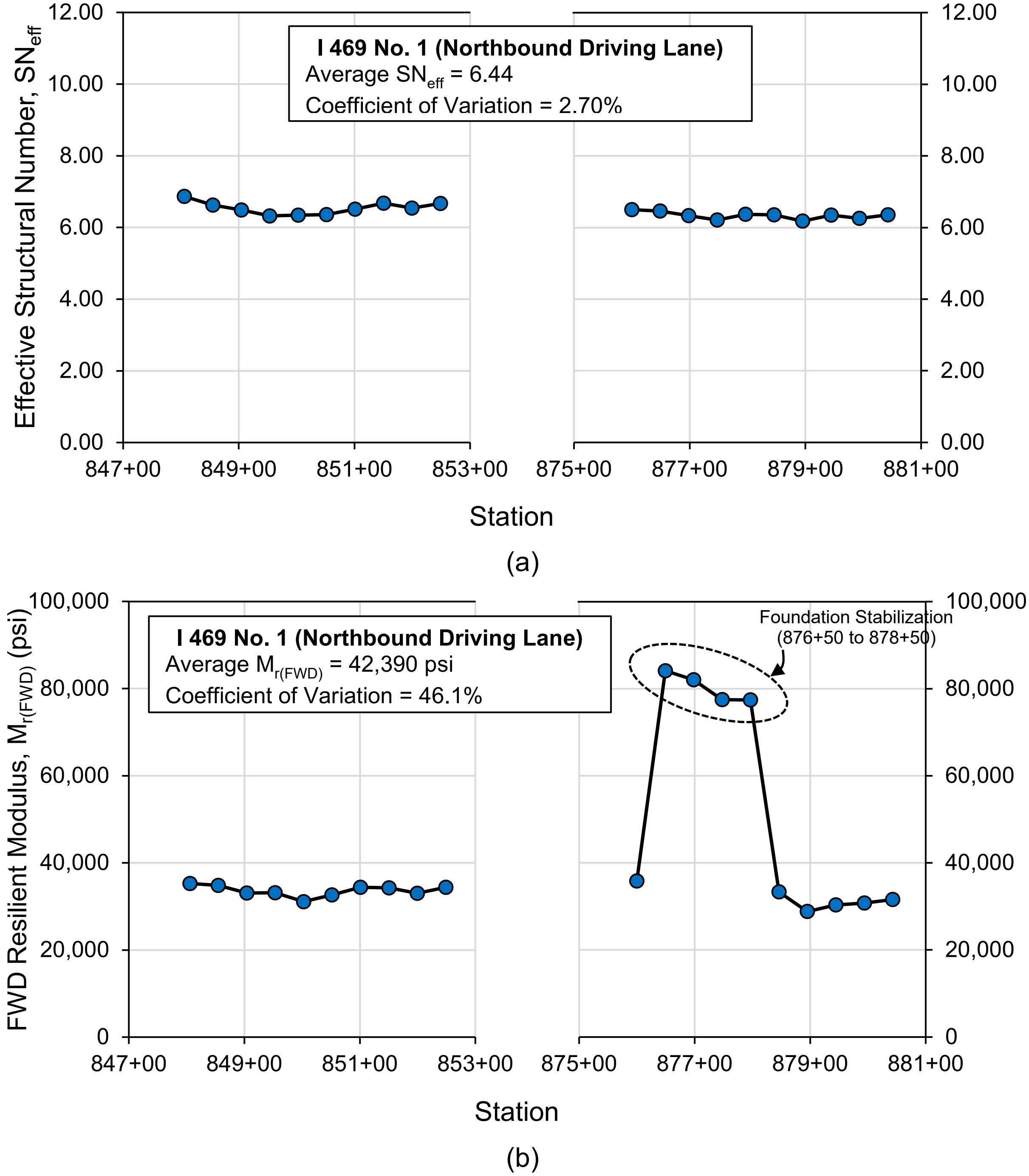
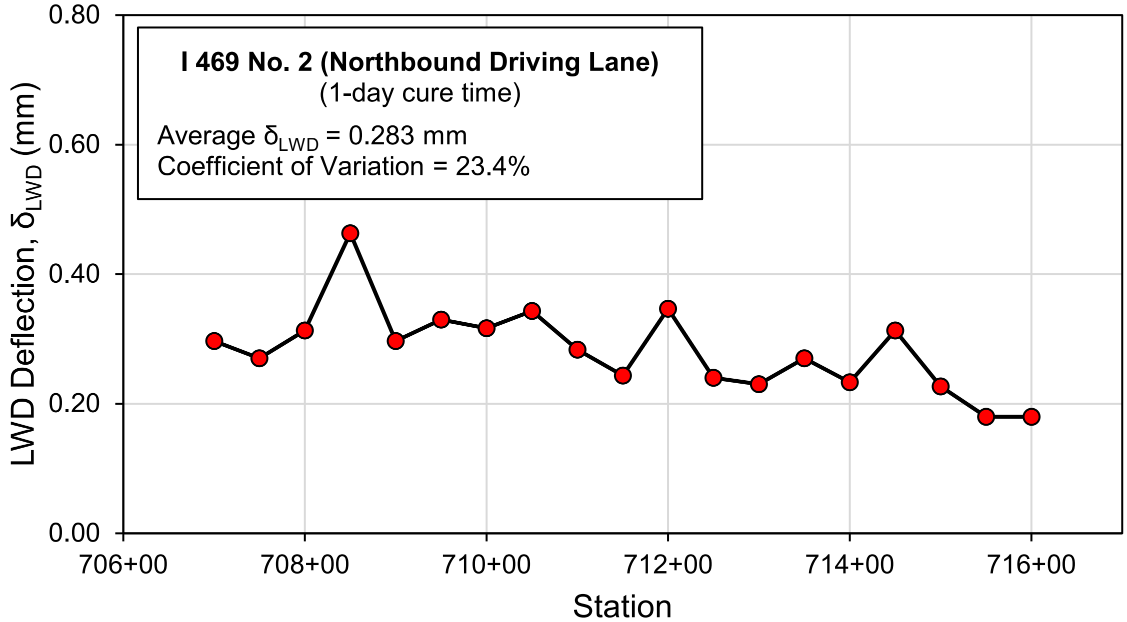
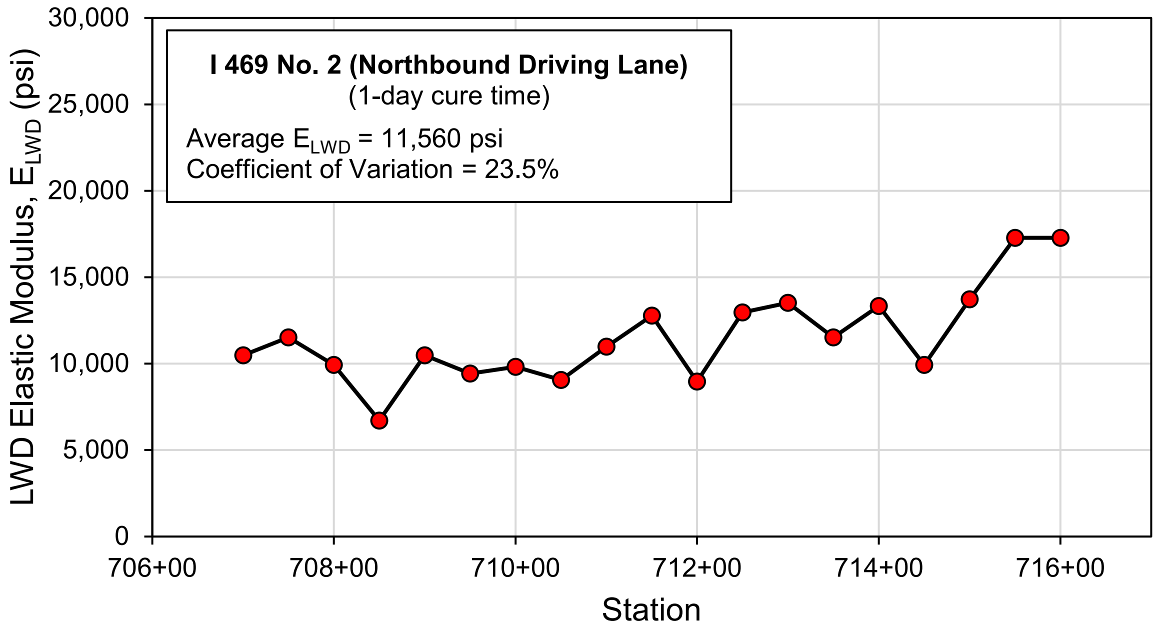


Figure D.7 I 469 No. 1 test section FWD testing results—(a) pavement effective structural numbers, (b) FWD backcalcualted resilient moduli.

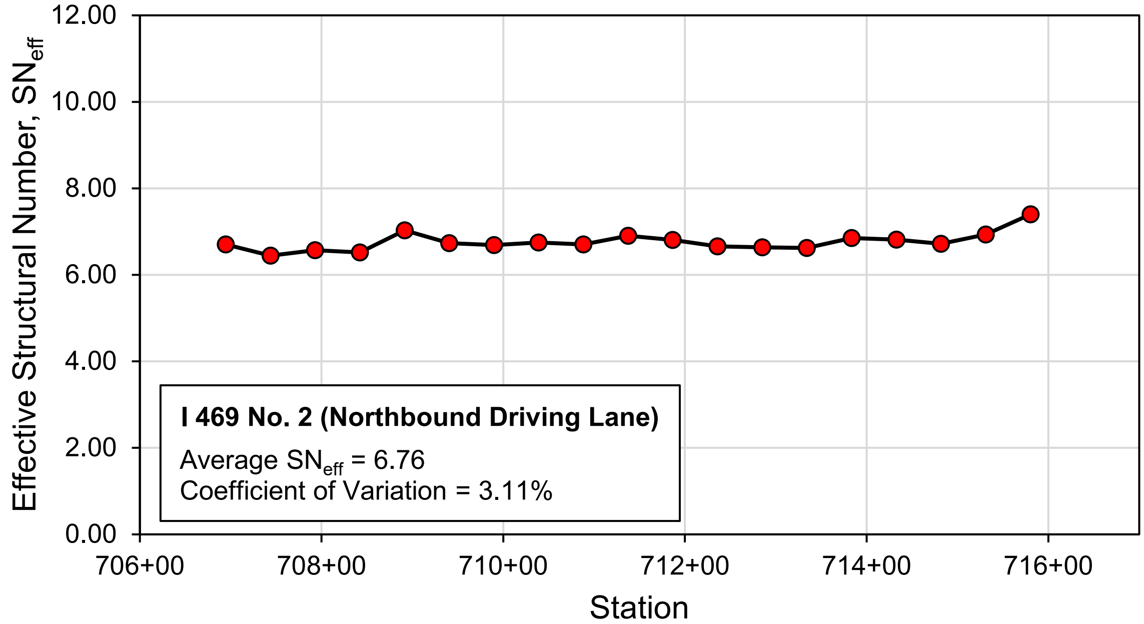


(a)

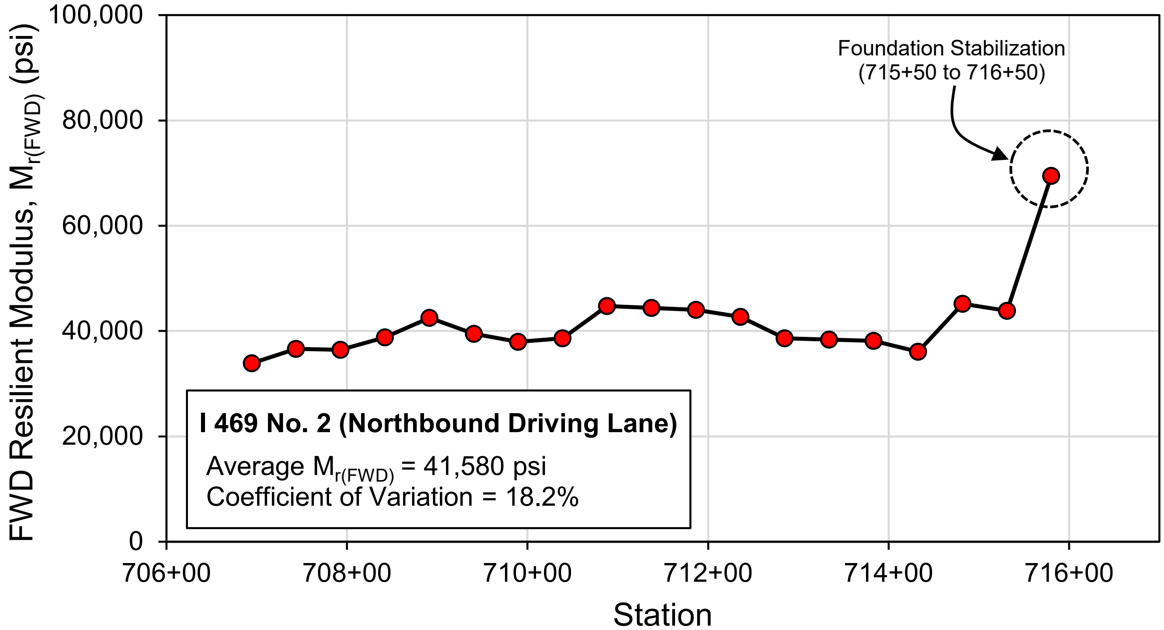


(b)

Figure D.8 I 469 No. 2 test section LWD testing results—(a) measured LWD deflections, (b) LWD elastic moduli.

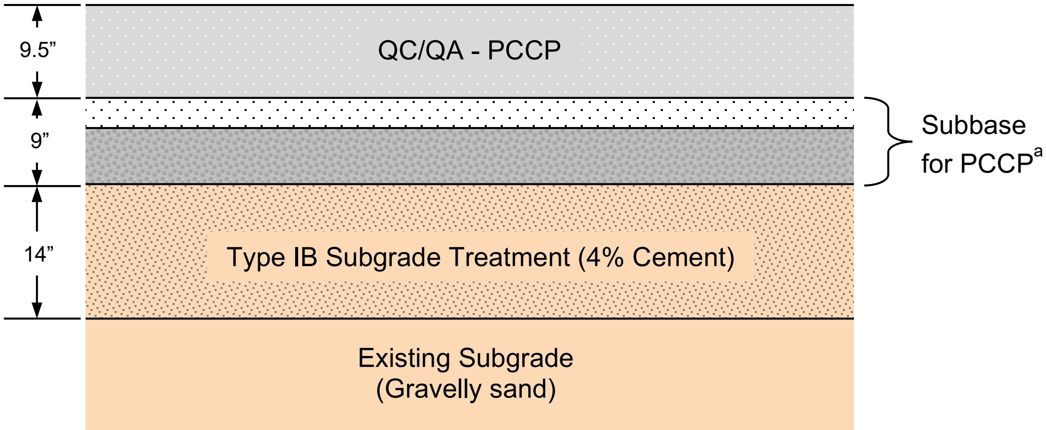


(a)



(b)

Figure D.9 I 469 No. 2 test section FWD testing results—(a) pavement effective structural numbers, (b) FWD backcalcualted resilient moduli.



Note:
[a]Subbase for PCCP comprises 3" open-graded aggregate (No. 8) over 6" dense-graded compacted aggregate (No. 53)

Figure D.10 Cleveland Road test section pavement cross section.

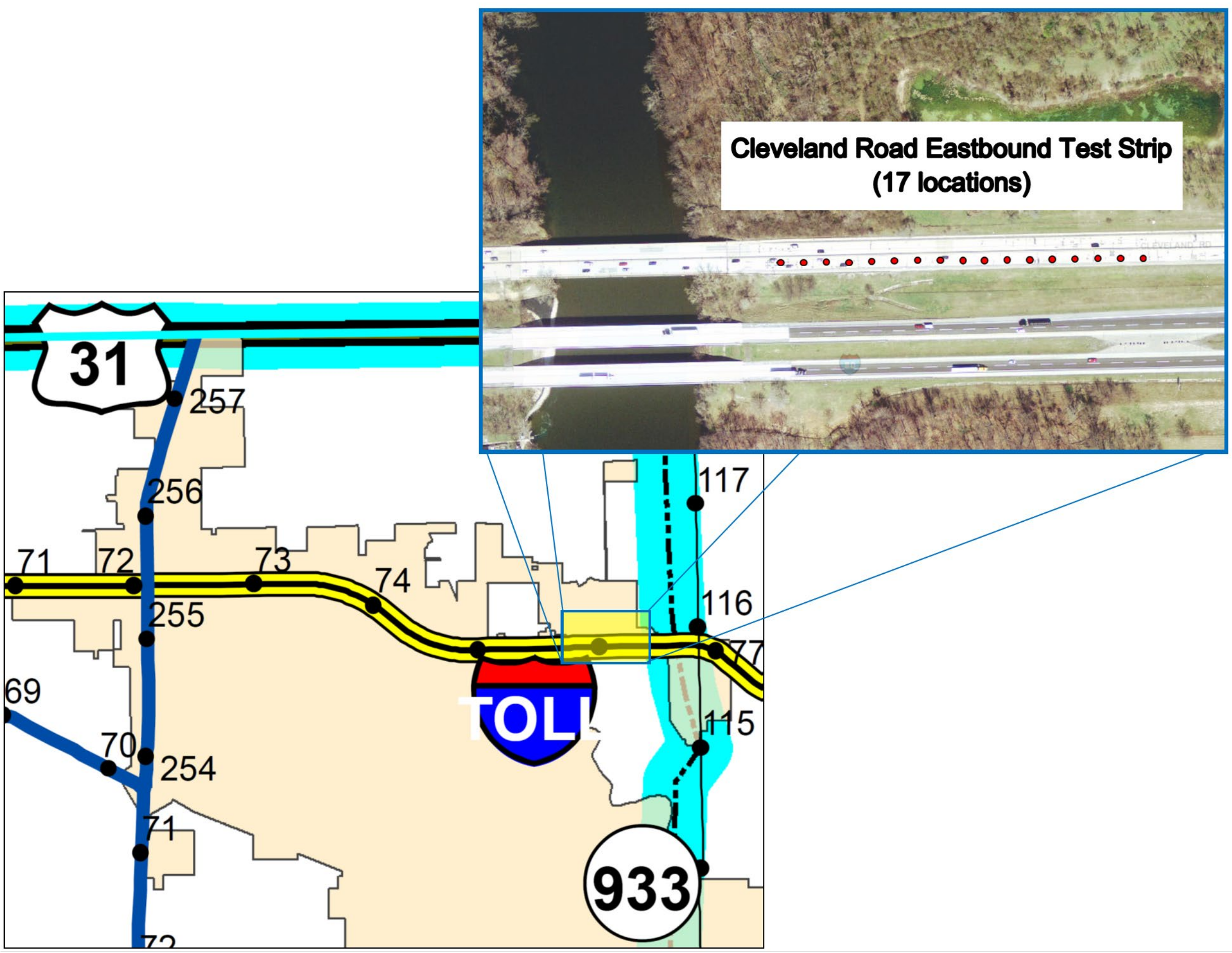
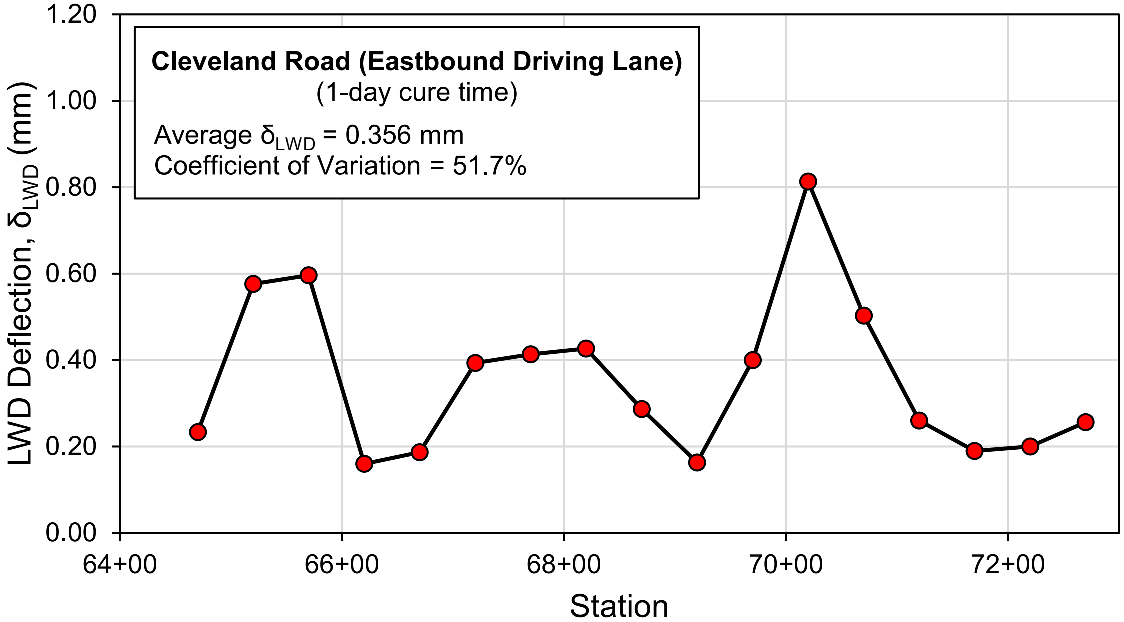
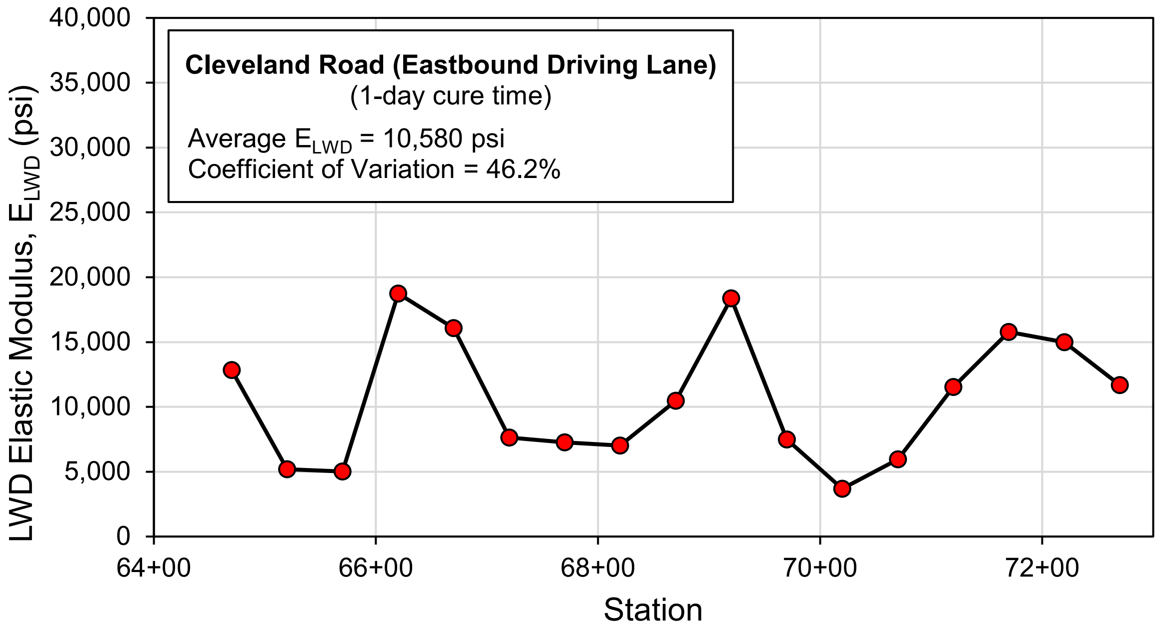


Figure D.11 Cleveland Road test section layout of testing locations.

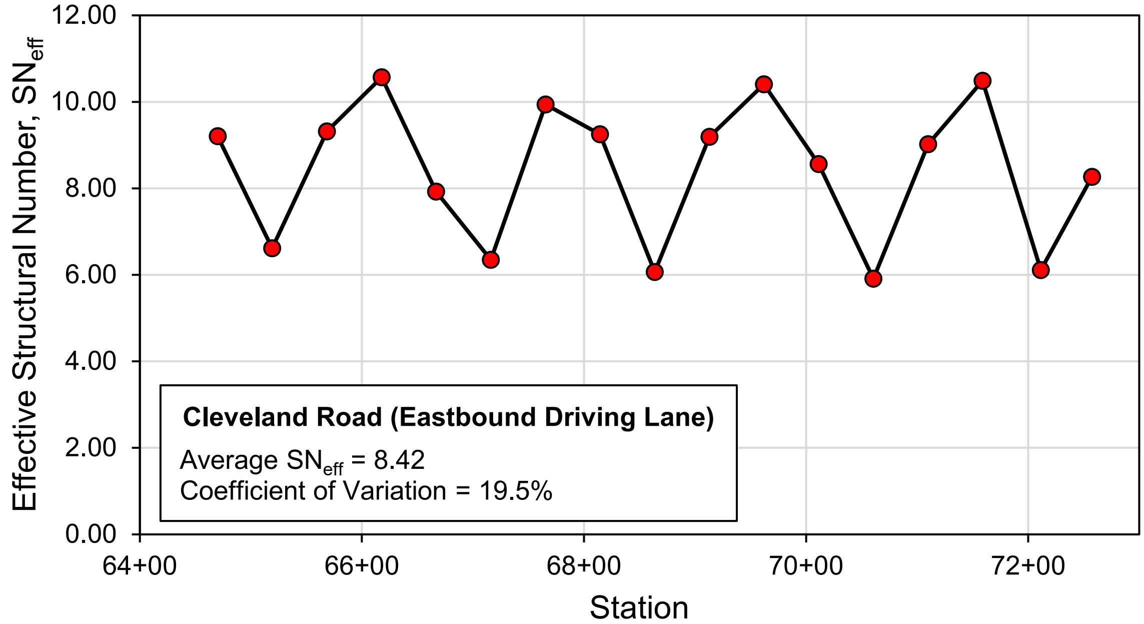


(a)

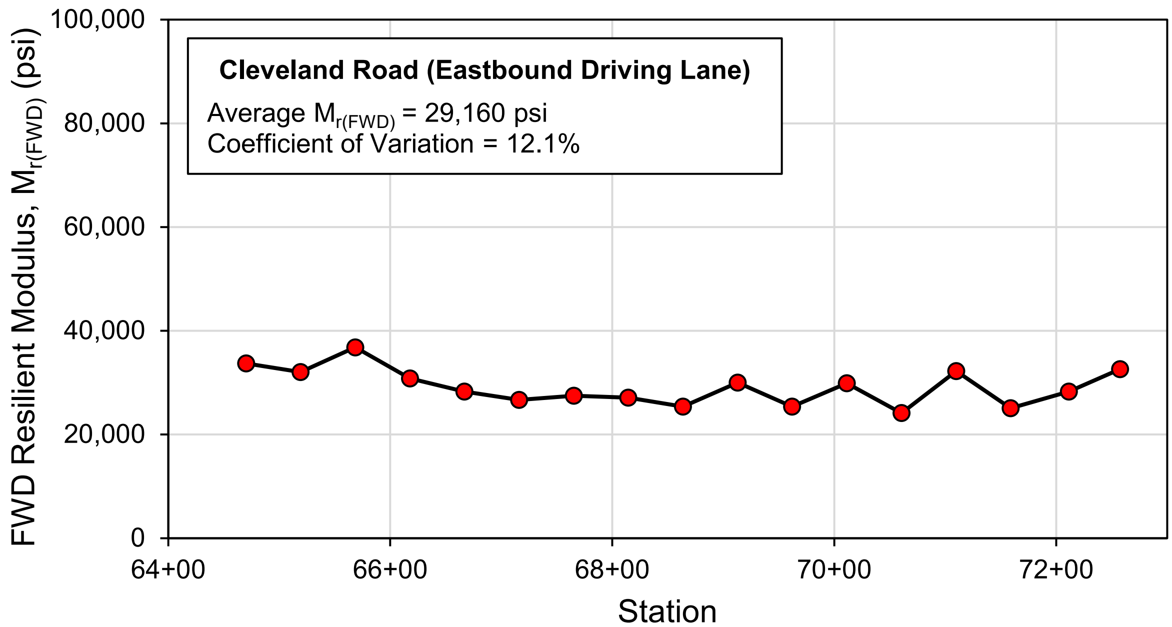


(b)

Figure D.12 Cleveland Road test section LWD testing results—(a) measured LWD deflections, (b) LWD elastic moduli.



(a)



(b)

Figure D.13 Cleveland Road test section FWD testing results—(a) pavement effective structural numbers, (b) FWD backcalcualted resilient moduli.

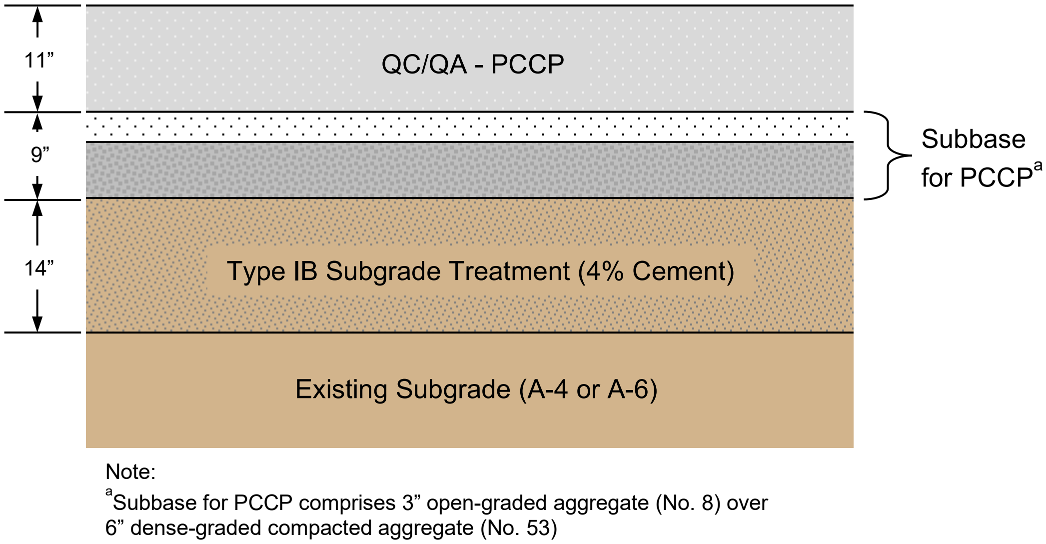


Figure D.14 I 65 test sections No. 1–4 pavement cross section.

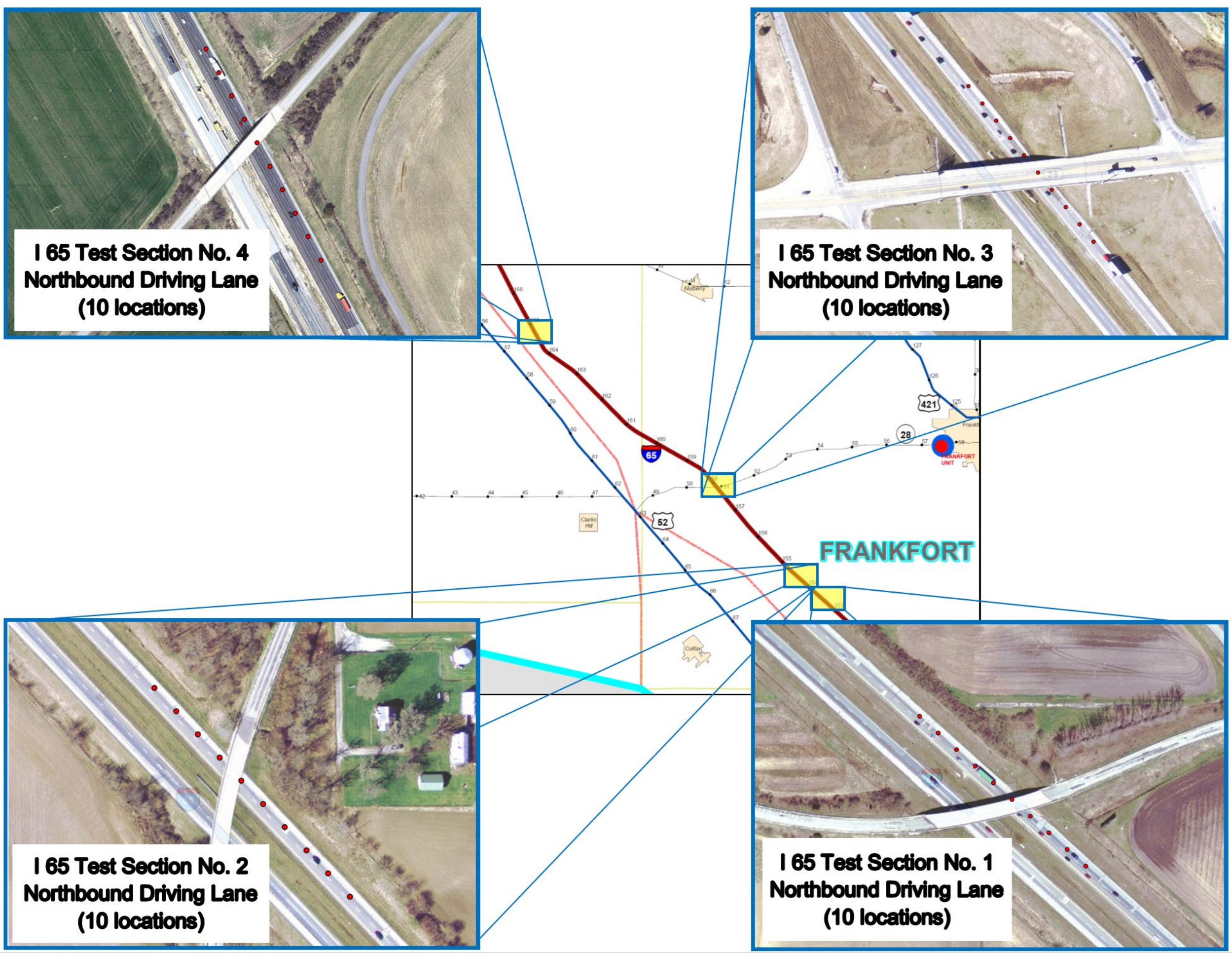
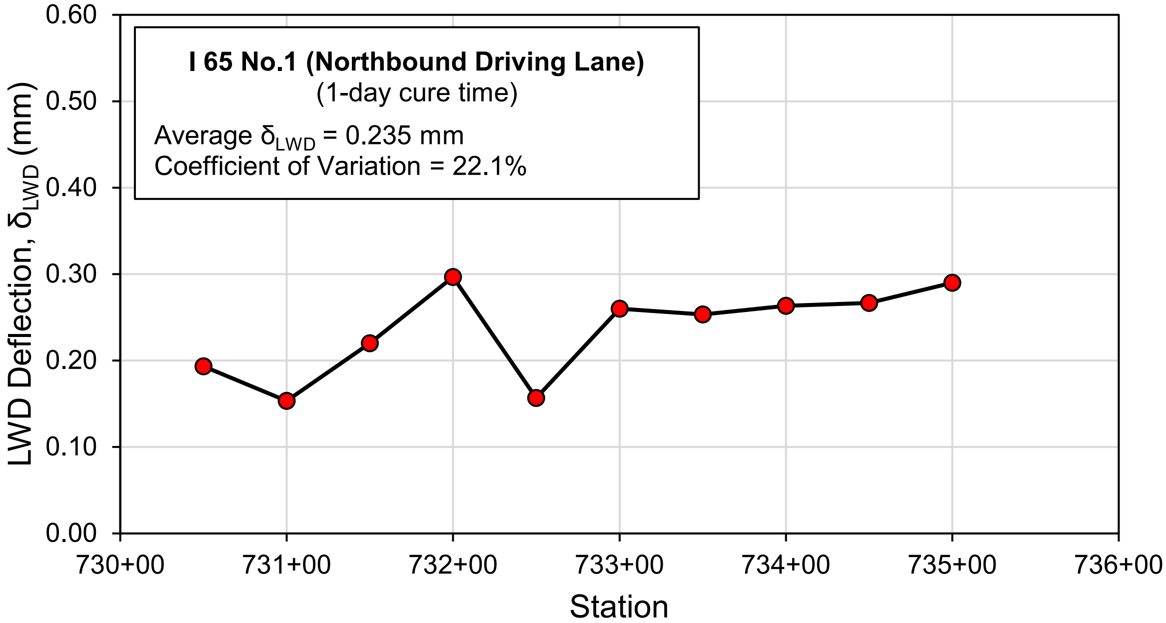
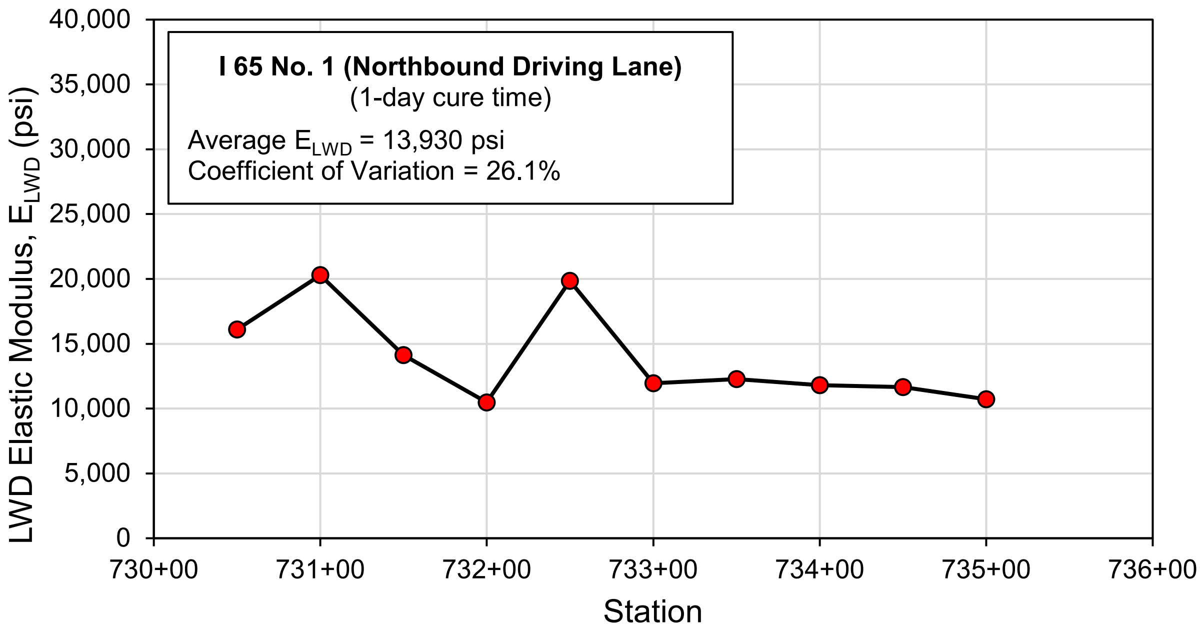


Figure D.15 I 65 test sections No. 1–4 layout of testing locations.

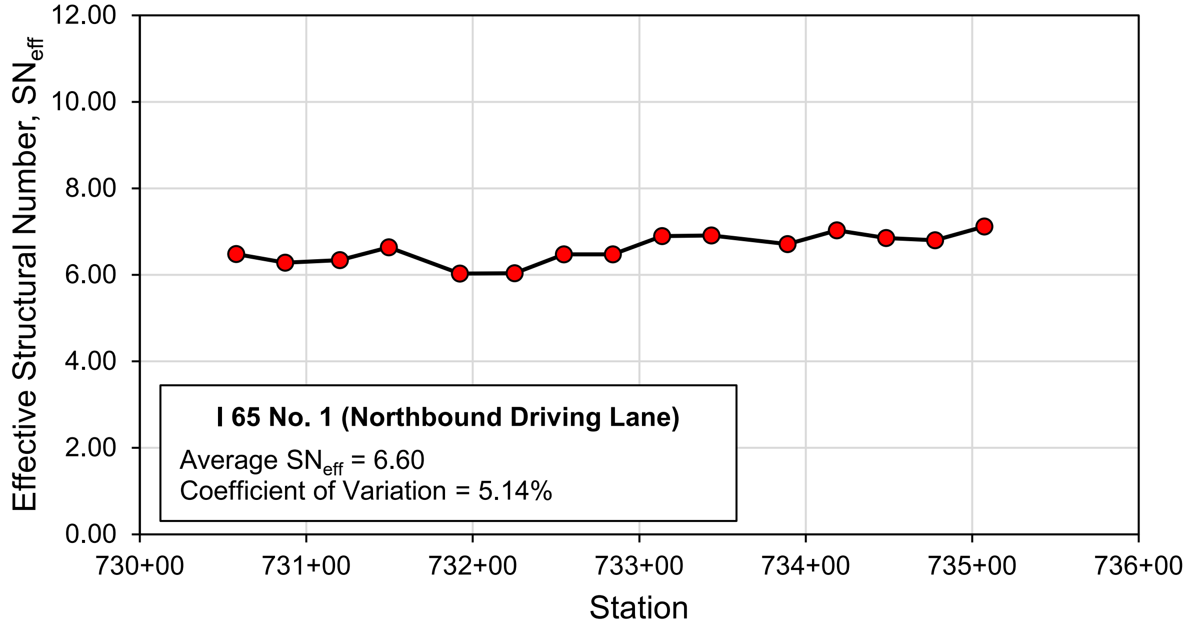


(a)

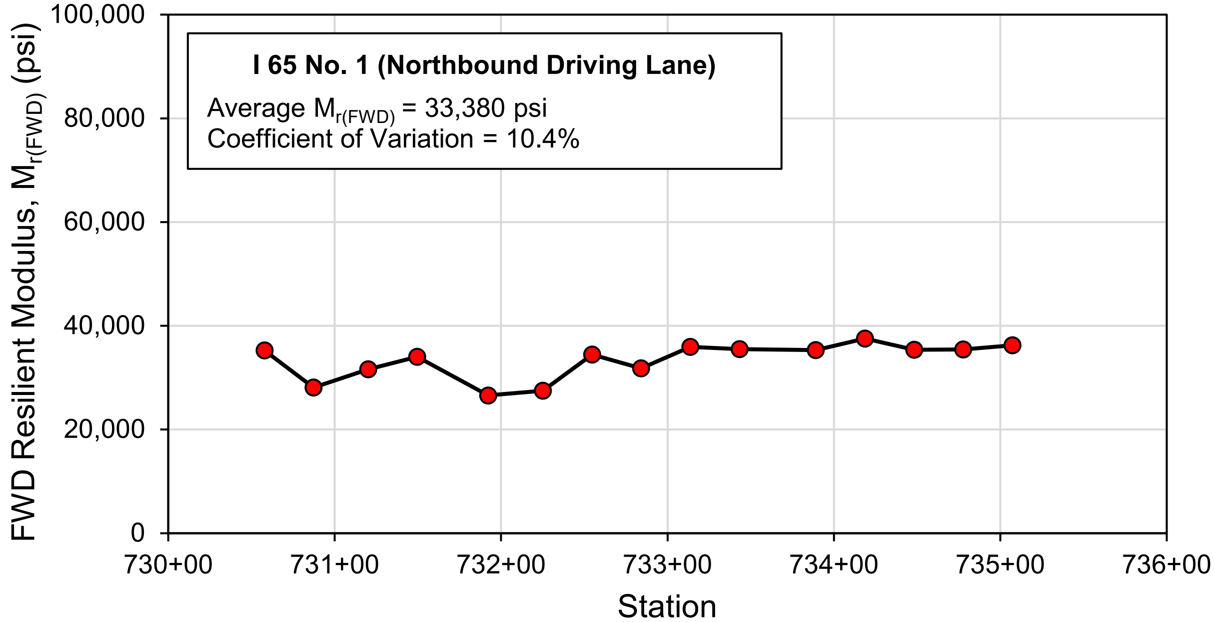


(b)

Figure D.16 I 65 No. 1 test section LWD testing results—(a) measured LWD deflections, (b) LWD elastic moduli.

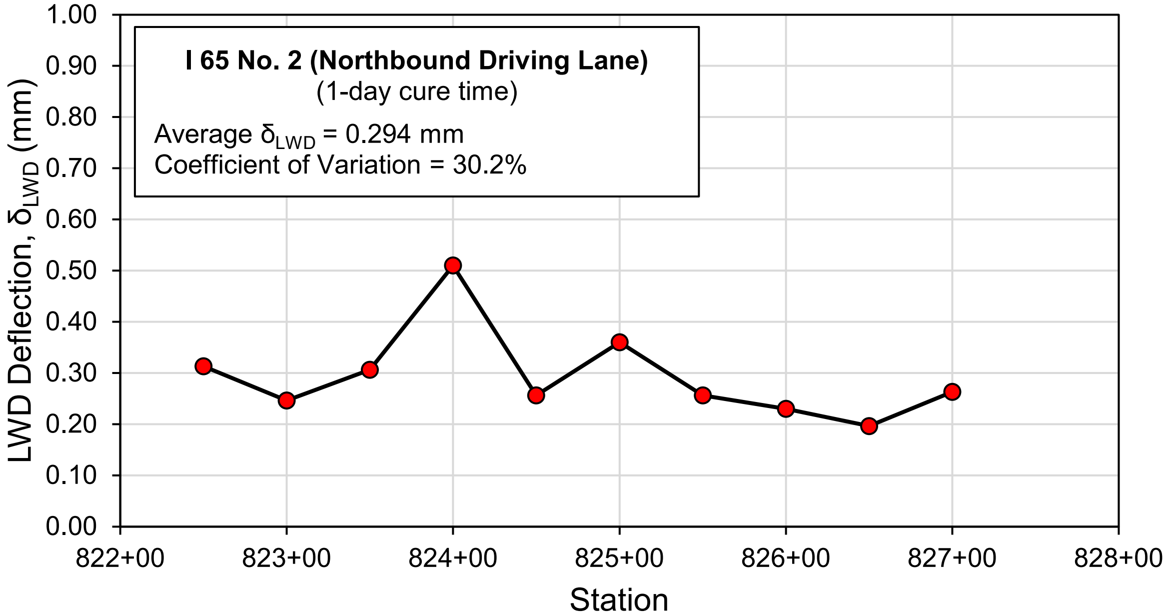


(a)

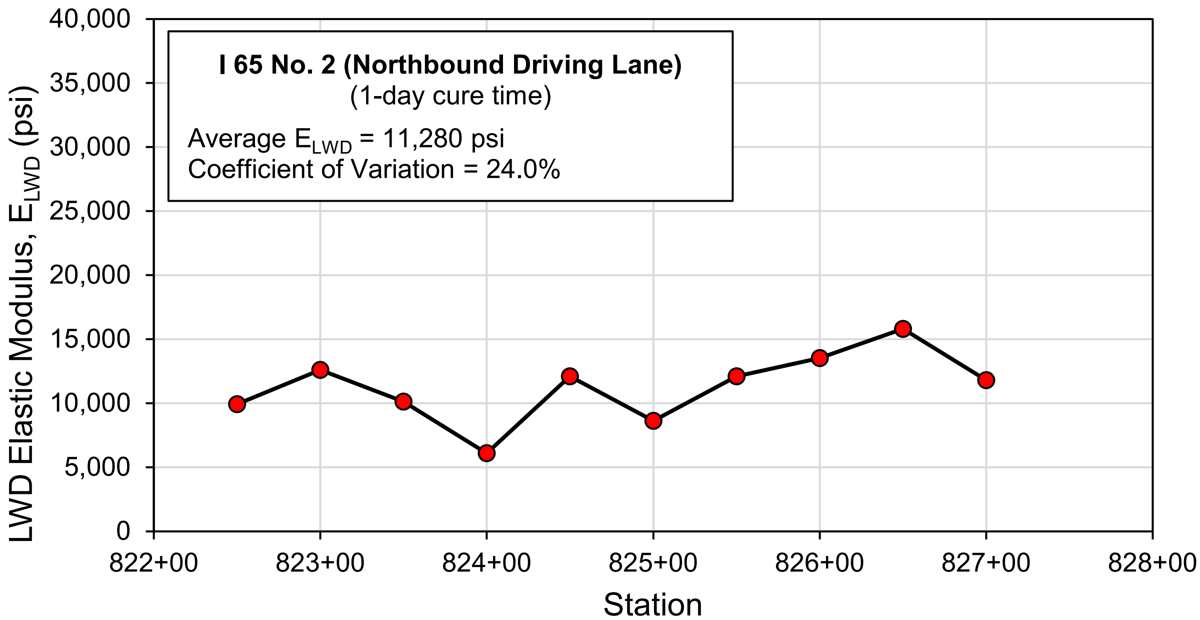


(b)

Figure D.17 I 65 No. 1 test section FWD testing results—(a) pavement effective structural numbers, (b) FWD backcalcualted resilient moduli.

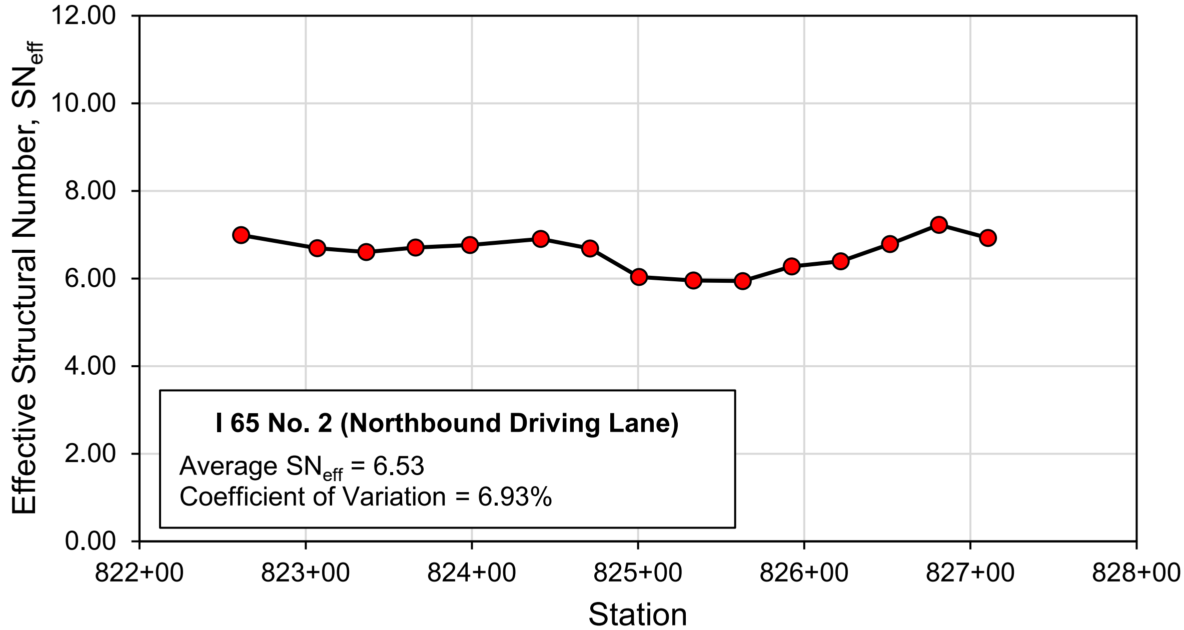


(a)

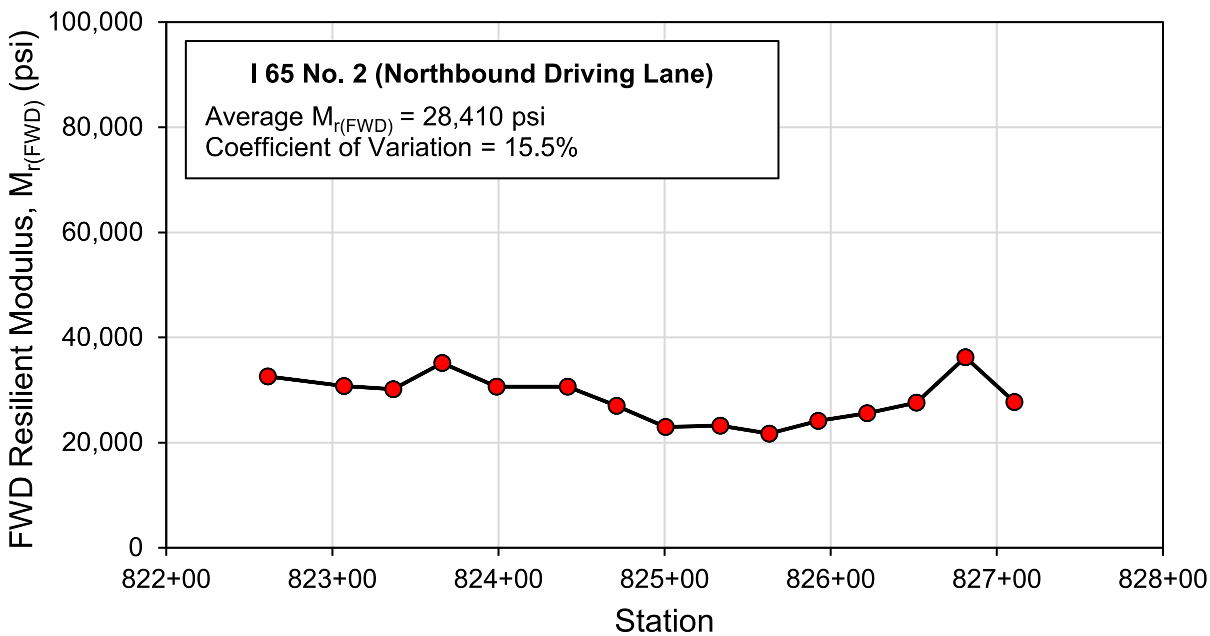


(b)

Figure D.18 I 65 No. 2 test section LWD testing results—(a) measured LWD deflections, (b) LWD elastic moduli.

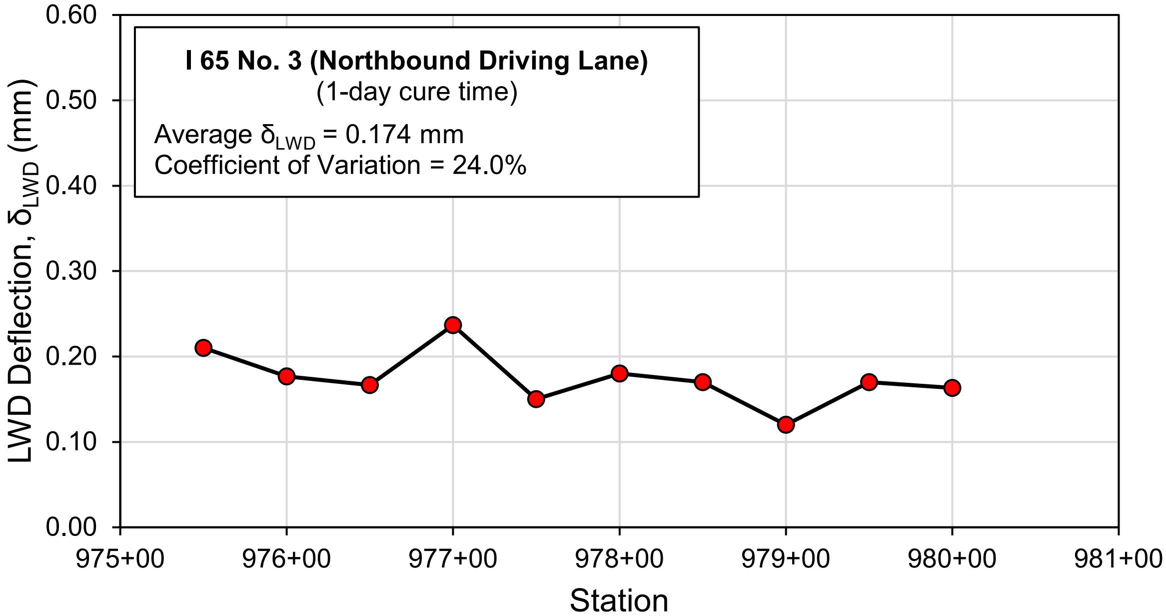


(a)

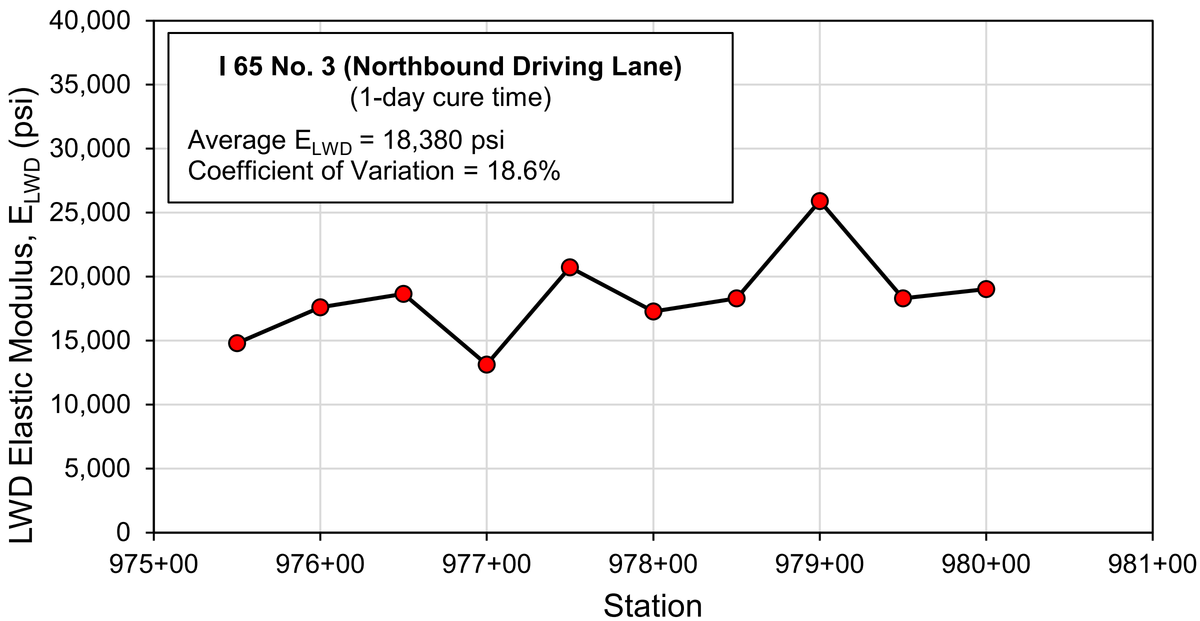


(b)

Figure D.19 I 65 No. 2 test section FWD testing results—(a) pavement effective structural numbers, (b) FWD backcalcualted resilient moduli.

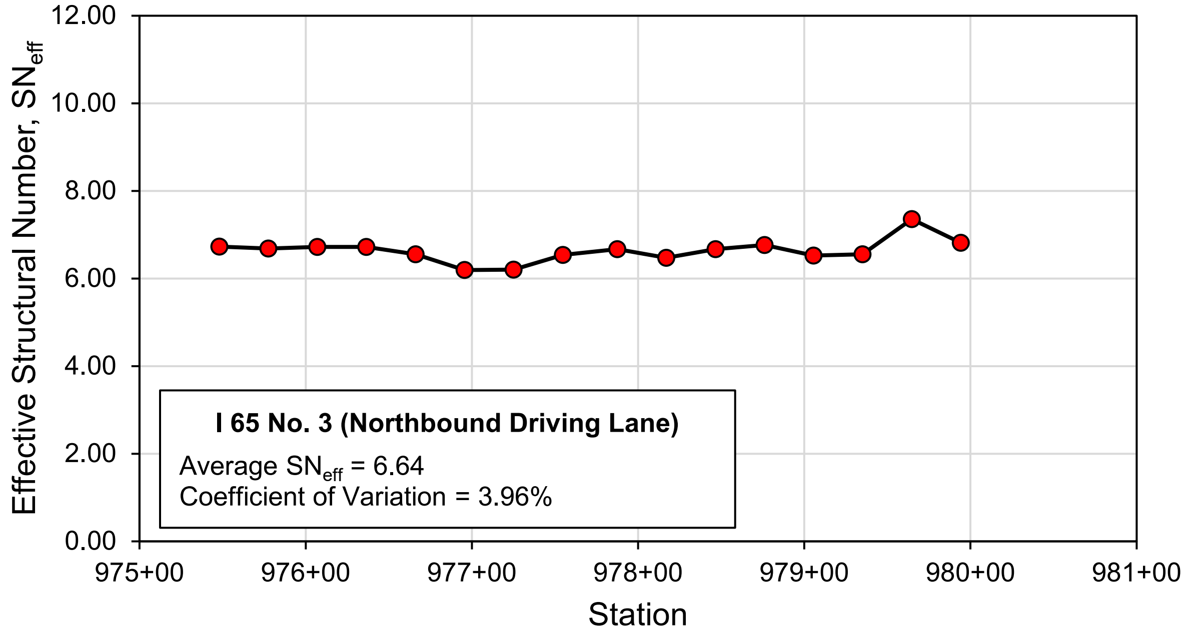


(a)

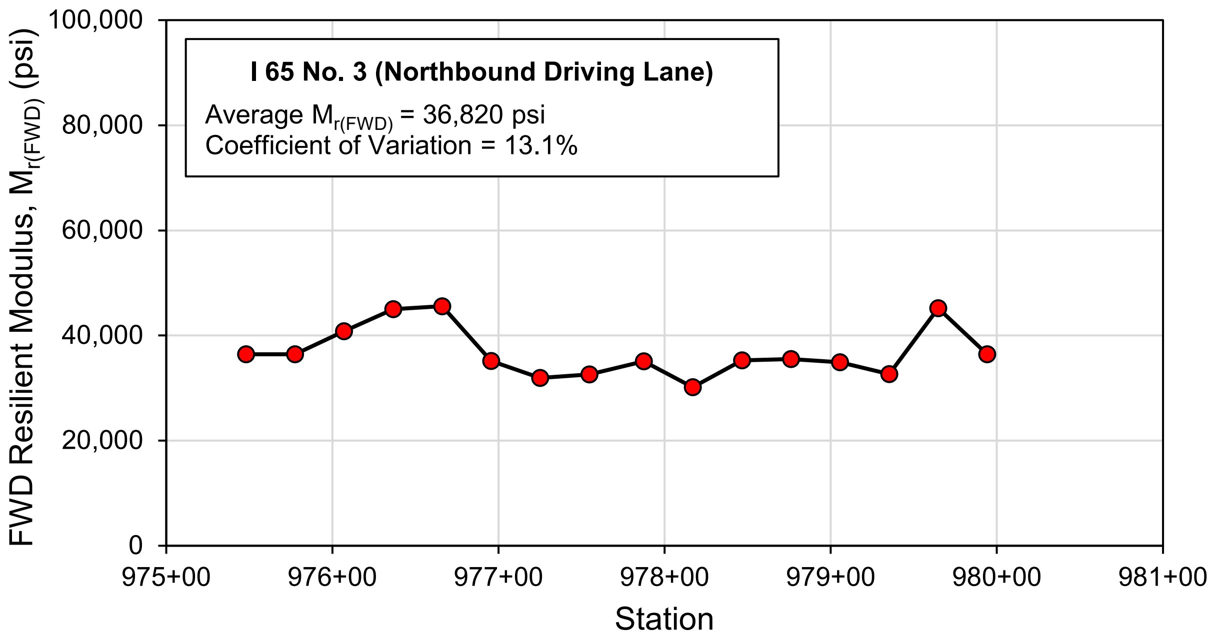


(b)

Figure D.20 I 65 No. 3 test section LWD testing results—(a) measured LWD deflections, (b) LWD elastic moduli.

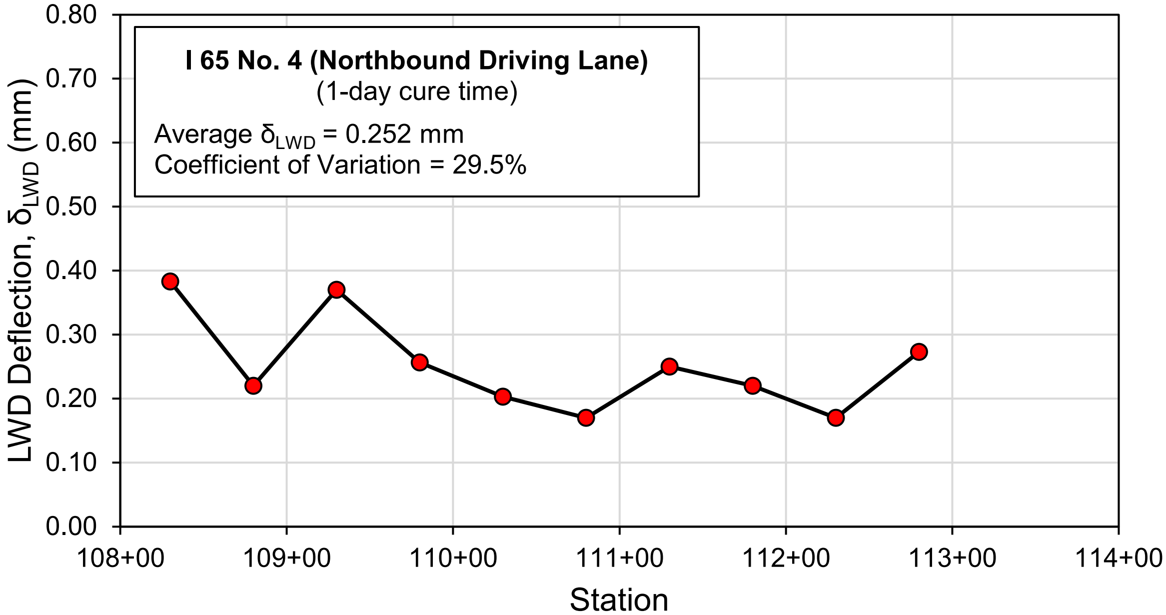


(a)

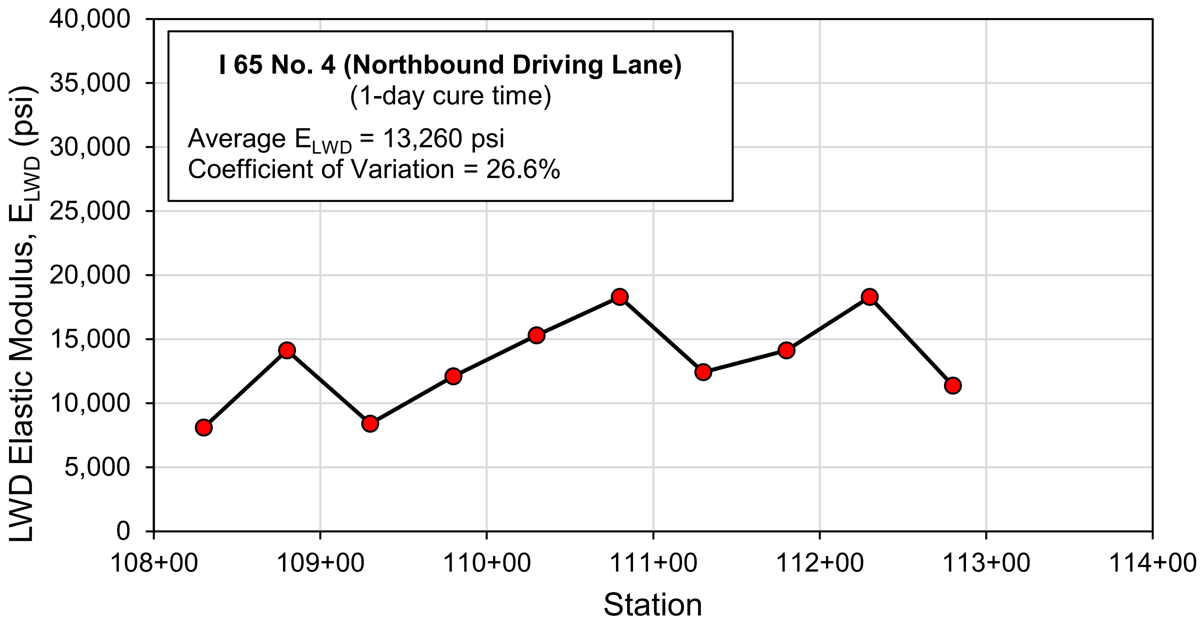


(b)

Figure D.21 I 65 No. 3 test section FWD testing results—(a) pavement effective structural numbers, (b) FWD backcalcualted resilient moduli.

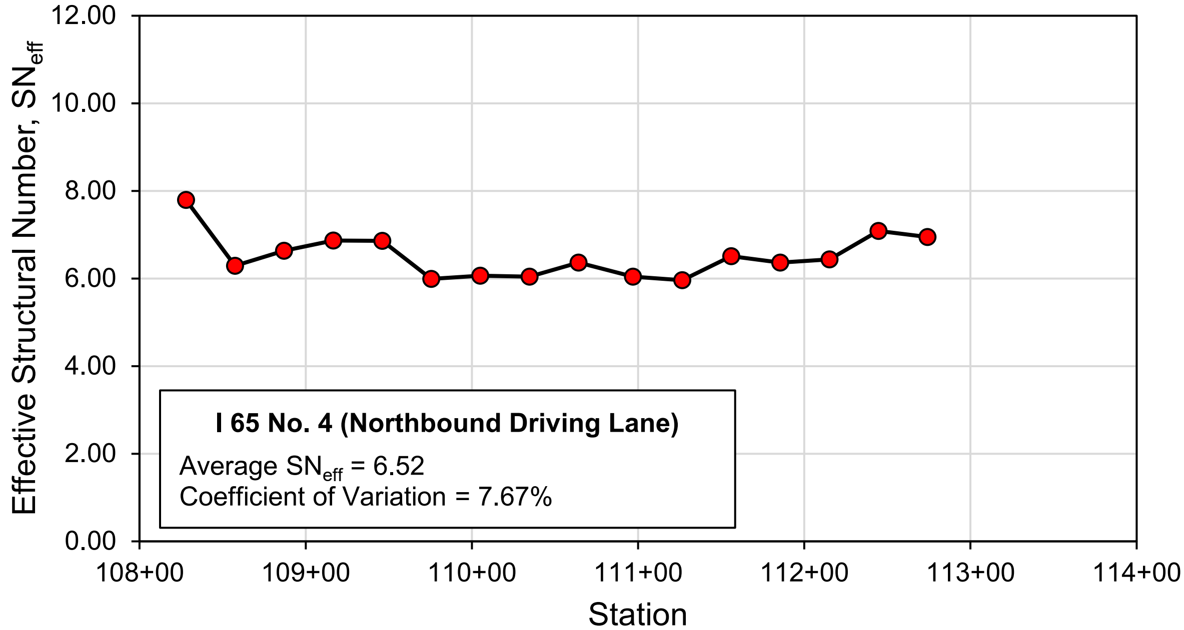


(a)

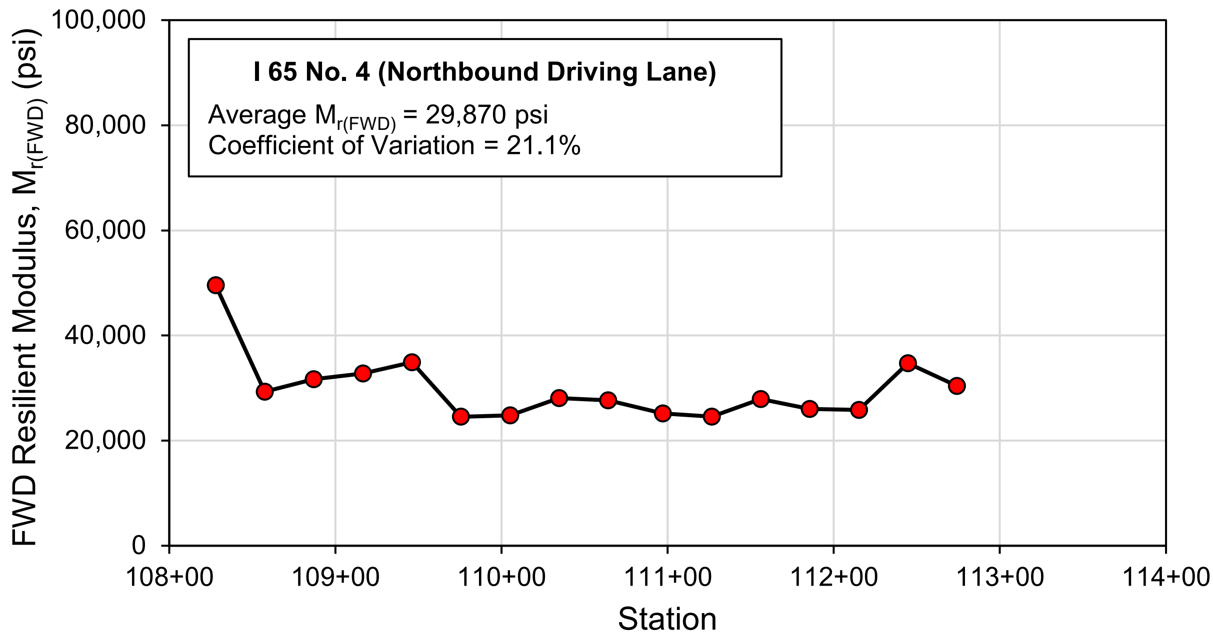


(b)

Figure D.22 I 65 No. 4 test section LWD testing results—(a) measured LWD deflections, (b) LWD elastic moduli.

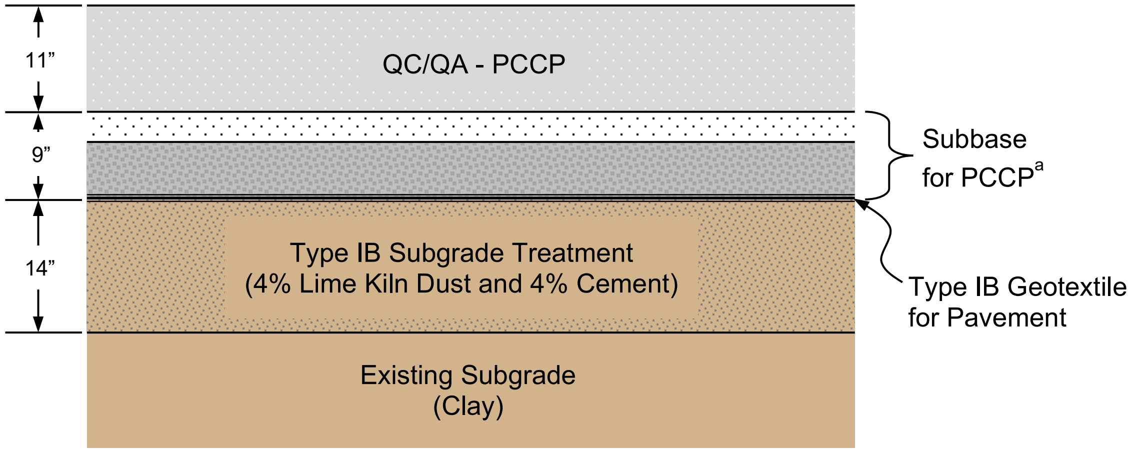


(a)



(b)

Figure D.23 I 65 No. 4 test section FWD testing results—(a) pavement effective structural numbers, (b) FWD backcalcualted resilient moduli.



Note:
[a]Subbase for PCCP comprises 3” open-graded aggregate (No. 8) over 6” dense-graded compacted aggregate (No. 53)

Figure D.24 SR 46 pavement cross section.

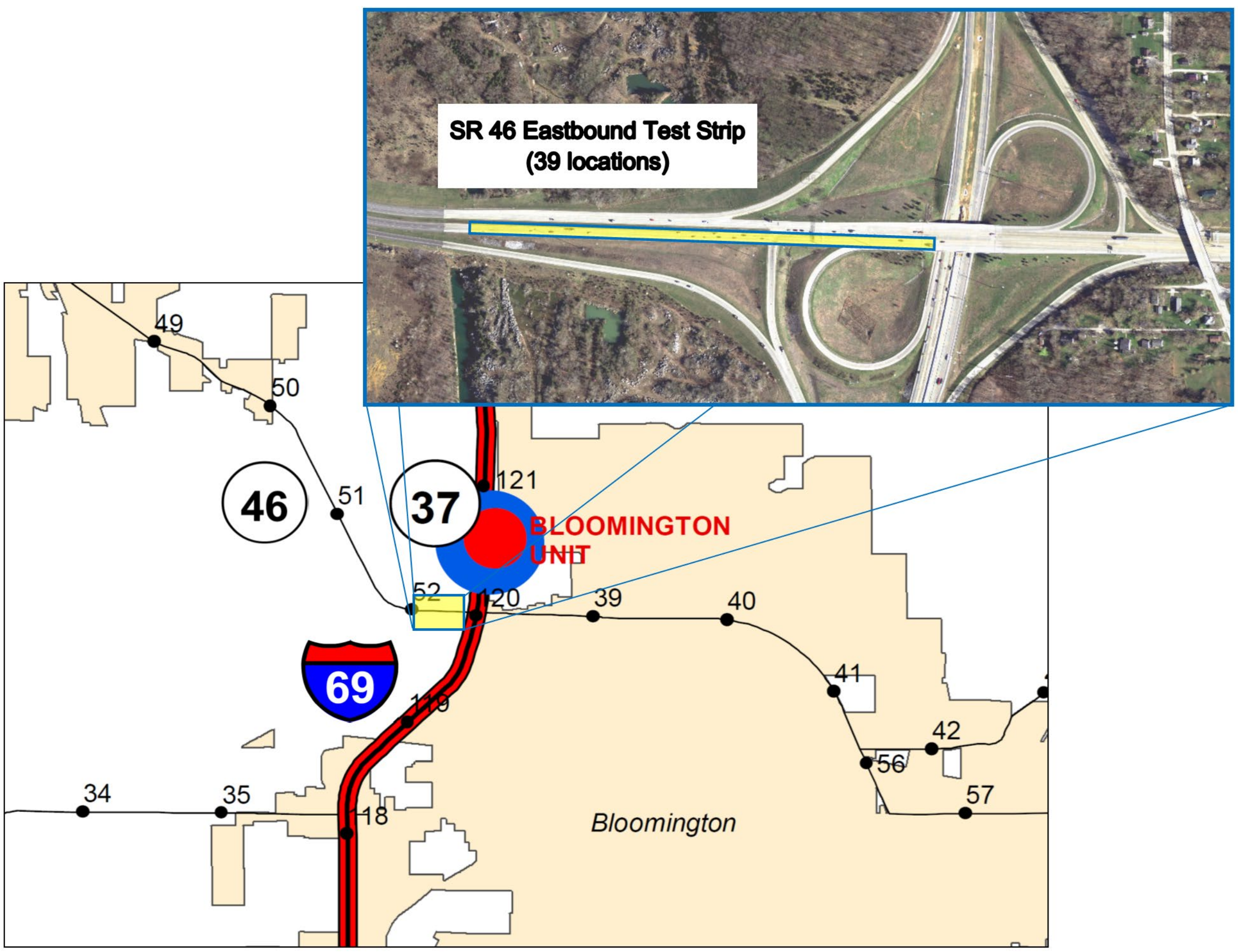
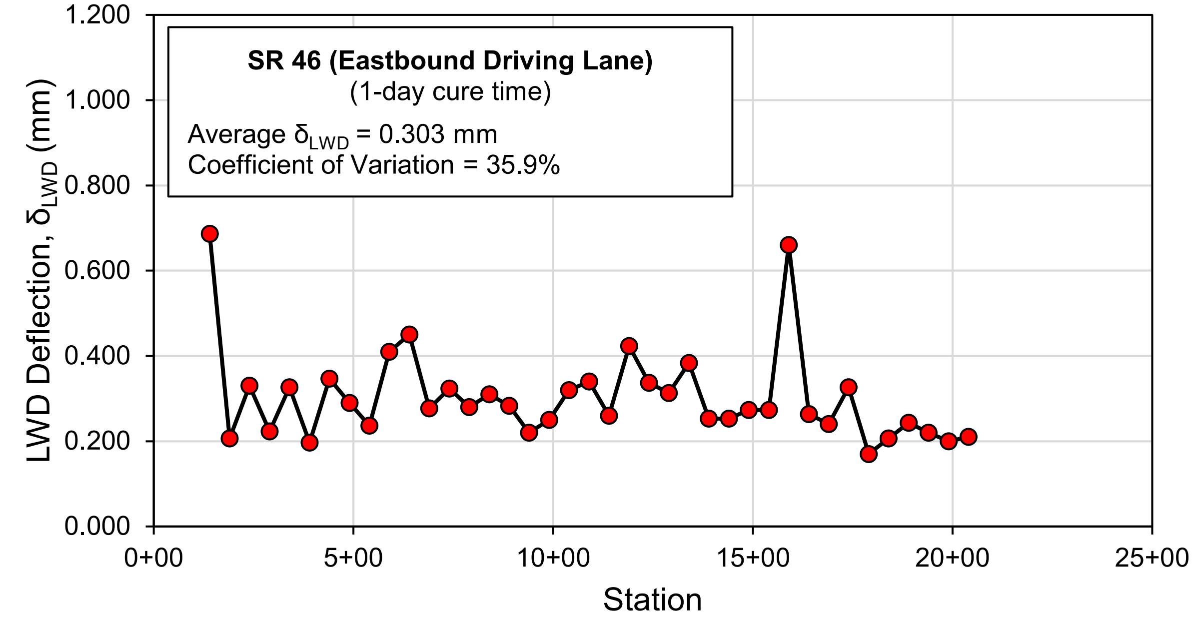
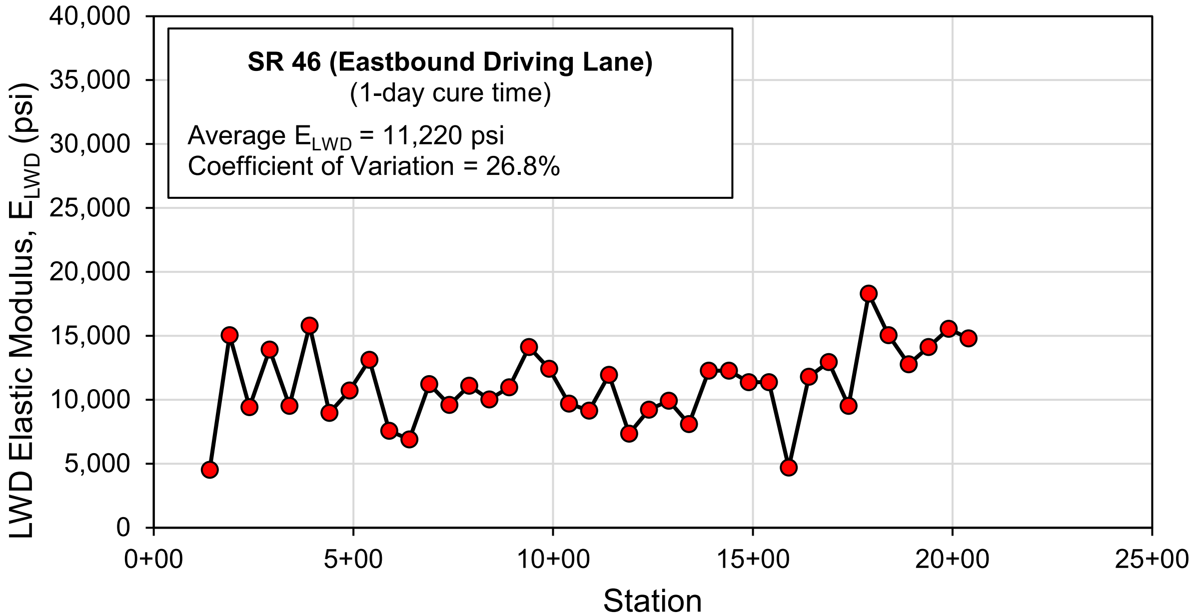


Figure D.25 SR 46 test section layout of testing locations.

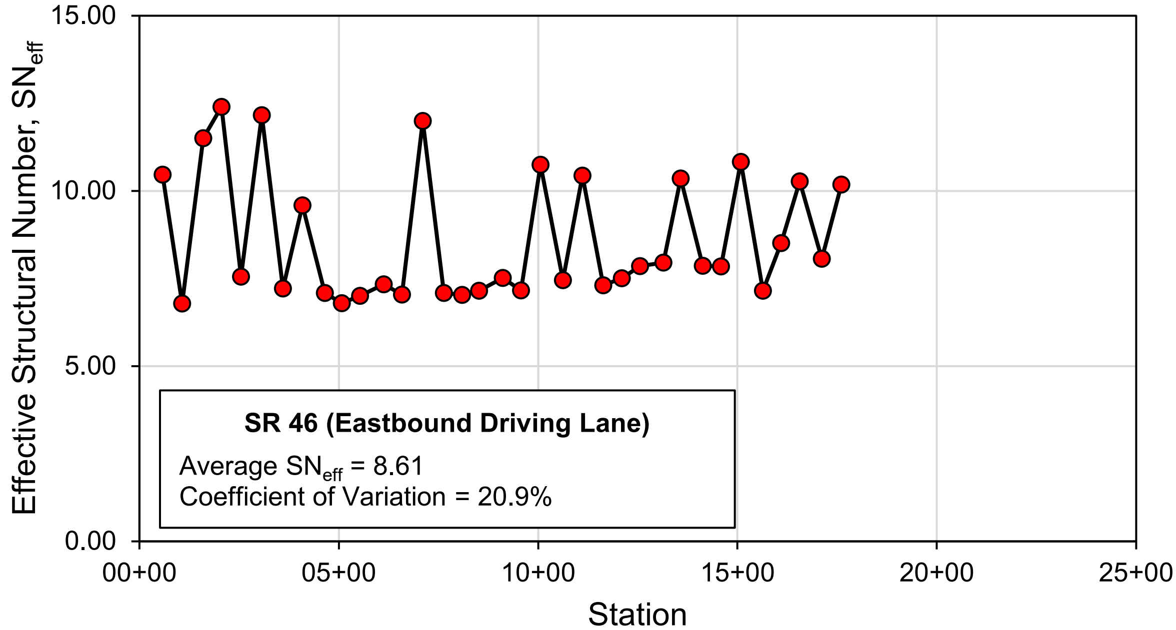


(a)

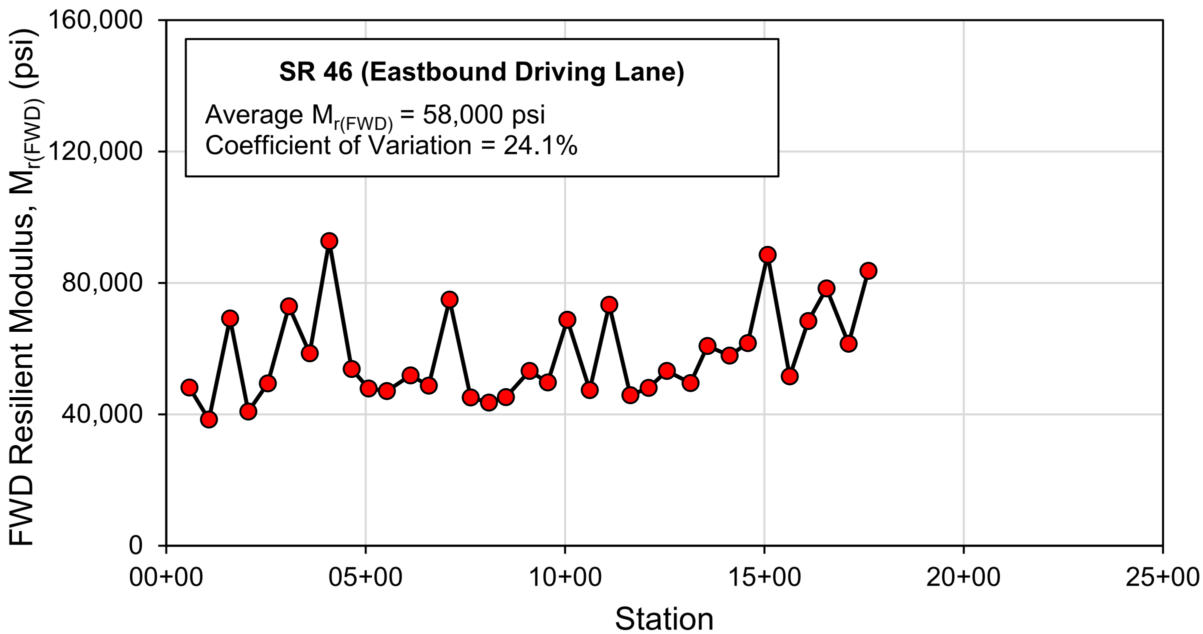


(b)

Figure D.26 SR 46 test section LWD testing results—(a) measured LWD deflections, (b) LWD elastic moduli.



(a)



(b)

Figure D.27 SR 46 test section FWD testing results—(a) pavement effective structural numbers, (b) FWD backcalcualted resilient moduli.

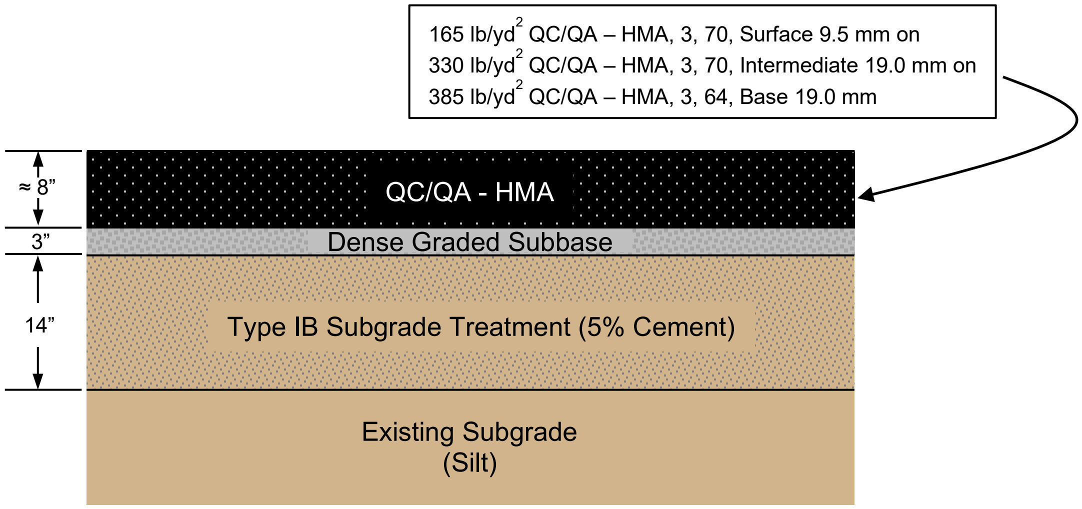


Figure D.28 SR 66 pavement cross section.

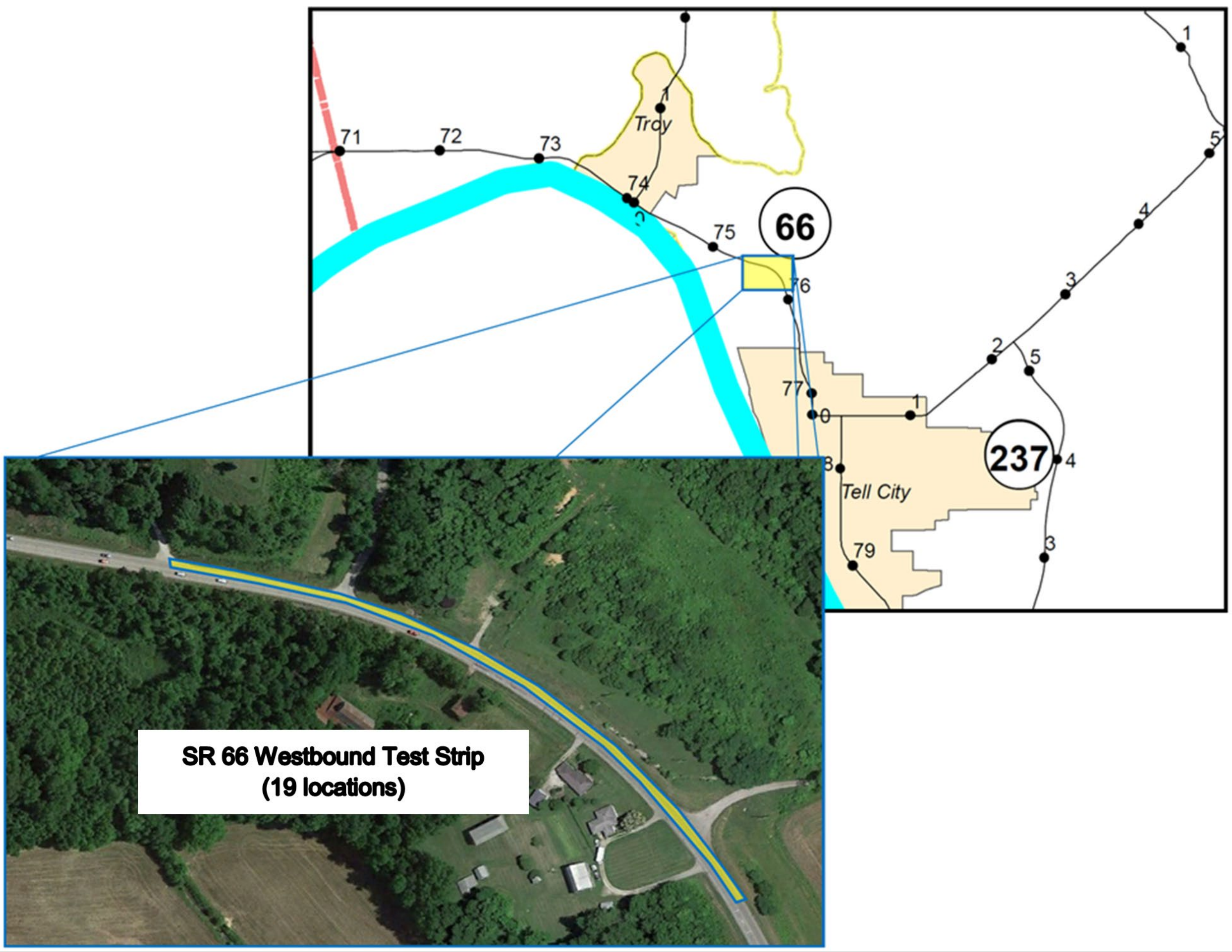
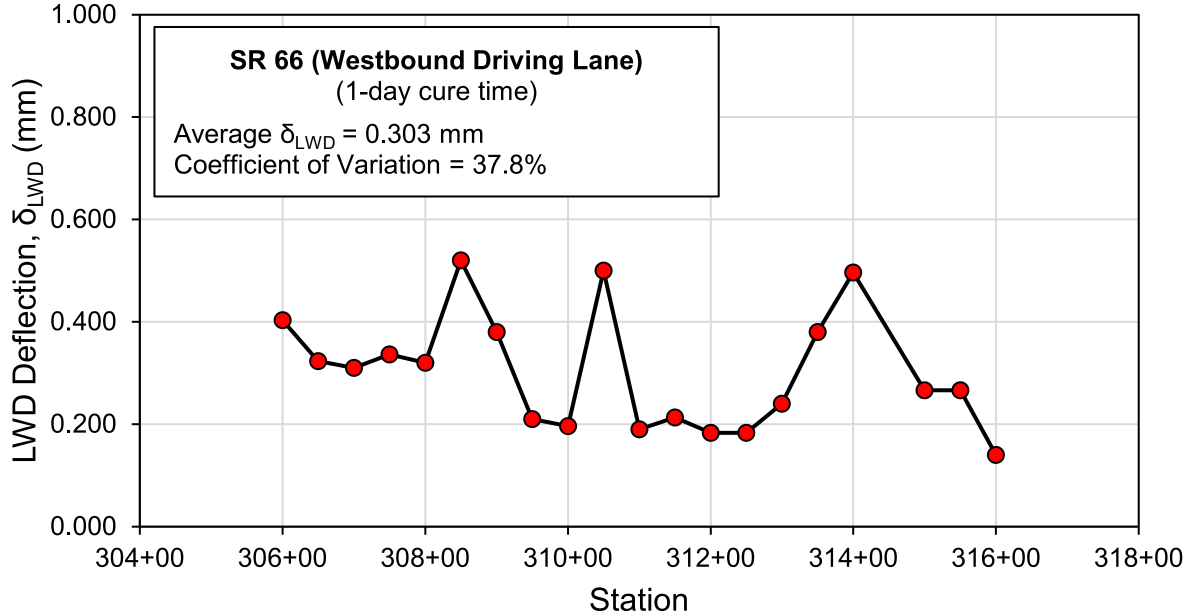
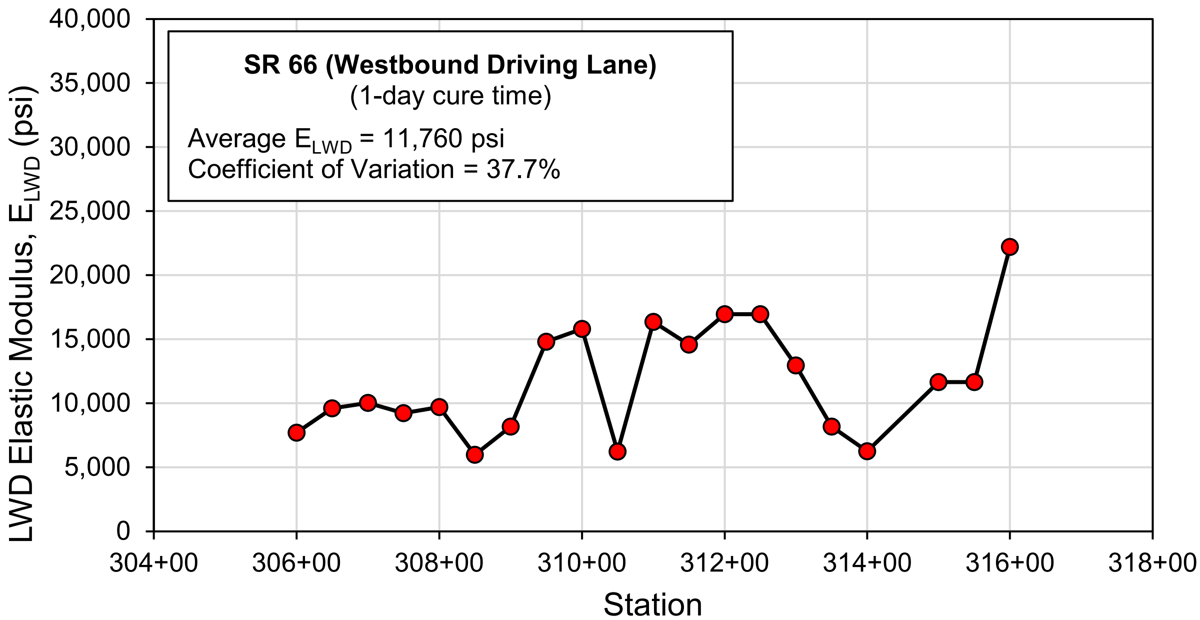


Figure D.29 SR 66 test section layout of testing locations.

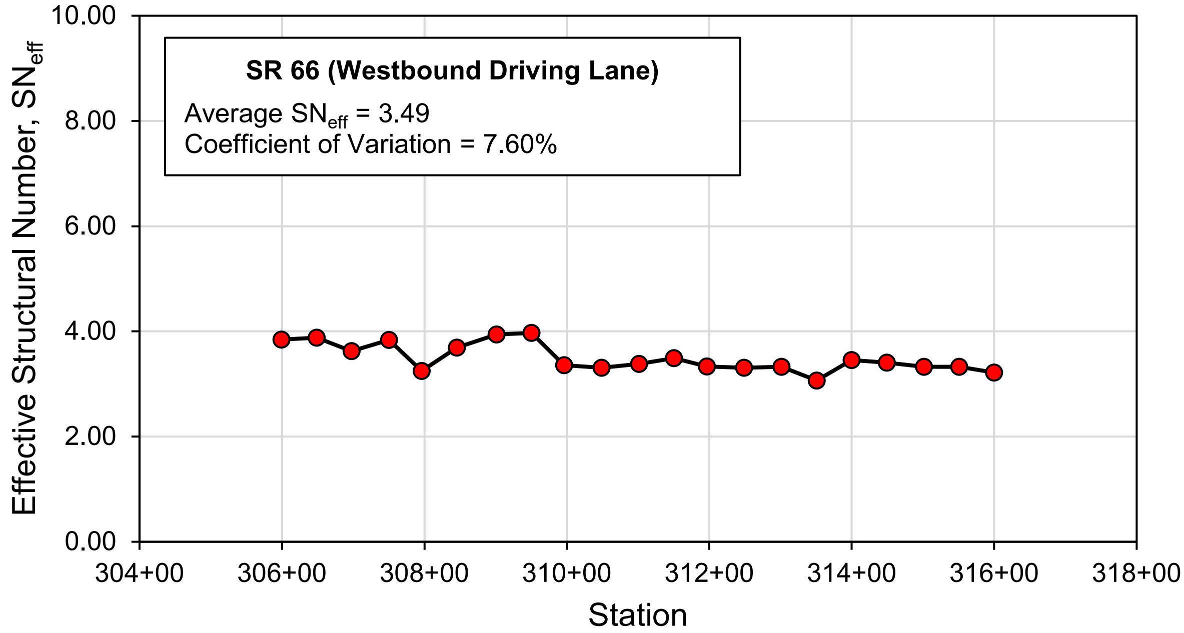


(a)

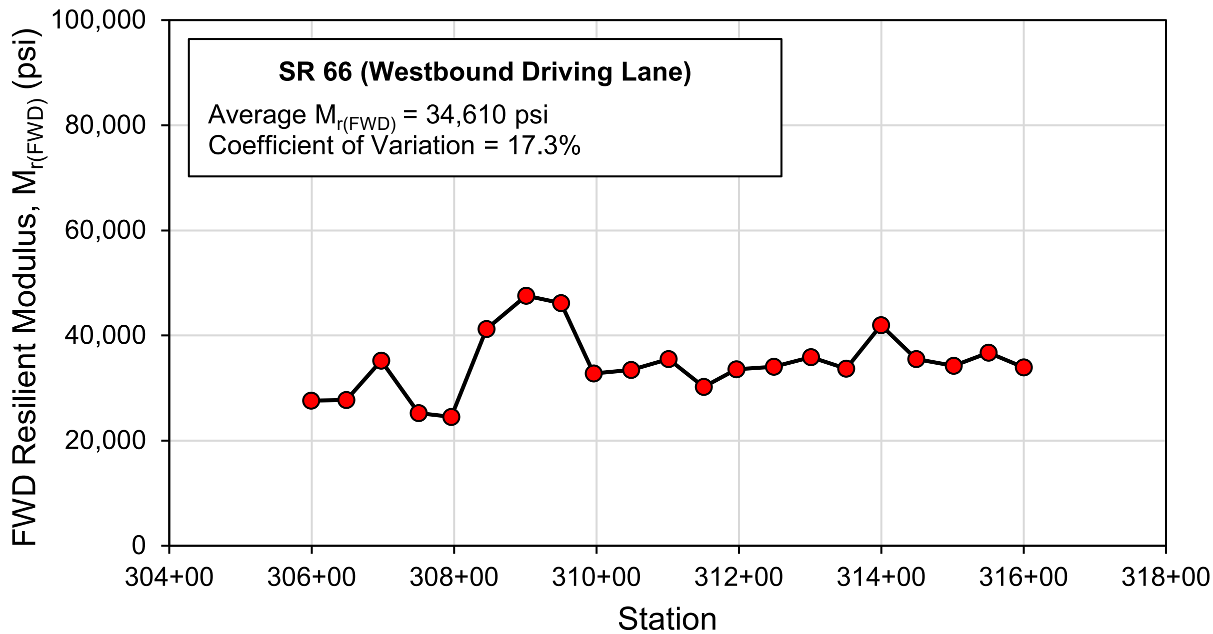


(b)

Figure D.30 SR 66 test section LWD testing results—(a) measured LWD deflections, (b) LWD elastic moduli.



(a)



(b)

Figure D.31 SR 66 test section FWD testing results—(a) pavement effective structural numbers, (b) FWD backcalcualted resilient moduli.

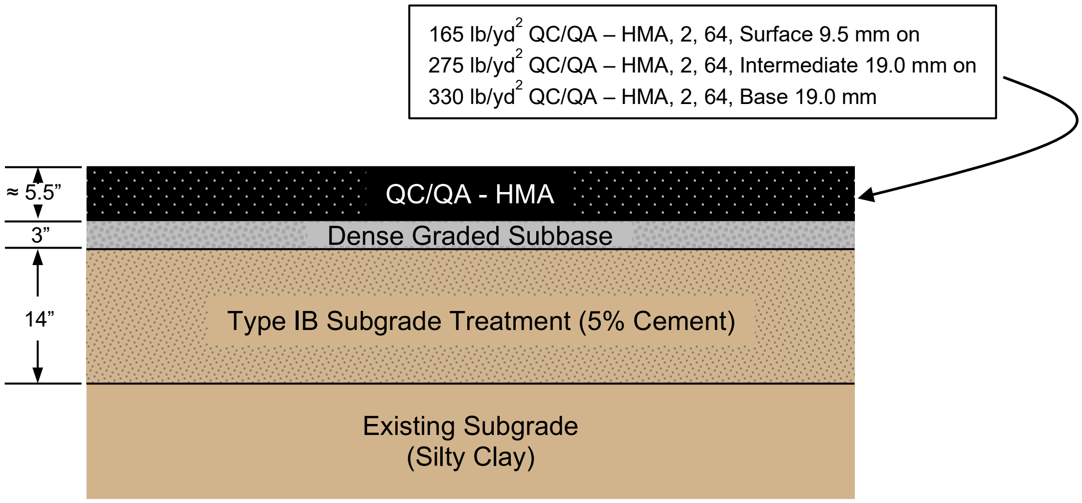


Figure D.32 CR 400 S pavement cross section.

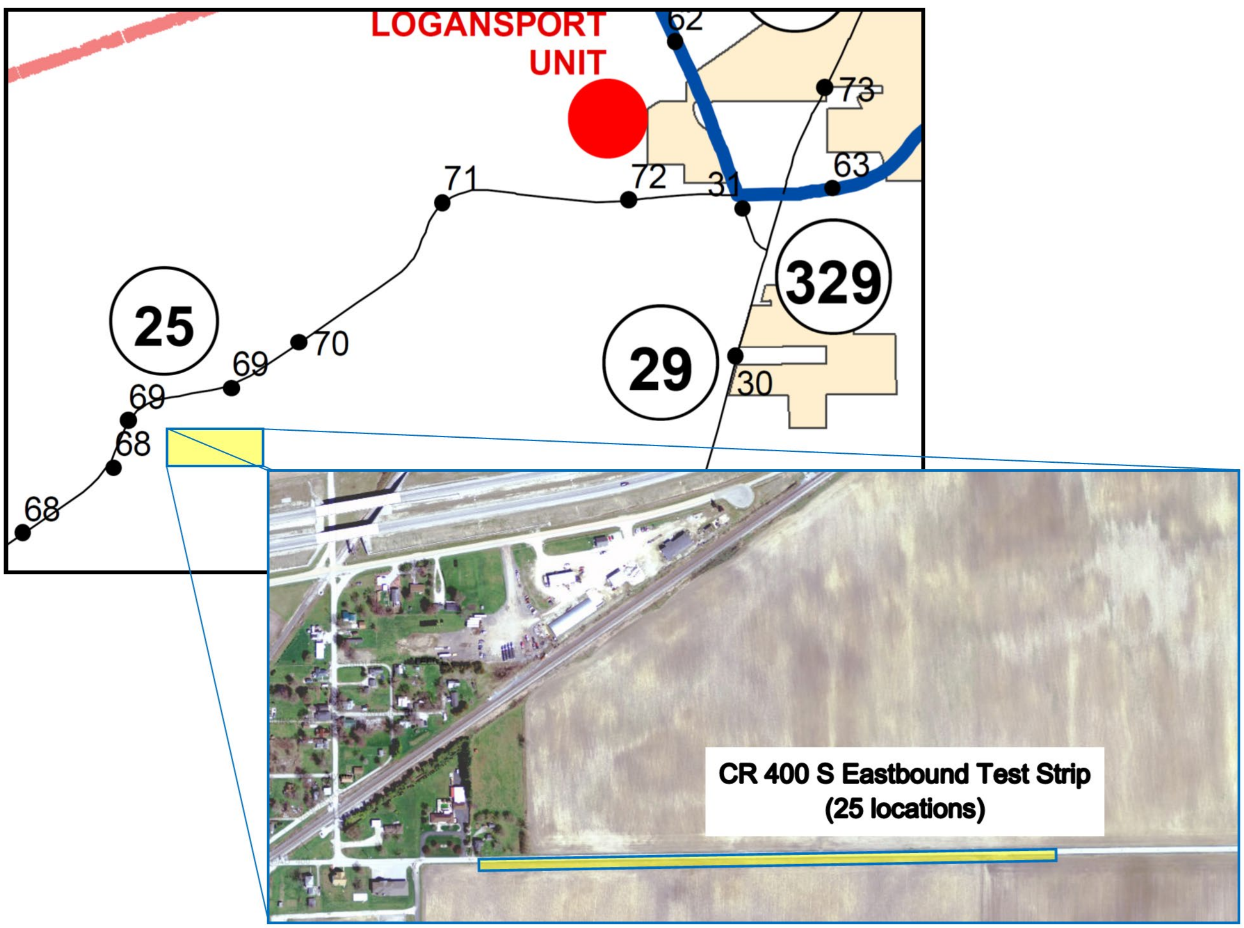
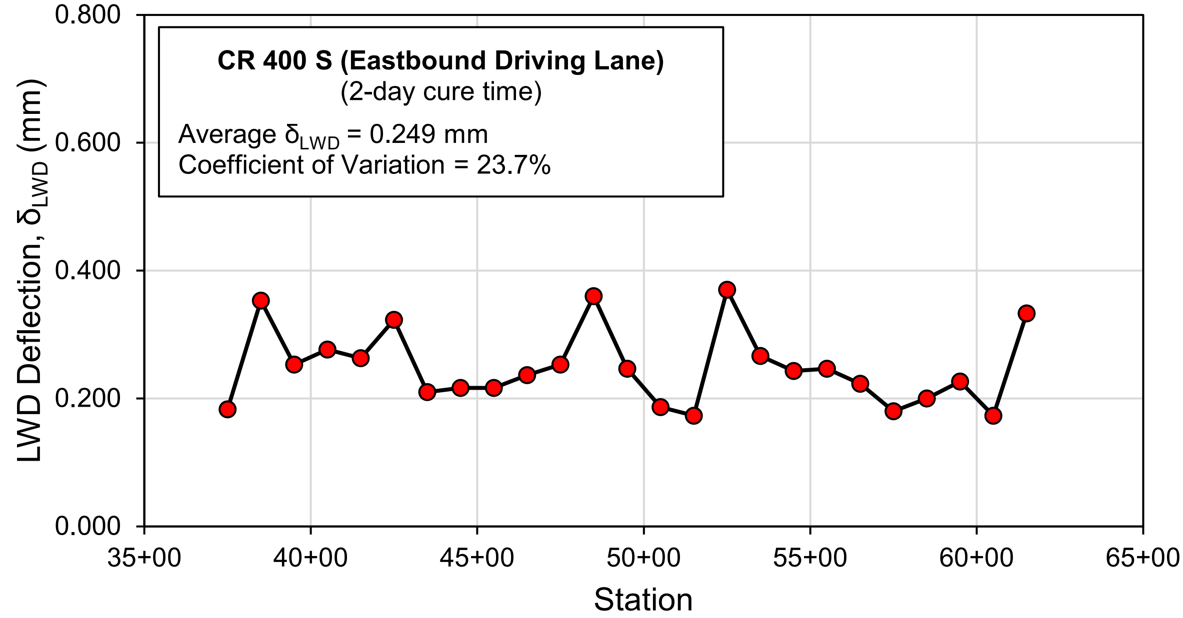
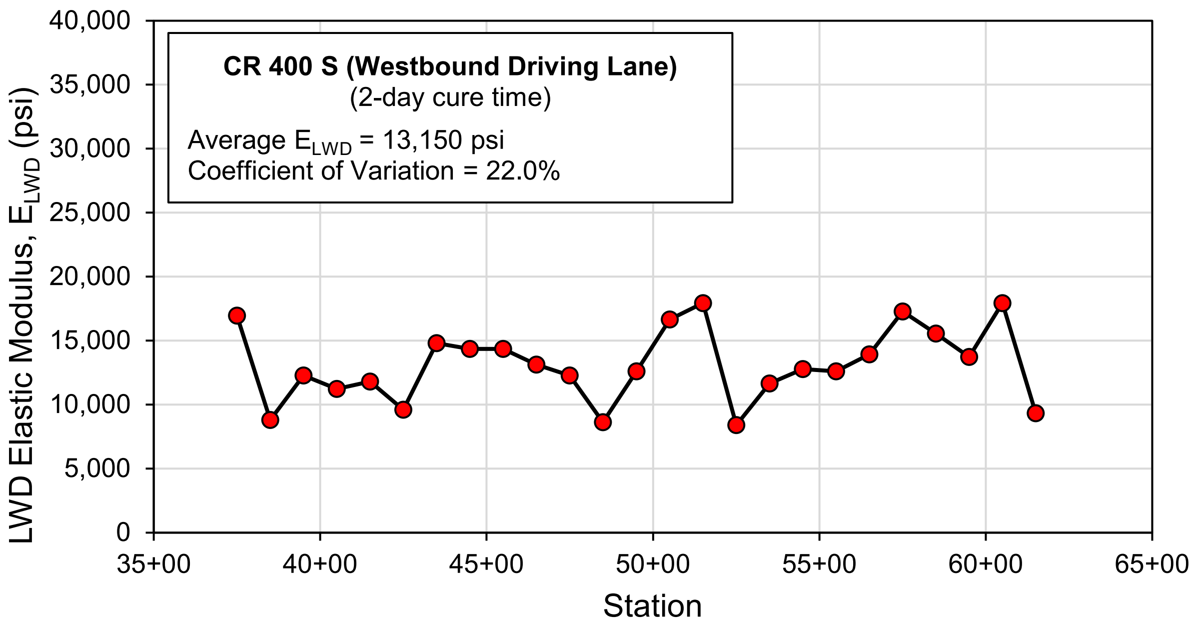


Figure D.33 CR 400 S test section layout of testing locations.

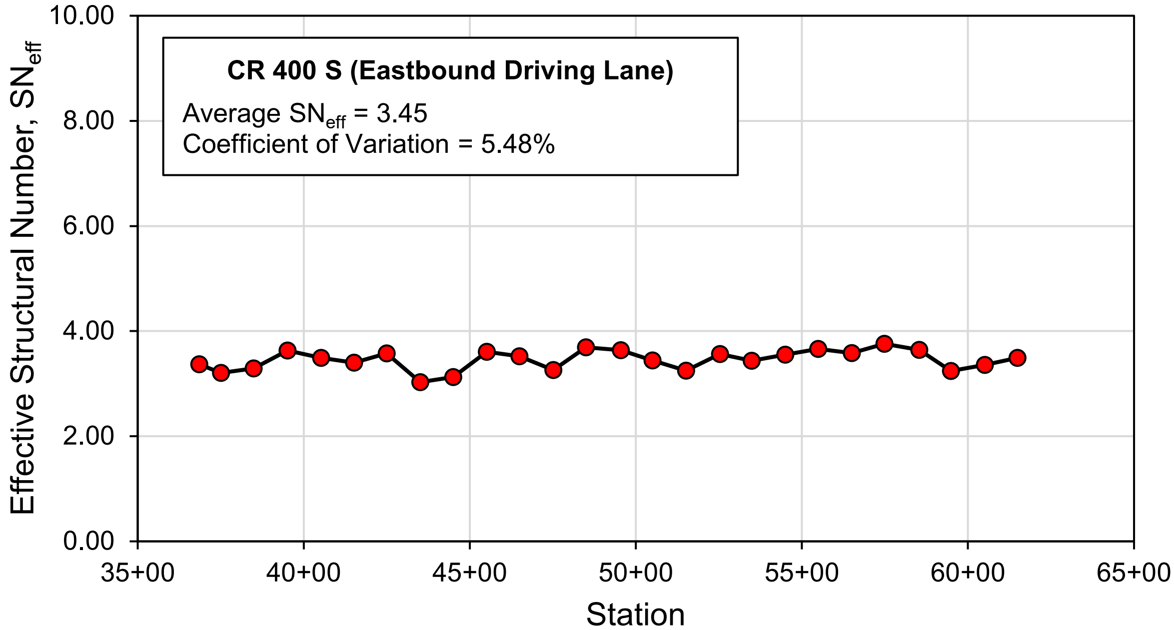


(a)

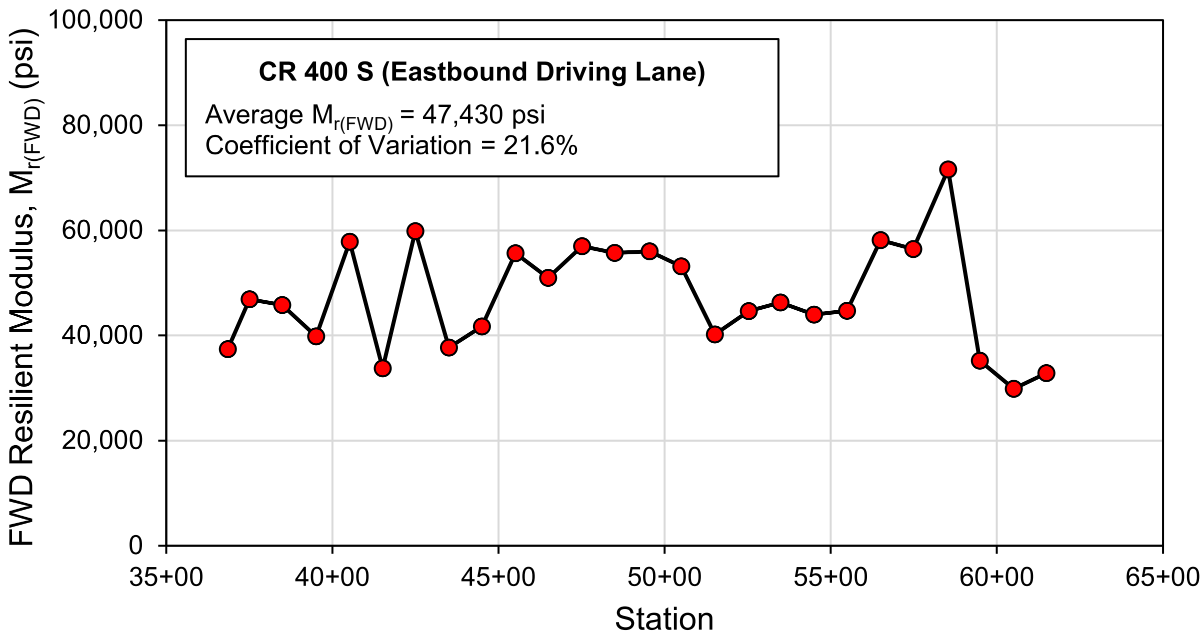


(b)

Figure D.34 CR 400 S test section LWD testing results—(a) measured LWD deflections, (b) LWD elastic moduli.



(a)



(b)

Figure D.35 CR 400 S test section FWD testing results—(a) pavement effective structural numbers, (b) FWD backcalcualted resilient moduli.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

An open access version of this publication is available online. See the URL in the citation below.

Becker, P. J. (2021). *Using the light weight deflectometer for performance-based quality assurance testing of cement modified subgrades* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2021/07). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317304