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Estimation of Subgrade Resilient Modulus Using the Unconfined Compression Test

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M. SHABBIR HOSSAIN, Ph.D., P.E.
Senior Research Scientist
Virginia Center for Transportation Innovation and Research

WAN SOO KIM, Ph.D., P.E.
Soils Engineer
Materials Division
Virginia Department of Transportation

Final Report VCTIR 15-R12

VIRGINIA CENTER FOR TRANSPORTATION INNOVATION AND RESEARCH
530 Edgemont Road, Charlottesville, VA 22903-2454
www.VTRC.net

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VCTIR 15-R12	2. Government Accession No.:	3. Recipient's Catalog No.:

4. Title and Subtitle:
Estimation of Subgrade Resilient Modulus Using the Unconfined Compression Test

5. Report Date:
November 2014

6. Performing Organization Code:

7. Author(s):
M. Shabbir Hossain, Ph.D., P.E., and Wan Soo Kim, Ph.D., P.E.

8. Performing Organization Report No.:
VCTIR 15-R12

9. Performing Organization and Address:
Virginia Center for Transportation Innovation and Research
530 Edgemont Road
Charlottesville, VA 22903

10. Work Unit No. (TRAIS):

11. Contract or Grant No.:
96993

12. Sponsoring Agencies' Name and Address:

Virginia Department of Transportation
1401 E. Broad Street
Richmond, VA 23219

Federal Highway Administration
400 North 8th Street, Room 750
Richmond, VA 23219-4825

13. Type of Report and Period Covered:
Final

14. Sponsoring Agency Code:

15. Supplementary Notes:

16. Abstract:

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The Virginia Department of Transportation (VDOT) uses a simple correlation with the California bearing ratio (CBR) to estimate the resilient modulus in their current pavement design procedure in accordance with the 1993 AASHTO design guide. As this correlation with CBR is considered to be poor, a simpler unconfined compression (UC) test was explored for better estimation of the resilient modulus of fine-grained soils. Several models were developed in this study to estimate the resilient modulus of fine-grained soil from the results of UC tests. The simplest model considers only the UC strength to predict the resilient modulus with a fair correlation. The more detailed models with stronger correlations also consider the plasticity index, percentage of materials passing the No. 200 sieve, and modulus of the stress-strain curve from the UC test. These models are recommended for implementation by VDOT.

17 Key Words:
Subgrade soil, resilient modulus, pavement. unconfined compression test

18. Distribution Statement:
No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.

19. Security Classif. (of this report):	20. Security Classif. (of this page):	21. No. of Pages:	22. Price:
Unclassified	Unclassified	37	

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M. Shabbir Hossain, Ph.D., P.E.
Senior Research Scientist
Virginia Center for Transportation Innovation and Research

Wan Soo Kim, Ph.D., P.E.
Soils Engineer
Materials Division
Virginia Department of Transportation

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Center for Transportation Innovation and Research
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

November 2014
VCTIR 15-R12

DISCLAIMER

ABSTRACT

To facilitate pavement design, the new proposed mechanistic-empirical pavement design guide recommends the resilient modulus to characterize subgrade soil and its use for calculating pavement responses attributable to traffic and environmental loading. Although resilient modulus values could be determined through laboratory testing of actual subgrade soil samples, such testing would require significant resources including a high level of technical capability to conduct the test and interpret results. For smaller or less critical projects, where costly and complex resilient modulus testing is not justified, correlation with the results of other simpler tests could be used.

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FINAL REPORT

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M. Shabbir Hossain, Ph.D., P.E.
Senior Research Scientist
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Wan Soo Kim, Ph.D., P.E.
Soils Engineer
Materials Division
Virginia Department of Transportation

INTRODUCTION

Subgrade is the underlying soil of a pavement structure, and its characterization allows for the design of a proper foundation for the pavement. Based on the available support from the subgrade soil, an adequate pavement structure may be designed for expected traffic and climate. Therefore, identifying and characterizing the subgrade support are essential for the design of a pavement structure.

The currently used *Guide for Design of Pavement Structures* (American Association of State Highway and Transportation Officials [AASHTO], 1993) developed in 1972 and updated in 1986 and 1993 (hereinafter the 1993 AASHTO design guide) is empirically based on the American Association of State Highway Officials (AASHO) road test of the early 1960s. Empirical test parameters such as the California bearing ratio (CBR), R-value, etc., are used to characterize subgrade soil. Resilient modulus testing, a basis for the mechanistic approach, was later incorporated into the AASHTO design guide for subgrade soils characterization, but most departments of transportation, including the Virginia Department of Transportation (VDOT), are still estimating the resilient modulus using empirical relations based on the CBR. Although the resilient modulus was incorporated in 1986, the basic pavement design process still depends on the results of the AASHO road test, which were limited to a particular soil and environmental condition. To overcome the limitations of empirical design, Project 1-37A of the National Cooperative Highway Research Program proposed a mechanistic-empirical pavement design procedure (ARA, Inc., 2004) in the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* (MEPDG) to replace the procedure in the 1993 AASHTO design guide. Again, the resilient modulus value, for use with an enhanced integrated climatic model, is recommended for subgrade characterization in the MEPDG.

Some agencies consider the cost, time, complication, and sampling resolution required for meaningful resilient modulus testing to be too cumbersome for its application in less critical projects. Regardless of project size, it is often difficult to predict and consequently reproduce the in situ conditions, usually with respect to the state of stress and moisture condition, further complicating the use of resilient modulus testing. Because of this, correlations are desired for estimating the resilient modulus, especially for use (or verification of default values) associated with MEPDG Level 2 or 3 design and analysis, which are applicable to less critical projects. The recently released implementable version of the MEPDG, i.e., AASHTOWare Pavement ME Design (AASHTO, n.d.), also uses a single value of the resilient modulus independent of stress condition for all projects.

Hossain (2008) evaluated fine-grained soils from Virginia using resilient modulus tests in accordance with AASHTO T 307-99, Standard Method of Testing for Determining the Resilient Modulus of Soils and Aggregate Materials (hereinafter AASHTO T 307) (AASHTO, 2010). At the end of the test, a static triaxial compression test known as the "quick shear test" is conducted. The researcher found that the results of the quick shear test had a stronger correlation than the results of the CBR test with the resilient modulus value of fine-grained soils. Correlations with the results of the unconfined compression (UC) test have been reported in other studies (Drumm et al., 1990; Lee et al., 1997; Thompson and Robnett, 1979). The UC test is simply the triaxial (quick shear) test without confinement. The UC test is a simple and relatively inexpensive test compared to the resilient modulus test. Therefore, further investigation with the UC test was warranted.

A study (Hossain, 2010) was planned to investigate the correlation between the results of the resilient modulus and UC tests for Virginia fine-grained soils. Fine-grained soils are defined as A-4 through A-7 soils in accordance with AASHTO M 145, Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes (AASHTO, 2010). As seasonal variation of moisture content in the subgrade is possible, the effect of moisture variation was also incorporated into the study. Fair correlations were found, but only six samples were used in the investigation. In order to verify those correlations, additional testing of more soil samples was conducted in a second phase of the study and correlations were refined to improve predictability. Although the primary focus of this report is Phase II of the study, the data from Phase I are also included for completeness.

PURPOSE AND SCOPE

The purpose of this study was to develop a correlation to estimate resilient modulus values for subgrade soil from UC test results for use in MEPDG Level 2 or 3 analysis. Currently used correlations, based on the CBR as suggested in the 1993 AASHTO design guide, showed poor predictability in a previous study (Hossain, 2008).

The objectives were as follows:

- Verify the correlation found by Hossain (2008) between the results of the resilient modulus and quick shear tests when both are conducted on the same sample.

- Verify the influence of moisture in terms of degree of saturation on resilient modulus and UC test results.

- Investigate the correlation between UC and resilient modulus test results.

- Develop a correlation model to estimate the resilient modulus from UC test results and other soil index properties.

METHODS

Overview

To achieve the study objectives, the following tasks were conducted:

1. A literature review was conducted to identify correlations proposed by other researchers.

2. Soil samples were collected from across Virginia and the resilient modulus test including the quick shear and the UC tests were conducted on the samples.

3. Soil samples were classified and moisture-density relationships determined using the standard Proctor test.

4. Regression analyses were performed to determine a suitable correlation to estimate the resilient modulus value from the results of the UC test and other soil index properties.

5. A correlation model to estimate the resilient modulus from UC test results and other soil properties was developed.

Literature Review

The literature regarding the use of UC test results to predict the resilient modulus for subgrade soils was identified and reviewed using the resources of the VDOT Research Library and the University of Virginia library. Online databases searched included the Transportation Research Information System (TRIS), International Transport Research Documentation (ITRD), the Engineering Index (EI Compendex), Transport, and WorldCat, among others.

Collection of Soil Samples and Laboratory Testing Program

Collection of Soil Samples

Soil samples were collected from the existing construction projects in the nine VDOT construction districts. A laboratory testing program was conducted in two phases. Six samples were tested in Phase I (Hossain, 2010), and 29 additional samples were tested in Phase II.

Phase I testing was conducted to explore the possible correlation between resilient modulus and UC test results. Phase II was conducted to verify and refine those relationships.

Soil samples were tested at the VDOT Materials Division Soils Laboratory (hereinafter VDOT soils lab) and the VCTIR laboratory (hereinafter VCTIR lab) in accordance with AASHTO standards (AASHTO, 2010). Testing at the VDOT soils lab included the resilient modulus test with the accompanying quick shear test; standard soils properties tests to determine gradation, liquid limit, and plastic limit; the standard Proctor test; and the CBR test. UC testing was done at both laboratories with different sample preparation techniques: with the static compactor at the VDOT soils lab and with impact compaction (using the standard Proctor hammer) at the VCTIR lab. Phase I samples were also tested by an outside vendor for resilient modulus only. The test matrix is summarized in Table 1.

Table 1. Laboratory Test Matrix

Test		Test Standard	No. of Samples per Source	
			Phase I	Phase II
Gradation		AASHTO T 87 and T 88	1	1
Specific Gravity		AASHTO T 100	1	1
Liquid Limit and Plastic Limit		AASHTO T 89 and T 90	1	1
Moisture-Density Relation (Standard Proctor Test)		AASHTO T 99	1	1
Resilient Modulus and Quick Shear Tests		AASHTO T 307	3	1
Unconfined Compression	Static Compaction	AASHTO T 208	1	1
	Impact Compaction	AASHTO T 208	3	3
California Bearing Ratio		AASHTO T 193 and VTM 8 (VDOT, 2007)	0	1

The AASHTO test standards may be found in AASHTO (2010).

Soil Index Properties and Standard Proctor Tests

AASHTO standards (AASHTO, 2010) were followed to determine soil index properties including gradation (AASHTO T 87, Standard Method of Test for Dry Preparation of Disturbed Soil and Soil-Aggregate Samples for Test, and AASHTO T 88, Standard Method of Test for Particle Size Analysis of Soils); specific gravity (AASHTO T 100, Standard Method of Test for Specific Gravity of Soils); liquid limit (AASHTO T 89, Standard Method of Test for Determining the Liquid Limit of Soils); and plastic limit (AASHTO T 90, Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils). The optimum moisture content (OMC) and maximum dry density (MDD) were determined using the standard Proctor test (AASHTO T 99, 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). The degrees of saturation of the tested samples were calculated using the sample moisture content, density, and specific gravity values.

Resilient Modulus Test

The resilient modulus tests were performed in accordance with AASHTO T 307 (AASHTO, 2010).

A sample 2.9 in in diameter was compacted at OMC and MDD using a static compactor. Five layers of equal mass were used to compact the specimens to the target density for an approximate height of 5.8 in. For each layer, a known mass of soil was compacted using static loading to a volume that is fixed by dimensions of the mold assembly. As the diameter of the mold is constant, the density was controlled by the compacted height only. Samples were prepared in accordance with AASHTO T 307 (AASHTO, 2010). The sample was loaded in accordance with AASHTO T 307 with 15 combinations of various confining and axial (vertical) stresses after a conditioning load. The confining stresses were applied using a triaxial pressure chamber in static mode. On the other hand, axial loads were dynamic (cyclic) using a haversine-shaped load pulse with 0.1-sec loading and a 0.9-sec rest period. The conditioning axial load was repeated 1,000 times whereas each of the 15 test loads was repeated 100 times only, and the recoverable strains were measured using two external linear variable differential transformers. Resilient modulus values were calculated as the ratio of the measured axial (deviator) stress to the average recoverable axial strain values for the last five cycles of each load combination. Measured resilient modulus values are used to fit the universal constitutive model shown in Equation 1, which is recommended in the MEPDG (ARA, Inc., 2004), and k-values are calculated through regression analysis. It is important to note that the coefficient of determination, R^2, of the regression equation for k-values was above 0.90 for all tests considered in the study.

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3} \qquad \text{[Eq. 1]}$$

where

M_r = resilient modulus value

k_1, k_2, and k_3 = regression coefficients

P_a = normalizing stress (atmospheric pressure, e.g., 14.7 psi)

θ = bulk stress = $(\sigma_1 + \sigma_2 + \sigma_3) = (3\sigma_3 + \sigma_d)$ where σ_1, σ_2, and σ_3 = principal stresses where $\sigma_2 = \sigma_3$ and σ_d = deviator (cyclic) stress = $\sigma_1 - \sigma_3$
τ_{oct} = octahedral shear stress

$$\frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} = \frac{\sqrt{2}}{3}\sigma_d .$$

Later, this model was used to calculate the resilient modulus value at a confining stress of 2 psi and a deviator stress of 6 psi. Instead of measured values, these calculated resilient modulus values were used for correlation analysis with UC test results.

To investigate the effect of moisture content on the resilient modulus value during Phase I, two additional sets of samples were compacted and tested for the resilient modulus at approximately 20% greater moisture than OMC and 20% less than OMC, respectively. Instead of exactly ±20%, a range of degrees of saturation was considered for selecting compaction moisture content. It is important to mention that the target density for all samples was always

100% of MDD. Although 100% of MDD was not achieved in all cases, in each case density was at least 95% of MDD. During Phase II, samples were tested for resilient modulus at only OMC but the degree of saturation was varied in UC tests.

Quick Shear Test

The quick shear test is a static triaxial compression test and was performed in accordance with AASHTO T 307(AASHTO, 2010) at a 5 psi confining pressure at the end of the resilient modulus testing without removal of the sample from the testing platen. This is an optional feature of AASHTO T 307 to estimate the shear strength of the soil. The rate of axial deviator loading was 1% strain per minute, which is assumed to be fast enough for the undrained condition. Stress and strain values were recorded until failure.

Unconfined Compression Test

UC tests on fine cohesive soil samples were conducted in accordance with AASHTO T 208, Standard Method of Test for Unconfined Compressive Strength of Cohesive Soil (AASHTO, 2010), but data collection was not limited to ultimate compressive strength. A continuous stress-strain response was recorded to produce a complete stress-strain diagram. The rate of loading for the UC test was 1% strain per minute, similar to the quick shear (triaxial) test. The test samples were prepared in two ways:

1. static compaction (static pressure)
2. impact compaction (Proctor hammer).

The static and impact samples were cylinders approximately 3 in in diameter by 6 in in length. Five layers of equal mass were used to compact the specimens to a target density. For each layer, a known mass of soil was compacted using static loading or impact loading (a certain number of drops of the Proctor hammer) to a volume that is controlled by the height of the compacted layer to produce desired density.

Three samples from each source at three moisture contents similar to the resilient modulus test samples were prepared using impact compaction (Proctor hammer); however, only one set of samples was prepared, at only OMC, for the static compactor.

California Bearing Ratio Test

During Phase II of the study, most soil samples were tested to determine the soaked CBR in accordance with Virginia Test Method (VTM) 8, Conducting California Bearing Ratio Test—(Soils Lab) (VDOT, 2007). This standard is similar to AASHTO T 193, Standard Method of Test for The California Bearing Ratio (AASHTO, 2010), and provides comparable results. A cylindrical soil sample 6 in by 6 in is compacted in a mold at OMC and MDD. This sample is axially loaded while still in the mold with a circular spindle of 3 in^2 area at a rate of 0.05 in/min. The CBR value (unsoaked) is calculated as the ratio of load (lbf) needed to have a 0.1-in penetration to 3,000 lbf, as a percentage. A soaked CBR is also determined similarly after the sample is soaked for 96 hr under water. VDOT conducts only soaked CBR tests, so soaked CBR values are included for information purposes.

Data Analysis

The main focus of the data analysis was to investigate a possible correlation between resilient modulus values and UC test results so that a suitable model could be found to estimate the resilient modulus. The basis for this investigation was the good relationship found between resilient modulus and quick shear test results in a previous study (Hossain, 2008). This relationship was first verified for Phase I and Phase II data. In addition, the influence of moisture and density on resilient modulus and UC test results was investigated to aid in correlation development. In addition to UC test results, soil index properties were used in a multiple regression analysis to determine if they improved the prediction capability with higher confidence.

Development of Resilient Modulus Prediction Model

To develop a meaningful prediction model, both UC and resilient modulus tests must be conducted on the same sample or on replicate samples. Considering the difficulty of producing a replicate sample, most researchers (Drumm et al., 1990; Lee et al., 1997; Thompson and Robnett, 1979) have used the same samples and subjected them to both tests, one after the other. The results presented in Figure 1 would be comparable to testing on the same sample. However, it is impractical to avoid the influences of one test on the other if the same sample is used. Therefore, two approaches were tried during this study.

1. *In the first approach, replicate sample testing was tried with limited success when static compaction was used.* Although the operational mode of the static compactor is such that it should easily achieve a certain density, it is difficult to match both moisture content (MC) and density at the same time.

2. *In the second approach, matching degrees of saturation was tried.* Since degree of saturation depends on both the MC and density of a soil sample, three samples were prepared using impact compaction (Proctor hammer) for UC tests at three different degrees of saturation. An interpolated value of unconfined compressive strength at the degree of saturation of the resilient modulus sample was used for the development of the model. It is important to note that achieved densities were always within ±5% of MDD; only moisture content was varied to achieve different degrees of saturation.

RESULTS AND DISCUSSION

Literature Review

A comprehensive synthesis of the literature pertaining to resilient modulus correlations can be found in the literature (Mokwa and Akin, 2009; Puppala, 2008). For reference, this section highlights some of the previous research attempts to establish correlations between resilient modulus and UC test results.

Lee et al. (1997) presented a simple relationship between conventional UC test results and the resilient modulus for fine cohesive soils. Three Indiana clayey soils with AASHTO soil classifications A-4/A-6 (CL), A-6 (CL), and A-7-6 (CH) underwent resilient modulus and UC tests with the same sample. Each sample was first subjected to 1% strain in UC before the resilient modulus test was conducted. For comparison purposes, the representative stress state for the resilient modulus was selected to be a 6 psi deviator stress with a 3 psi confining pressure. These resilient modulus values (M_r) showed strong correlation with the stresses at 1% strain ($S_{u1\%}$) from the UC test. Equation 2 represents the correlation, for which the coefficient of determination (R^2) = 0.97, irrespective of actual moisture content or compaction density.

$$M_r = 695.4 \times (S_{u1\%}) - 5.93 \times (S_{u1\%})^2 \qquad \text{[Eq. 2]}$$

Thompson and Robnett (1979) identified the soil properties that influence resilient behavior. Their study focused mainly on fine-grained soil from Illinois. The important soil properties considered in the study were soil classification, including soil index properties, CBR, and stress-strain behavior from the UC test. The degree of saturation was found to be one of the most statistically significant factors controlling the resilient behavior of the soil. The researchers developed correlations (Eqs. 3 and 4) to estimate the resilient modulus from the UC test results, with standard errors in the range of 1.5 to 3.5 ksi and coefficient of determination, R^2 from 0.47 to 0.53.

$$M_r \text{ (ksi)} = 3.49 + 1.9 \times \text{Initial tangent modulus} \qquad \text{[Eq. 3]}$$

$$M_r \text{ (ksi)} = 0.86 + 0.307 \times \text{Unconfined compressive strength} \qquad \text{[Eq. 4]}$$

Drumm et al. (1990) used 11 soils from Tennessee to develop the correlation in Equation 5 that estimates the resilient modulus from soil index properties, and strength and moduli obtained from the UC test. Six soils were classified as A-4 (3 CL, 1 SM-CL, and 2 ML); one as A-2-4 (SM), one as A-6 (CL), two as A-7-5 (MH), and one as A-7-6 (CL). Each soil was tested at two different degrees of saturation. A deviator stress of 6 psi and a confining stress of 0 were selected for the resilient modulus tests. It is important to note that UC tests were conducted on the same samples that had first been subjected to resilient modulus testing.

$$M_r \text{ (ksi)} = 45.8 + 0.00052(1/a) + 0.188(q_u) + 0.45(PI) - 0.216(\gamma_d) - 0.25(S) - 0.15(P_{200}) \qquad \text{[Eq. 5]}$$

where

Coefficient of determination, $R^2 = 0.83$
M_r (ksi) = resilient modulus value
a = initial tangent modulus of a stress-strain curve from UC tests (psi)
q_u = unconfined compressive strength (psi)
PI = plasticity index (%)
γ_d = dry unit weight (pcf)

S = degree of saturation (%)
P_{200} = percent passing the No. 200 sieve.

Drumm et al. (1990) developed another equation (Eq. 6) using the same resilient modulus test results with data for deviator stress ranging from 2.5 to 25 psi.

$$M_r \text{ (ksi)} = (a' + b'\sigma_d) / \sigma_d \qquad \text{[Eq. 6]}$$

where

Coefficient of determination, R^2, = 0.73

M_r (ksi) = resilient modulus value

$a' = 318.2 + 0.337(q_u) + 0.73(\%clay) + 2.26(PI) - 0.92(\gamma_d) - 2.19(S) - 0.304(P_{200})$, where q_u = unconfined compressive strength (psi), $\%clay$ = percent finer than 0.002 mm, PI = plasticity index (%), γ_d = dry unit weight (pcf), S = degree of saturation (%), P_{200} = percent passing the No. 200 sieve

$b' = 2.10 + 0.00039(1/a) + 0.104(q_u) + 0.09(LL) - 0.10(P_{200})$, where a = initial tangent modulus of a stress-strain curve from UC tests (psi), q_u = unconfined compressive strength (psi), LL = liquid limit (%), P_{200} = percent passing the No. 200 sieve

σ_d = deviator stress (psi).

Hossain et al. (2011) developed Equation 7 to estimate the resilient modulus using unconfined compressive strength data measured for 130 soil samples (AASHTO soil classifications A-4, A-6, and A-7-6) from Oklahoma.

$$M_r/P_a = 2494.2 + 0.6(PI) - 8.66(P_{200}) + 16.4(GI) + 165.53(MCR) - 1961(DR) + 185.29(q_u/P_a) \qquad \text{[Eq. 7]}$$

where

Coefficient of determination, R^2, = 0.44

M_r (kPa) = resilient modulus at a deviator stress of 41.34 kPa (6 psi) and a confining stress of 13.78 kPa (2 psi)

P_a = atmospheric pressure (kPa)

PI = plasticity index (%)

P_{200} = percent passing the No. 200 sieve

GI = group index

MCR = moisture content ratio (Moisture content/Optimum moisture content)

DR = density ratio (Dry density/Maximum dry density)

q_u = unconfined compressive strength (psi).

Louay et al. (1999) presented a study of eight soils from Louisiana to estimate the resilient modulus from soil properties, CBR, and unconfined compressive strength. Statistically, soil properties provided the best estimation. Unlike other research, this study estimated the regression coefficients of an octahedral stress state model to characterize the resilient modulus of subgrade soils. Their proposed stress-dependent universal constitutive model with the developed regression coefficients estimates resilient modulus. On the other hand, all other studies discussed, including the current study, focused on developing a model to estimate resilient modulus without considering the stress condition.

Laboratory Tests

Soil Index Properties, Moisture-Density Relationship, and CBR

Soil classification, specific gravity, moisture-density relationship (standard Proctor test), and CBR test results for Phase I and II soil samples are presented in Table 2. The standard Proctor test was used to determine OMC and MDD from the moisture-density relationship.

Resilient Modulus

All samples were tested in accordance with AASHTO T 307 (AASHTO, 2010). Although the target compacted dry density for all samples was 100% MDD in accordance with the standard Proctor test, all samples actually achieved above 95%. Samples were prepared at three moisture contents using static compaction during Phase I of the study, but only OMC was used in Phase II. As mentioned earlier, data were fit into the universal constitutive model (Eq. 1), which was used instead of directly measured values to calculate resilient modulus values for further correlation analysis.

This constitutive model, like others, is stress dependent, and stress calculation is dependent on the pavement structure, traffic load, and the subgrade resilient modulus itself. This iterative process is conveniently carried out internally in the software for MEPDG Level 1 design/analysis. But MEPDG Level 2 and Level 3 design/analysis, which are used in the implementable version of the MEPDG (AASHTOWare Pavement ME Design) (AASHTO, n.d.), and the 1993 AASHTO design guide (AASHTO, 1993) require a specific resilient modulus value as an input; this value is selected independent of stress condition. Therefore, it is necessary to estimate stresses to calculate the resilient modulus for further analysis for the benefit of using estimated values in accordance with MEPDG Level 2 and Level 3 design/analysis and the 1993 AASHTO design guide. Layered elastic analysis could be used to estimate in situ stresses if the pavement structure is known, but the selection of pavement structure depends on the resilient modulus of the subgrade. As explained by Hossain (2008), a confining pressure of 2 psi and a deviator stress of 6 psi are suggested by many researchers and were used in this study.

Table 2. Soil Index Properties, Moisture-Density Relationship (Standard Proctor Test), and CBR Results

Soil Source	Soil Classification: AASHTO (GI)	Soil Classification: USCS	Specific Gravity	Plasticity Index (PI)[a]	% Passing No. 200 Sieve	Optimum Moisture Content (%)	Maximum Dry Density (lb/ft^3)	96-hr Soaked CBR (%)
Phase I								
FS-5	A-4(2)	SC	2.862	9.8	47.2	21.5	102.7	-
FS-2	A-4(3)	ML	2.820	NP	52.5	16.5	109.8	-
FS-6	A-6(5)	CL	2.630	15.5	51.9	15.9	112.1	-
FS-4	A-7-5(12)	MH	2.837	10.8	78.2	28.2	91.25	-
FS-1	A-7-5(25)	CH	2.734	35.3	72.0	23.6	101.1	-
FS-3	A-7-6(41)	CH	2.773	43.5	83.5	33.75	86.4	-
Phase II								
57-80488	A-1-b(0)	SM	-	NP	19.2	7.2	132.7	25.2
9-116-11	A-2-4(0)	SM	2.679	NP	24.3	13.5	114.2	32.8
9-150-11	A-2-4(0)	SM	2.607	NP	21.8	12.3	112.5	46.2
54-104-11	A-2-4(0)	SC-SM	2.670	4.7	34.0	10.7	123.4	10.2
57-80478	A-2-4(0)	SC-SM	2.706	5	25.5	10.2	124.1	16.0
57-80477	A-2-6(1)	SC	2.707	13	33.6	10.2	124.1	2.7
9-486-11	A-4(0)	SM	2.737	NP	43.3	11.8	122.1	15.5
54-111-11	A-4(0)	SM	2.668	NP	37.1	10	125.2	11.5
57-80489	A-4(0)	SM	2.693	NP	35.8	11.4	120.4	12.3
57-80325	A-4(0)	ML	2.755	NP	68.8	15.8	109.8	3.9
57-80484	A-4(0)	ML	2.647	NP	52.1	11.2	119.8	1.4
54-113-11	A-4(5)	ML	2.675	10.2	62.0	16.7	108.9	8.8
57-80320	A-5(2)	ML	2.791	NP	73.4	19.2	104.7	2.2
53-25933	A-5(6)	MH	2.735	4	61.3	26.2	93.9	-
9-46-11	A-6(1)	SC	2.692	12.2	40.1	11.9	119.9	15.0
54-107-11	A-6(4)	CL	2.646	15.2	51.3	13	118.1	4.7
57-80483	A-6(5)	SC	-	19	45.7	11.1	122.3	7.6
57-80308	A-6(6)	SC	2.702	21	48.3	13.6	116.9	9.1
11RZ06	A-6(8)	CL	2.656	18	60.2	15.4	109.7	7.7
11RY03	A-6(9)	CL	2.741	16	64	19.5	106.7	4.7
11VVB04	A-6(10)	CL	2.743	18	66.4	15.4	116.2	3.3
57-80321	A-7-5(12)	ML	2.795	12	79.4	21.9	99.8	5.5
57-80322	A-7-5(29)	MH	2.789	25	87.8	24.7	95.8	6.2
54-99-11	A-7-6(13)	CH	2.677	23.8	60.5	20	103.3	11.3
11ML05	A-7-6(16)	CL	-	27	65.4	20.2	105.7	3.8
54-112-11	A-7-6(19)	CL	2.893	20.1	87.6	18.9	106	1.6
57-80319	A-7-6(25)	CH	2.795	29	79.4	27.3	93.5	6.9
57-80309	A-7-6(27)	CH	2.721	37	74.6	19.4	106.3	2.5
57-80307	A-7-6(30)	CH	2.731	39	74.6	23.3	97.4	2.9

AASHTO = American Association of State Highway & Transportation Officials; GI = Group Index;
USCS = Unified Soil Classification System.
[a] NP = non-plastic soil, and PI = 0 is assumed for the regression analysis.

Calculated resilient modulus values for samples from Phases I and II are presented in Table 3. The degree of saturation and the respective moisture content, dry density, and specific gravity are also presented. The stresses at 0.1% strain were determined from the stress-strain curve developed during quick shear tests of the same samples and are included in Table 3.

Table 3. Resilient Modulus Along With Quick Shear Test Results

Soil Source	Soil Type, AASHTO (GI)/USCS	Compaction Moisture Content (%)	Density, % MDD	Degree of Saturation, S (%)	Measured Resilient Modulus Value (psi)[a]	Stress at 0.1% Strain (psi)[b]
Phase I						
FS-5	A-4(2)/SC	21.3	98.6	80.0	4,045	4.2
FS-2	A-4(3)/ML	16.3	95.2	66.9	3,473	4.1
FS-6	A-6(5)/CL	15.4	98.9	84.4	15,243	11.9
FS-4	A-7-5(12)/MH	27.8	97.1	97.1	7,176	5.9
FS-1	A-7-5(25)/CH	23.8	97.3	88.4	10,445	8.0
FS-3	A-7-6(41)/CH	34.5	97.6	91.0	11,050	8.8
Phase II						
57-80488	A-1-b(0)/SM	8.2	95.3	80.8	8,912	9.1
9-116-11	A-2-4(0)/SM	14.2	97.0	74.8	7,847	7.7
9-150-11	A-2-4(0)/SM	12.4	96.3	64.4	7,147	7.7
54-104-11	A-2-4(0)/SC-SM	10.5	98.1	74.6	8,990	8.2
57-80478	A-2-4(0)/ C-SM	9.5	99.0	68.5	12,172	10.0
57-80477	A-2-6(1)/SC	10.3	99.0	74.2	7,070	7.3
9-486-11	A-4(0)/SM	11.4	98.4	74.1	13,310	10.6
54-111-11	A-4(0)/SM	10.2	97.8	75.8	8,480	8.6
57-80489	A-4(0)/SM	12.3	98.0	70.4	8,311	7.9
57-80325	A-4(0)/ML	15.7	97.1	70.6	7,112	6.1
57-80484	A-4(0)/ML	12.1	99.8	77.3	5,945	6.2
54-113-11	A-4(5)/ML	16.1	98.1	76.5	11,572	9.2
57-80320	A-5(2)/ML	19.6	95.4	73.6	6,688	6.0
53-25933	A-5(6)/MH	25.4	97.6	80.5	7,316	6.1
9-46-11	A-6(1)/SC	11.9	98.5	75.8	11,001	9.3
54-107-11	A-6(4)/CL	12.4	98.9	79.3	13,417	10.7
57-80483	A-6(5)/SC	11.1	97.6	83.1	13,515	10.7
57-80308	A-6(6)/SC	12.8	99.3	76.5	16,322	12.5
11RZ06	A-6(8)/CL	14.7	99.3	74.8	12,004	9.8
11RY03	A-6(9)/CL	19.2	98.8	84.5	10,511	8.2
11VVB04	A-6(10)/CL	15	98.5	83.1	15,972	14.4
57-80321	A-7-5(12)/ML	21.1	97.6	74.6	9,539	7.6
57-80322	A-7-5(29)/MH	25.1	96.9	80.0	13,816	11.7
54-99-11	A-7-6(13)/CH	19.4	98.7	81.4	16,789	13.3
11ML05	A-7-6(16)/CL	20.1	98.3	87.3	16,115	13.1
54-112-11	A-7-6(19)/CL	18.2	98.8	72.7	15,397	12.1
57-80319	A-7-6(25)/CH	28.5	100.7	93.6	13,964	9.9
57-80309	A-7-6(27)/CH	19.5	97.8	83.9	18,340	16.1
57-80307	A-7-6(30)/CH	22.1	99.2	79.0	15,148	13.8

AASHTO = American Association of State Highway & Transportation Officials; GI = Group Index; USCS = Unified Soil Classification System; MDD = maximum dry density.
[a]Confining pressure = 2 psi; cyclic deviator stress = 6 psi.
[b]Stress from quick shear test performed at end of resilient modulus test in accordance with AASHTO T 307 (AASHTO, 2010).

Unconfined Compression Test

The UC test was conducted on the soil samples for Phases I and II. A stress-strain diagram was produced as part of the results. The stress-strain diagram was corrected for the initial concave portion of the curve as shown in Figure 1, which is thought to be the effect of sample preparation, loading surface irregularity, and seating loads. The initial tangent modulus was calculated as the slope of the tangent to the initial straight portion of the corrected curve drawn through the origin. Finally, the failure strength is noted as the conventional result of a standard UC test. The stress-strain behavior was influenced by the sample preparation method such as static versus impact compaction and respective data were considered and analyzed separately. The VDOT soils lab used the same static compaction as in the resilient modulus test to prepare samples at OMC and 100% MDD. The actual moisture content and density and the UC test results for samples prepared with a static compactor are presented in Table 4.

The VCTIR lab produced three samples for each source using impact compaction (Proctor hammer) at three moisture contents but at the same target 100% MDD to produce a range of degrees of saturation from 50% to 100%. The results for these samples are presented in Table 5.

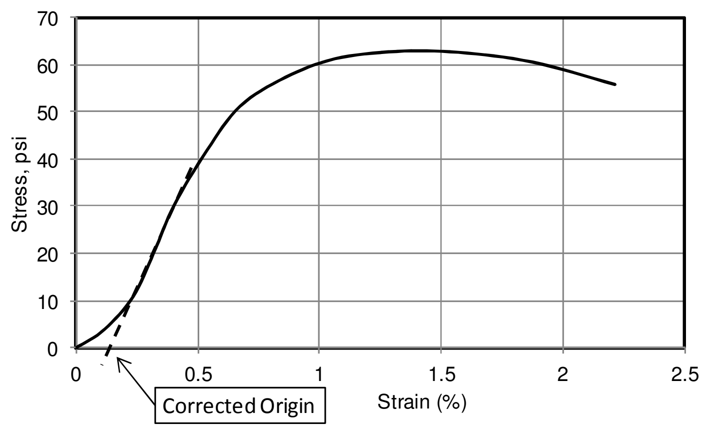

Figure 1. Correction of Stress-Strain Diagram From Unconfined Compression Test

Data Analysis

Relationship Between Resilient Modulus and Quick Shear Tests

The quick shear test, a triaxial test run in the static mode as part of AASHTO T 307 (AASHTO, 2010), was performed at the end of the resilient modulus test on the same sample without removing it from the test platen. These tests were performed by the VDOT soils lab. The stresses at 0.1% strain from the quick shear test were strongly correlated with the resilient modulus values (at a confining stress of 2 psi and a deviator stress of 6 psi), similar to findings in a previous study (Hossain, 2008). Correlations for Phases I and II are shown in Figure 2. The strong correlations ($R^2 > 0.9$) indicate a good possibility that resilient modulus values can be predicted from an independently run static triaxial test such as the UC test.

Table 4. Unconfined Compression Test Results for Static Compaction Samples

Soil Source	Soil Type, AASHTO (GI)/USCS	Compaction Moisture (%)	Density, % MDD	S (%)	Initial Tangent Modulus (psi)	Stress at 1.0% Strain (psi)	Failure Strength (psi)
Phase I							
FS-5	A-4(2)/SC	21.1	95.5	73.6	1,660	12.0	24.6
FS-2	A-4(3)/ML	15.8	95.4	65.5	600	7.0	14.7
FS-6	A-6(5)/CL	15.0	99.1	82.7	7,000	43.0	53.3
FS-4	A-7-5(12)/MH	29.1	96.0	80.9	1,655	19.5	33.4
FS-1	A-7-5(25)/CH	23.4	97.7	88.0	5,640	40.0	65.8
FS-3	A-7-6(41)/CH	33.4	98.3	89.2	6,000	38.5	52.3
Phase II							
57-80488	A-1-b(0)/SM	7.9	95.9	80.6	2,400	12.9	13.0
9-116-11	A-2-4(0)/SM	14.1	96.8	73.8	695	7.0	10.1
9-150-11	A-2-4(0)/SM	12.2	96.8	64.4	306	3.9	6.1
54-104-11	A-2-4(0)/SC-SM	10.8	98.3	77.3	1,581	15.5	20.7
57-80478	A-2-4(0)/SC-SM	9.8	98.5	69.4	1,800	23.0	29.3
57-80477	A-2-6(1)/SC	9.7	99.0	70.1	797	7.7	8.4
9-486-11	A-4(0)/M	11.0	98.6	72.0	4,865	49.0	64.7
54-111-11	A-4(0)/SM	10.0	97.9	74.4	1,440	17.2	23.9
57-80489	A-4(0)/SM	12.3	95.1	70.8	1,433	15.3	24.6
57-80325	A-4(0)/ML	16.1	104.7	89.6	3,856	17.0	30.0
57-80484	A-4(0)/ML	12.0	96.9	75.2	753	6.3	6.9
54-113-11	A-4(5)/ML	16.8	97.3	78.0	1,956	26.0	45.5
57-80320	A-5(2)/ML	19.7	95.5	74.2	1,096	18.0	27.1
53-25933	A-5(6)/MH	26.0	97.4	82.1	1,046	17.3	31.1
9-46-11	A-6(1)/SC	12.0	98.0	75.2	2,088	24.0	37.1
54-107-11	A-6(4)/CL	13.0	98.0	80.5	2,500	28.0	42.4
57-80483	A-6(5)/SC	10.5	98.2	80.5	3,850	44.0	53.6
57-80308	A-6(6)/SC	13.1	98.9	77.3	3,334	26.7	33.6
11RZ06	A-6(8)/CL	14.0	99.3	71.2	3,211	33.5	41.8
11RY03	A-6(9)/CL	18.0	99.3	80.3	1,918	22.0	34.3
11VVB04	A-6(10)/CL	15.0	98.5	82.9	8,936	65.0	92.4
57-80321	A-7-5(12)/ML	22.5	95.9	76.4	1,101	15.5	25.1
57-80322	A-7-5(29)/MH	24.7	96.8	78.5	3,097	43.0	66.5
54-99-11	A-7-6(13)/CH	20.0	98.5	83.4	9,600	39.0	50.9
11ML05	A-7-6(16)/CL	20.0	98.2	86.7	3,977	43.0	60.3
54-112-11	A-7-6(19)/CL	18.5	98.3	73.1	4,600	33.0	48.8
57-80319	A-7-6(25)/CH	27.0	102.4	91.8	2,857	22.0	38.2
57-80309	A-7-6(27)/CH	20.0	97.5	85.3	6,660	49.0	66.8
57-80307	A-7-6(30)/CH	23.0	98.5	81.0	7,100	44.5	52.8

AASHTO = American Association of State Highway & Transportation Officials; GI = Group Index; USCS = Unified Soil Classification System; MDD = maximum dry density; S = degree of saturation.

Table 5. Unconfined Compression Test Results for Impact Compaction Samples

Soil Source	Soil Type, AASHTO (GI)/USCS	Compaction Moisture Content (%)	Density, % MDD	Degree of Saturation, S (%)	Failure Strength, Q_u (psi)	Regression R^2 (Q_u vs. S%)
Phase I						
FS-5 Stadium	A-4(2)/SC	18.5	98.0	68.4	25.7	1.00
		22.1 (OMC 21.5)	96.7	79.3	26.4	
		24.6	95.5	85.9	17.0	
FS-2 Culpeper	A-4(3)/ML	16.7 (OMC 16.5)	98.2	74.1	17.5	0.99
		19.7	95.7	82.0	11.6	
		21.1	94.4	85.0	8.7	
FS-6 Hampton	A-6(5)/CL	12.0	92.3	53.9	66.0	0.94
		16.0 (OMC 15.9)	98.8	87.2	83.4	
		17.5	98.4	94.3	60.1	
FS-4 NOVA	A-7-5(12)/MH	22.8	101.9	72.1	51.7	0.99
		27.1 (OMC 28.2)	102.7	87.4	42.0	
		30.8	99.0	92.0	20.6	
FS-1 Amherst	A-7-5(25)/CH	18.2	99.8	92.3	33.3	0.94
		23.4 (OMC 23.6)	96.2	98.8	78.0	
		27.3	97.5	68.0	39.2	
FS-3 Salem	A-7-6(41)/CH	26.5	99.7	72.9	104.8	0.86
		32.6 (OMC 33.75)	102.5	95.0	65.5	
		35.4	99.0	96.0	34.7	
Phase II						
9-116-11	A-2-4(0)/SM	10.5	98.4	57.9	17.8	0.96
		12.9 (OMC 13.5)	99.6	73.6	14.8	
		14.9	99.7	85.4	13.7	
54-104-11	A-2-4(0)/SC-SM	9.6	99.2	70.9	37.0	0.99
		10.8 (OMC 10.7)	100.3	83.4	24.6	
		12.3	99.4	91.5	18.9	
57-80478	A-2-4(0)/SC-SM	7.9	100.2	59.7	65.3	0.91
		10.7 (OMC 10.2)	98.7	76.9	19.0	
		12.1	98.5	86.0	17.0	
57-80477	A-2-6(1)/SC	8.0	101.4	63.1	19.0	0.96
		9.9 (OMC 10.2)	101.3	78.0	11.0	
		11.8	99.3	86.4	9.4	
54-111-11	A-4(0)/SM	7.9	94.6	52.0	35.7	0.89
		9.9 (OMC 10)	100.3	80.7	28.6	
		12.3	98.7	94.2	17.4	
57-80489	A-4(0)/SM	11.0 (OMC 11.4)	102.7	73.6	50.5	0.97
		12.8	103.4	87.5	32.8	
		15.3	99.6	92.2	21.0	
57-80325	A-4(0)/ML	13.6	99.3	65.0	32.7	1.00
		16.0 (OMC 15.8)	99.7	77.3	27.4	
		18.9	98.3	87.6	23.7	
57-80484	A-4(0)/ML	10.4	106.6	84.7	22.1	0.67
		12.0 (OMC 11.2)	103.9	88.4	10.3	
		14.1	101.2	94.4	9.6	
54-113-11	A-4(5)/ML	14.6	105.5	85.9	93.4	0.81
		16.6 (OMC 16.7)	102.1	88.8	51.9	
		17.3	101.9	91.9	46.7	
57-80320	A-5(2)/ML	15.8	96.9	61.7	34.1	0.65
		19.1 (OMC 19.2)	97.9	76.4	26.3	
		22.0	98.0	88.2	27.8	
53-25933	A-5(6)/MH	21.7	100.3	73.2	44.9	0.72
		27.3 (OMC 26.2)	98.3	87.9	26.7	
		27.3	100.6	92.5	32.6	
9-46-11	A-6(1)/SC	9.9	99.7	65.7	62.8	0.98
		12.2 (OMC 11.9)	100.8	84.0	36.5	
		13.4	99.2	87.8	36.5	

Soil Source	Soil Type, AASHTO (GI)/USCS	Compaction Moisture Content (%)	Density, % MDD	Degree of Saturation, S (%)	Failure Strength, Q_u (psi)	Regression R^2 (Q_u vs. S%)
54-107-11	A-6(4)/CL	9.9	99.8	65.1	77.2	0.96
		12.8 (OMC 13.0)	100.7	86.8	46.1	
		13.5	100.4	91.1	29.3	
11RY03	A-6(9)/CL	15.7	99.5	70.4	42.8	1.00
		17.4	101.5	82.4	36.2	
		19.6 (OMC 19.5)	101.9	93.8	29.1	
11VVB04	A-6(10)/CL	13.6	99.3	77.1	88.1	0.47
		15.3 (OMC 15.4)	102.5	95.8	75.4	
		17.1	98.9	95.6	37.3	
57-80321	A-7-5(12)/ML	18.5	99.7	68.6	33.8	0.28
		21.9 (OMC 21.9)	98.3	78.6	23.2	
		23.8	99.7	88.2	28.3	
57-80322	A-7-5(29)/MH	19.1	97.4	61.6	75.7	0.91
		24.2 (OMC 24.7)	98.5	80.0	61.8	
		28.0	96.2	87.8	43.5	
54-112-11	A-7-6(19)/CL	16.2	105.2	75.6	81.3	0.99
		18.2 (OMC 18.9)	104.3	83.4	52.1	
		20.3	101.1	86.0	35.8	
57-80309	A-7-6(27)/CH	16.8	101.2	79.1	84.7	0.97
		18.3	101.0	85.7	81.4	
		19.8 (OMC 19.4)	104.0	100.4	77.5	
57-80307	A-7-6(30)/CH	17.9	99.7	64.7	64.6	0.99
		22.4 (OMC 23.3)	102.6	87.0	49.4	
		25.1	101.6	94.7	41.0	

AASHTO = American Association of State Highway & Transportation Officials; GI = Group Index;
USCS = Unified Soil Classification System; MDD = maximum dry density; OMC = optimum moisture content.

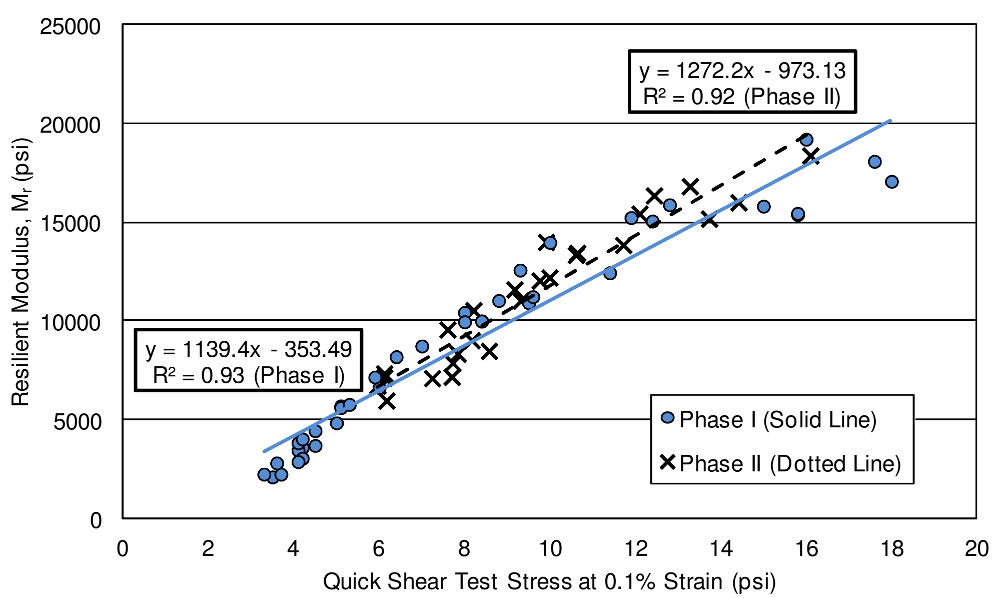

Figure 2. Relationship Between Resilient Modulus and Stress at 0.1% Strain From Quick Shear Test

Influence of Moisture and Density on Resilient Modulus

In previous studies, Hossain (2008, 2010) found that both moisture and density affect the resilient modulus value of a soil sample. In Phase I, three samples from each source were compacted to a target of 100% MDD with three different moisture contents, resulting in three different degrees of saturation, and tested for resilient modulus. Results are presented in the Phase I report (Hossain, 2010), which includes the degree of saturation and the measured resilient modulus at a confining stress of 2 psi and a cyclic deviator stress of 6 psi. The achieved densities were above 95% of MDD in most cases. Since the degree of saturation incorporates moisture and density into one parameter, it was calculated for each sample to investigate the influence on resilient modulus measurements. The expected trend of lower resilient modulus values for a higher degree of saturation was seen in all cases, but some cases showed a stronger correlation than others. Figure 3 shows the trend for fine-grained soils from Phase I; all samples had a very strong correlation except for those from one source. It is important to note that these relationships are unique for a particular soil for a specified compaction effort. Resilient modulus was measured in two laboratories and there were differences between the measurements, but the influence of moisture was similar, as shown in Figure 3 (Hossain, 2010).

During Phase II of the study, only one sample was prepared per source, so the influence of moisture on the resilient modulus could not be verified. However, other researchers (Thompson and Robnett, 1979) found a similar effect of moisture and density as measured by the degree of saturation.

Influence of Moisture and Density on Unconfined Compression Test Results

The effect of moisture and density on the UC test results was also evaluated for samples prepared using impact compaction (Proctor hammer) during Phase I, and the results are presented in the Phase I study (Hossain, 2010). As mentioned earlier, the combined effect of moisture and density on the ultimate compressive (failure) strength was investigated using the degree of saturation. Again, the target density was 100% of MDD, but achieved densities were within ±5%. In general, a linear decreasing value of strength with increasing degree of saturation was found, similar to the resilient modulus variation.

During Phase II, samples from only a few sources were prepared and tested at three moisture contents using impact compaction (Proctor hammer). Similar to Phase I, the effect of the degree of saturation on ultimate compressive strength was investigated, and the resulting plots are provided in the Appendix; only R^2 values from the regression analysis are presented in Table 5. Unconfined compressive strength decreased with increasing degrees of saturation; correlations between them were very strong ($R^2 > 0.9$) except for a few samples that were mostly silty soils. In general, silty soils are difficult to prepare as unconfined samples because of low cohesion and they show relatively less sensitivity to moisture for unconfined compressive strength.

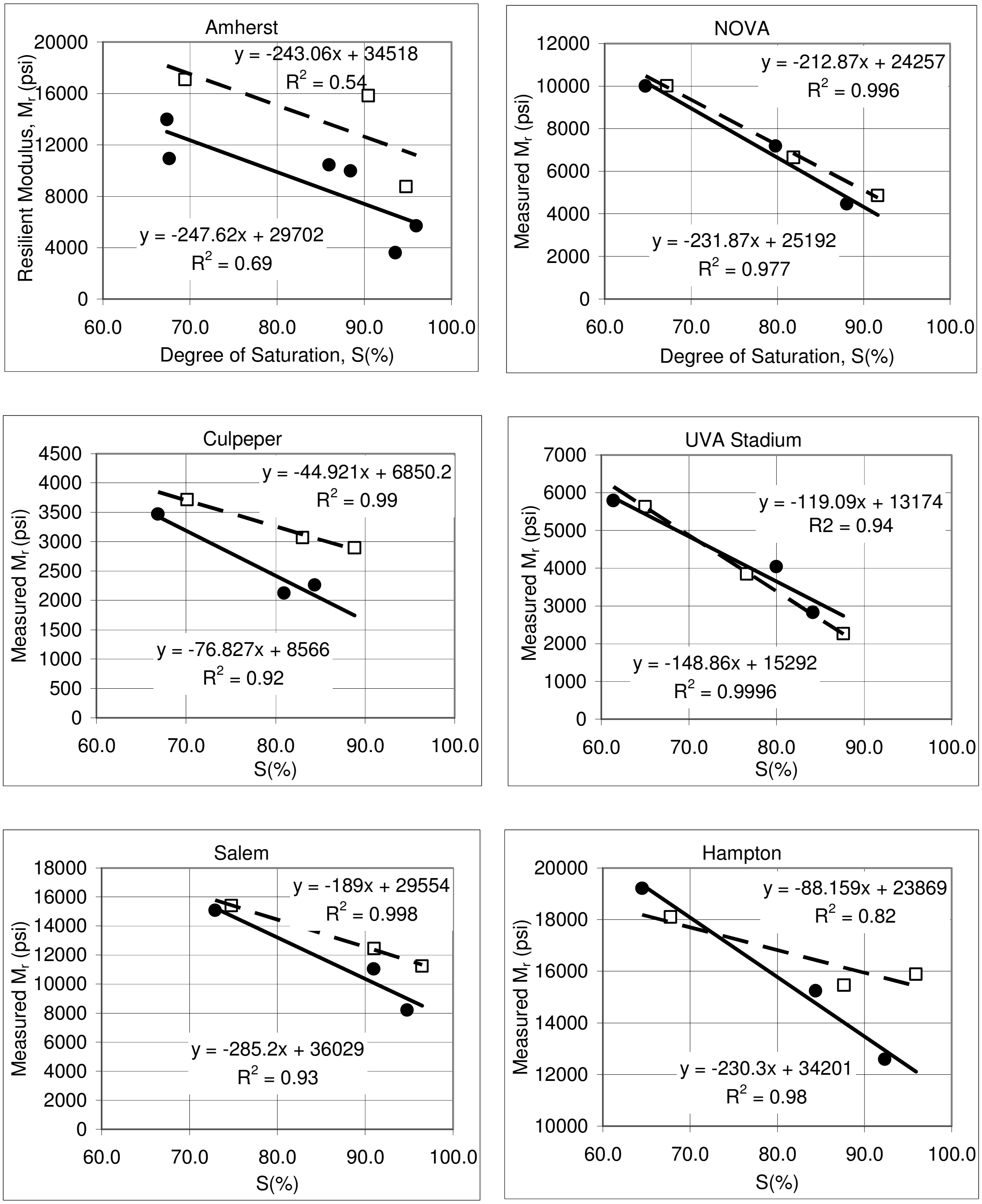

Figure 3. Influence of Moisture Content on Resilient Modulus of Fine-Grained Soil. Solid line = values measured by VDOT soils lab; dotted line = values measured by outside vendor. NOVA = Northern Virginia; UVA = University of Virginia.

Effect of Sample Preparation on Results of Unconfined Compression Tests

The stress-strain behavior and ultimate failure strength from UC tests were influenced by the sample preparation method. During the Phase I study (Hossain, 2010), the Harvard compaction samples, which used static compaction, showed somewhat higher strength compared to both static and impact samples. Lee et al. (1997) also found that the sample preparation technique or effort has a noticeable effect on measured soil strength and/or stiffness.

The unconfined compressive strengths of impact and static compaction samples were compared during Phase II at a matching degree of saturation. As mentioned earlier, only one set of samples per source was prepared using static compaction but three samples per source were prepared using impact compaction at three moisture contents. As such, the static samples had only 1 degree of saturation whereas the impact samples had 3. Therefore, data interpolation was used for the impact compaction samples to select a strength value at the matching degree of saturation from a plot of strength versus degree of saturation; the plots are provided in the Appendix. Unconfined compressive strength values at the same (matching) degree of saturation from both sample preparation techniques are summarized in Table 6 and compared in Figure 4.

Table 6. Unconfined Compressive Strengths for Static and Impact Compaction Samples

Soil Source	Soil Type, AASHTO (GI)/USCS	Degree of Saturation, S (%)	Unconfined Compressive Strength (psi)	
			Static Compaction	Impact Compaction
57-80488	A-1-b(0)/SM	80.6	13.0	-
9-116-11	A-2-4(0)/SM	73.8	10.1	15.0
9-150-11	A-2-4(0)/SM	64.4	6.1	-
54-104-11	A-2-4(0)/SC-SM	77.3	20.7	33.3
57-80478	A-2-4(0)/SC-SM	69.4	29.3	44.9
57-80477	A-2-6(1)/SC	70.1	8.4	13.9
9-486-11	A-4(0)/SM	72.0	64.7	-
54-111-11	A-4(0)/SM	74.4	23.9	27.2
57-80489	A-4(0)/SM	70.8	24.6	56.0
57-80325	A-4(0)/ML	89.6	30.0	30.3
57-80484	A-4(0)/ML	75.2	6.9	28.0
54-113-11	A-4(5)/ML	78.0	45.5	159.3[a]
57-80320	A-5(2)/ML	74.2	27.1	29.8
53-25933	A-5(6)/MH	82.1	31.1	37.9
9-46-11	A-6(1)/SC	75.2	37.1	49.6
54-107-11	A-6(4)/CL	80.5	42.4	53.7
57-80483	A-6(5)/SC	80.5	53.6	-
57-80308	A-6(6)/SC	77.3	33.6	-
11RZ06	A-6(8)/CL	71.2	41.8	-
11RY03	A-6(9)/CL	80.3	34.3	34.7
11VVB04	A-6(10)/CL	82.9	92.4	77.8
57-80321	A-7-5(12)/ML	76.4	25.1	29.5
57-80322	A-7-5(29)/MH	78.5	66.5	56.3
54-99-11	A-7-6(13)/CH	83.4	50.9	-
11ML05	A-7-6(16)/CL	86.7	60.3	-
54-112-11	A-7-6(19)/CL	73.1	48.8	94.4
57-80319	A-7-6(25)/CH	91.8	38.2	-
57-80309	A-7-6(27)/CH	85.3	66.8	82.7
57-80307	A-7-6(30)/CH	81.0	52.8	54.1

AASHTO = American Association of State Highway & Transportation Officials; GI = Group Index; USCS = Unified Soil Classification System.
[a] Value was extrapolated. All other values were interpolated based on degree of saturation.

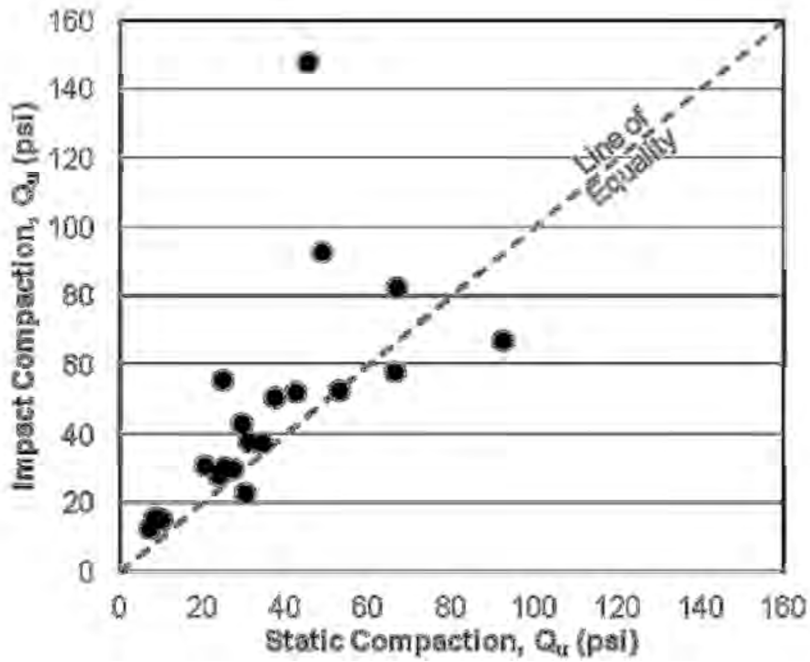

Figure 4. Comparison of Strength Between Impact- and Static-Compacted Samples for Phase II

Samples prepared with the impact compaction method were always stronger than samples prepared with the static compaction method; the reason two impact compaction samples had very high values in Figure 4 could not be determined, but it may be partially attributable to the extrapolation of data. It is also important to note that samples for static and impact compaction were prepared and tested at two laboratories: the VDOT soils lab and the VCTIR lab, respectively.

Resilient Modulus Prediction Models

Model Based on Initial Tangent Modulus

The strong correlation, as shown in Figure 2, between resilient modulus and the stresses at 0.1% strain from the quick shear (triaxial) test (conducted on the same sample) indicates the possibility of predicting resilient modulus from the initial tangent modulus derived from a UC test (conducted on a replicate sample) of fine-grained soil. Both the initial tangent modulus and the stresses at 0.1% strain represent the initial stress-strain behavior of the soil sample. The initial modulus was calculated as the tangent slope of the initial portion of the stress-strain curve from the UC test. The initial tangent modulus for both impact and static compaction samples showed a very strong correlation with the resilient modulus during the Phase I study (Hossain, 2010). However, only six points (sources) were used to develop these models, so they needed to be updated or verified as more data became available.

Therefore, during Phase II of the study, the correlation with the initial tangent modulus was investigated again with the new set of data, but no definitive relationship was found. As more data were collected, the subjectivity in determining the initial tangent modulus became apparent and was thought to have influenced the correlation shown in Figure 5. Some judgments were applied to correct the initial readings (which included corrections for concave curvature, negative numbers, and irregular points) and a corrected initial modulus was calculated; both sets of data are shown in Figure 5. This kind of interpretation to determine the initial modulus seems cumbersome for routine field or laboratory operations. Moreover, accurate measurement of the stress-strain response is very difficult at such a low level of strain. Initial responses could also be influenced by surface irregularities and initial seating at the top and bottom of samples. These were not the case when the same sample was used for both tests in the correlation analysis by other researchers (Drumm et al., 1990; Lee et al., 1997). So the ultimate compressive strength, a definitive result of the test that does not require any subjective evaluation, was used as the independent variable in the regression analysis to predict the resilient modulus.

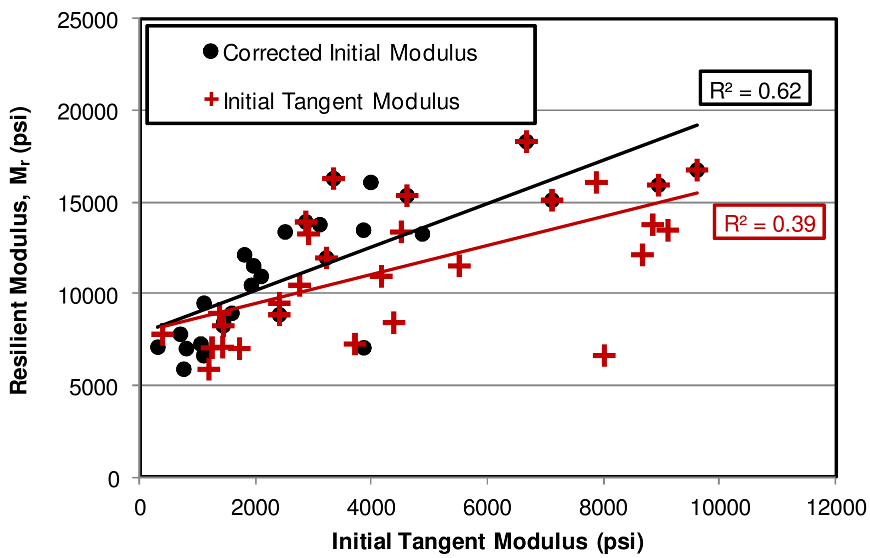

Figure 5. Relationship Between Resilient Modulus and (Uncorrected and Corrected) Initial Tangent Modulus From Unconfined Compression Tests

Model Based on Unconfined Compressive Strength

Prediction models were evaluated for unconfined compressive strength from the impact and static compaction samples. It is important to note that resilient modulus data were available from static compaction samples only and were used for both analyses. The unconfined compressive strength and resilient modulus were selected based on matching the degree of saturation for the impact compaction sample model. On the other hand, only one set of data at OMC was available for static compaction samples so the degree of saturation did not always match. Fair correlations were found for both models, with an R^2 of 0.66 and 0.73 for the static and impact samples, respectively. Both models are presented in Figure 6. The statistics for the regression analysis are summarized in Table 7. Both models showed strong correlation and all the coefficients for the variables were statistically significant ($p < 0.05$). The standard errors for the static and impact models were 2,159 psi and 1,963 psi, respectively.

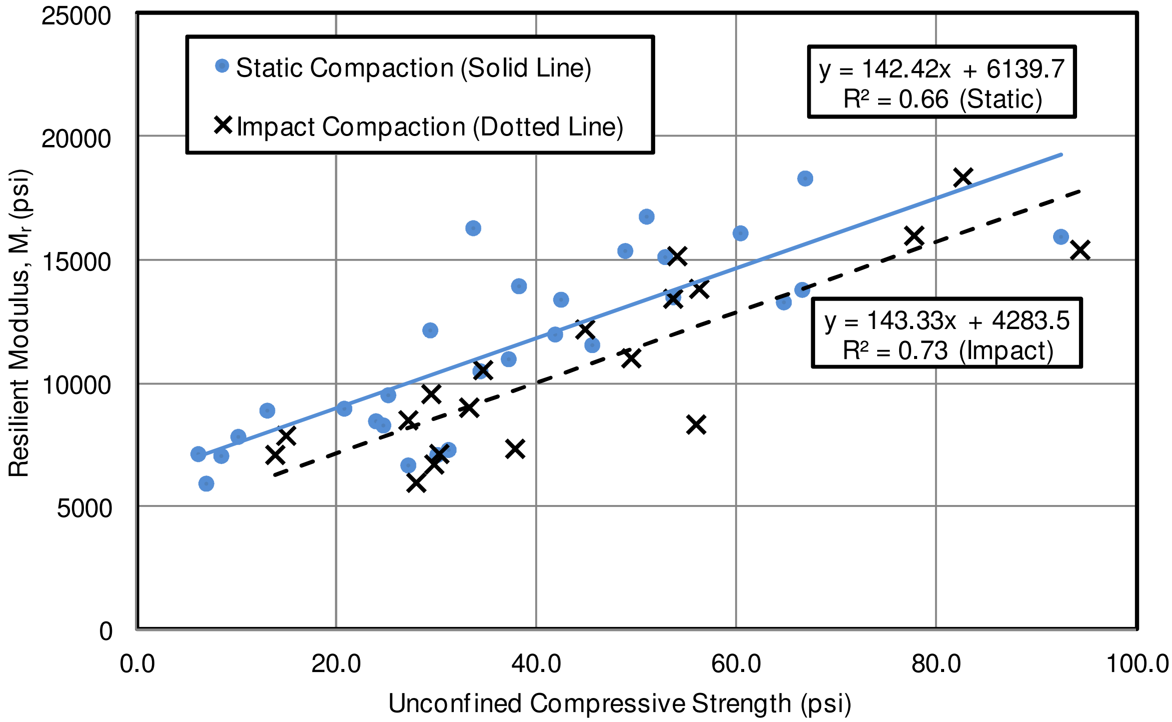

Figure 6. Correlation of Resilient Modulus and Unconfined Compressive Strength

Table 7. Regression Statistics for Unconfined Compressive Strength Model

Statistic	Static Compaction Model	Impact Compaction Model
Model Parameters: M_r = resilient modulus (psi) Q_u = ultimate compressive strength (psi)	$M_r = 6082 + 142 \times (Q_u)$	$M_r = 4283 + 143 \times (Q_u)$
Coefficient of determination, R^2	0.64	0.73
Adjusted R^2	0.62	0.71
No. of observations	26	19
Intercept	Non-zero	Non-zero
Standard error	2263	1963
Significance of model and coefficients at 5% level	Yes	Yes

Model Based on Unconfined Compressive Strength and Soil Index Properties

A fair correlation with ultimate compressive strength was observed, as reported in the preceding sections. In order to improve the predictability or strength of a model, other soil properties, such as the plasticity index (PI) and percent passing the No. 200 sieve, were tried in multiple regression analyses. For non-plastic soils, a value of zero was used for PI in the regression analysis. There is a good indication of the influence of these properties on the resilient modulus in literature (Drumm et al., 1990; Thompson and Robnett, 1979). Both of these properties along with ultimate compressive strength have improved the strength of the model in a multiple regression analysis; R^2 increased from 0.66 to 0.86 for a static compaction model and from 0.73 to 0.91 for an impact compaction (Proctor hammer) model. The standard errors of the estimate for the static and impact models were 1,423 psi and 1,225 psi, respectively. The important statistics of regression analysis are presented in Table 8.

Table 8. Statistics for Multiple Regression Model

Statistic	Static Compaction Model	Impact Compaction Model
Model Parameters: M_r = resilient modulus (psi) Q_u = ultimate compressive strength (psi) PI = plasticity index (non-plastic soil, PI = 0) P_{200} = % passing No. 200 sieve	$M_r = 7884.2 + 99.7 \times (Q_u) + 193.1 \times PI - 47.9 \times P_{200}$	$M_r = 6113.0 + 95.1 \times (Q_u) + 173.7 \times PI - 27.8 \times P_{200}$
Coefficient of determination, R^2	0.86	0.91
Adjusted R^2	0.85	0.89
No. of observations	29	19
Intercept	Non-zero	Non-zero
Standard error	1423	1225
Significance of model and coefficients at 5% level	Yes	Yes, except P_{200}. It is significant at 12% level.

Model Based on Stresses at 1.0% Strain From UC Test

Among other models tried by the researchers, estimation of resilient modulus from stresses ($S_{u1\%}$) at 1.0% strain of a UC test was the best available in the literature. The quadratic relationship developed by Lee et al. (1997) was tried with data from this study for static compaction samples. The stresses at 1.0% strain from the UC test were collected for static compaction samples and correlated with resilient modulus values from replicate samples. Similar mismatches in degree of saturation mentioned previously were also present in this analysis. A strong correlation, similar to that reported by Lee et al., was found, with an R^2 of 0.97 and a standard error of 2148. The statistics are presented in Table 9. Although both studies used a deviator stress of 6 psi, Lee et al. used a confining pressure of 3 psi as compared to 2 psi for the current study. As before, application of the 1.0% strain model involves correction of stress-strain curves for sample disturbance and non-uniform contact of sample ends attributable to surface irregularities. However, the model will not be influenced by the inaccuracy of stress measurements at the very low level of strain, such as 0.1%, associated with the initial tangent modulus.

Table 9. Regression Statistics for Stresses at 1.0% Strain Model

Statistic	Current Study	Lee et al. (1997)
Models: M_r = resilient modulus (psi) $S_{u1\%}$ = stresses at 1% strain (psi)	$M_r = 657 \times (S_{u1\%}) - 6.75 \times (S_{u1\%})^2$	$M_r = 695.4 \times (S_{u1\%}) - 5.93 \times (S_{u1\%})^2$
Coefficient of determination, R^2	0.97	0.97
Adjusted R^2	0.93	N/A
No. of observations	29	N/A
Intercept	Zero	Zero
Standard error	2148	N/A
Significance of model and coefficients at 5% level	Yes	N/A

N/A = information not available.

Summary and Model Selection

Four models with varying degrees of predictability are presented. Depending on the availability of resources for data interpretation, any of the four models could be used. For easy reference, Table 10 summarizes all models except the initial tangent modulus model. Both the sample preparation technique and degree of saturation influence soil strength and stiffness, so these should be carefully considered in using the prediction models.

All models provided good correlations except the initial tangent modulus model, which gave $R^2 = 0.39$ without any corrections being applied. Even with corrections, the R^2 was 0.62, which was the lowest among all the models. Moreover, there are some judgments involved in calculating initial tangent modulus values. This can become challenging in regular field operations. Therefore, this model was not considered further.

Although fair in accuracy ($R^2 > 0.6$), the model that predicts resilient modulus from the unconfined (ultimate) compressive strength would be the simplest to use. Unconfined compressive strength is a definitive value from the UC test, and no further interpretation is involved. Adding two more variables, PI and P_{200}, to this model improved the strength of the correlation to a value of $R^2 = 0.9$. So these values could be used, if available, for better predictability.

The correlation of resilient modulus with stress at 1% strain from the UC test provides the strongest mathematical model, but the determination of stress at 1.0% strain would require that a correction be applied for initial loading conditions such as surface irregularities and sample disturbance where the initial portion of the stress-strain curve is usually concave. This could be cumbersome for field or day-to-day laboratory application. One way to avoid such disturbance

Table 10. Resilient Modulus Prediction Models for Fine-Grained Soils

Model	Sample Preparation for UC[a]	Regression Model	Model Strength[b] (R^2)	Model Parameters
Unconfined compressive strength	Static compaction	$M_r = 6082 + 142 \times Q_u$	0.64	M_r = resilient modulus (psi)
	Impact compaction (Proctor hammer)	$M_r = 4283 + 143 \times Q_u$	0.73	Q_u = ultimate compressive strength (psi)
Unconfined compressive strength and soil index properties	Static compaction	$M_r = 7884.2 + 99.7 \times (Q_u) + 193.1 \times PI - 47.9 \times P_{200}$	0.86	PI = plasticity index (non-plastic soil, PI = 0)
	Impact compaction (Proctor hammer)	$M_r = 6113.0 + 95.1 \times (Q_u) + 173.7 \times PI - 27.8 \times P_{200}$	0.91	P_{200} = % passing No. 200 sieve
Stress at 1.0% strain from UC test	Static compaction	$M_r = 657 \times (S_{u1\%}) - 6.75 \times (S_{u1\%})^2$	0.97	$S_{u1\%}$ = stresses at 1% strain (psi)

All samples for the resilient modulus test were prepared with the static compactor.
[a] UC = unconfined compression test.
[b] Coefficient of determination for regression analysis.

and the need for correction could be loading and unloading the sample a few times with a low load, perhaps 10% to 20% of the ultimate load, before the actual UC test is performed. Such an approach would need to be studied further or verified before implementation.

CONCLUSIONS

- *Resilient modulus values for fine-grained soil were strongly correlated with the results of the quick shear (triaxial) test (AASHTO T 307)* (AASHTO, 2010). Correlations ($R^2 > 0.9$) were strong between the resilient modulus value measured at a confining pressure of 2 psi and a deviator stress of 6 psi and the stresses at 0.1% strain obtained from the stress-strain diagram of the quick shear (triaxial) test on the same sample at the end of the resilient modulus test.

- *The degree of saturation inversely influences the resilient modulus and UC strength values, but the nature of the effect varies by the specific soil.* The variation of the effect has been attributed to the different pore structures and suction characteristics of soils. This correlation was poor for many silty samples.

- *UC test results depend on the compaction technique used, such as static versus impact compaction; impact compaction produces stronger samples.* It is important to note that the effect of compaction techniques was not evaluated for the resilient modulus test.

- *The resilient modulus value for fine-grained soil can be estimated from UC test results.* Four sets of models were presented: one based on initial tangent modulus from Phase I; two based on results of the UC test without and with soil index properties and each with two alternate compaction techniques; and one based on 1% strain. Those developed in this Phase II study had fair or better correlations ($R^2 > 0.6$) between the UC test results and resilient modulus values measured at a confining pressure of 2 psi and a deviator stress of 6 psi. These correlations are dependent on the sample preparation technique and degree of saturation of the corresponding samples. A UC test is the simplest form of triaxial test and could be conducted only for fine cohesive soils.

RECOMMENDATIONS

1. *VDOT's Materials Division should implement the use of UC tests instead of CBR tests to predict the resilient modulus using one of the five models presented in Table 10 for fine-grained soils.*

2. *VCTIR should investigate ways of eliminating irregularities in the initial portion of the stress-strain curve when performing UC tests on fine-grained soils.* The model relating resilient modulus to stresses at 1% strain is the strongest mathematical model, but the determination of stresses at 1.0% strain would require corrections for initial loading conditions, such as surface irregularities, and sample disturbance. This could become

cumbersome for field or day-to-day laboratory application. One way to avoid the need for such correction could be loading and unloading the sample a few times with a low load (e.g., 10% to 20% of ultimate load) before the actual UC test is performed.

BENEFITS AND IMPLEMENTATION PROSPECTS

The benefits of implementing the use of UC tests instead of CBR tests include both time and material savings. In the CBR test, a 96-hr soaking is required, whereas the UC test could be done immediately after the sample is prepared. In addition, the sample size for the CBR test is about 4 times larger in volume than the sample size for the UC test (3- versus 6-in diameter). Additional savings relate to the less complex equipment and expertise necessary to perform the UC test. The UC and CBR tests could be conducted with a similar equipment setup. The use of UC test to estimate resilient modulus is expected to be readily implementable by VDOT.

ACKNOWLEDGMENTS

The author acknowledges the cooperation of VDOT's Materials Division in supplying soils and conducting some of the tests in their soils laboratory. The members of the technical advisory panel for the project are acknowledged for their contributions: Mohamed Elfino, Affan Habib, Don French, and Ed Hoppe. The author also acknowledges Linda Evans and Mary Bennett of VCTIR for their support in reviewing and preparing the report.

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APPENDIX

INFLUENCE OF MOISTURE AND DENSITY AS MEASURED BY DEGREE OF SATURATION ON UNCONFINED COMPRESSION TESTS (SAMPLES PREPARED USING IMPACT COMPACTION)

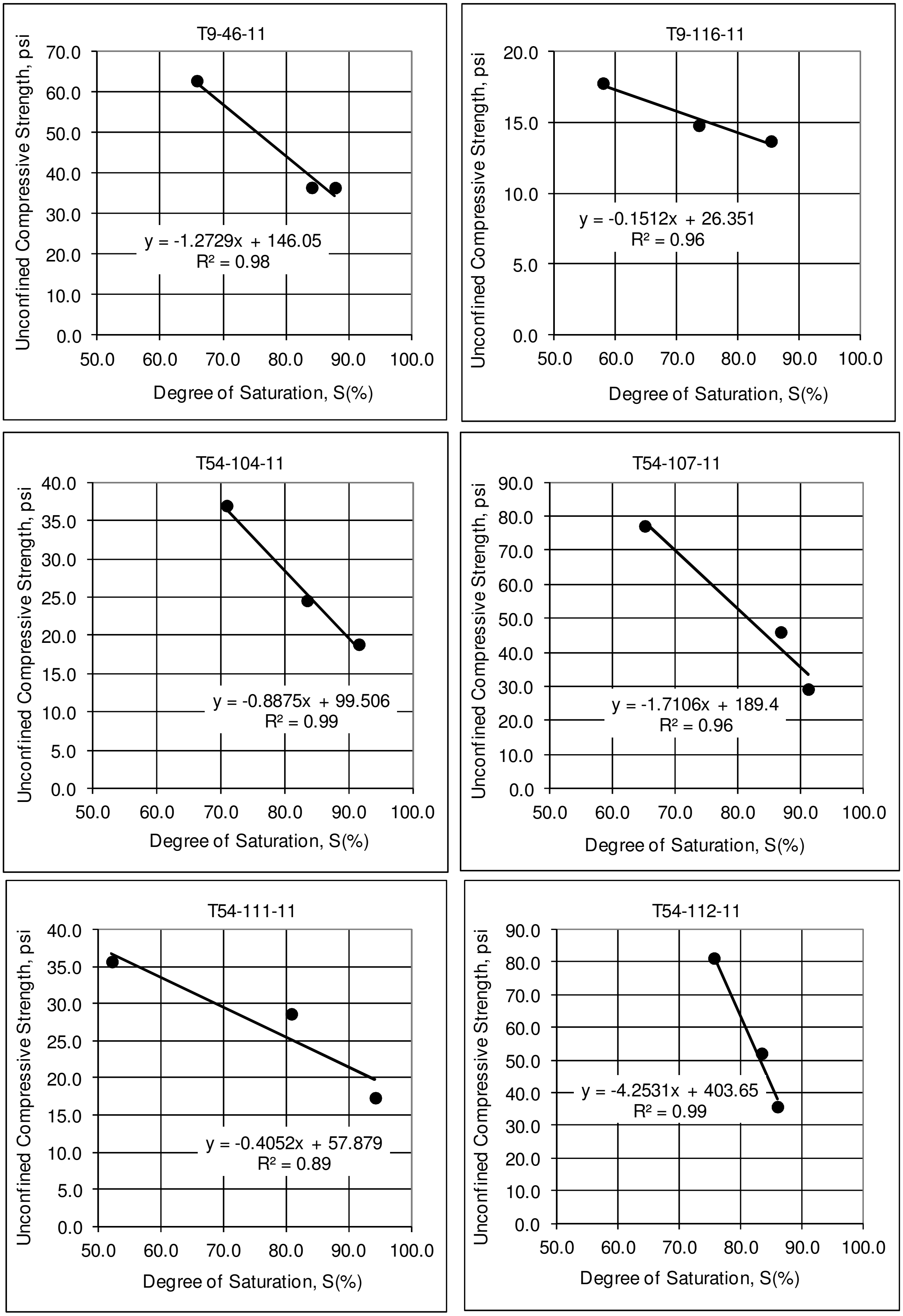

Figure A1. Influence of Moisture Content on Unconfined Compressive Strength (Impact Samples)

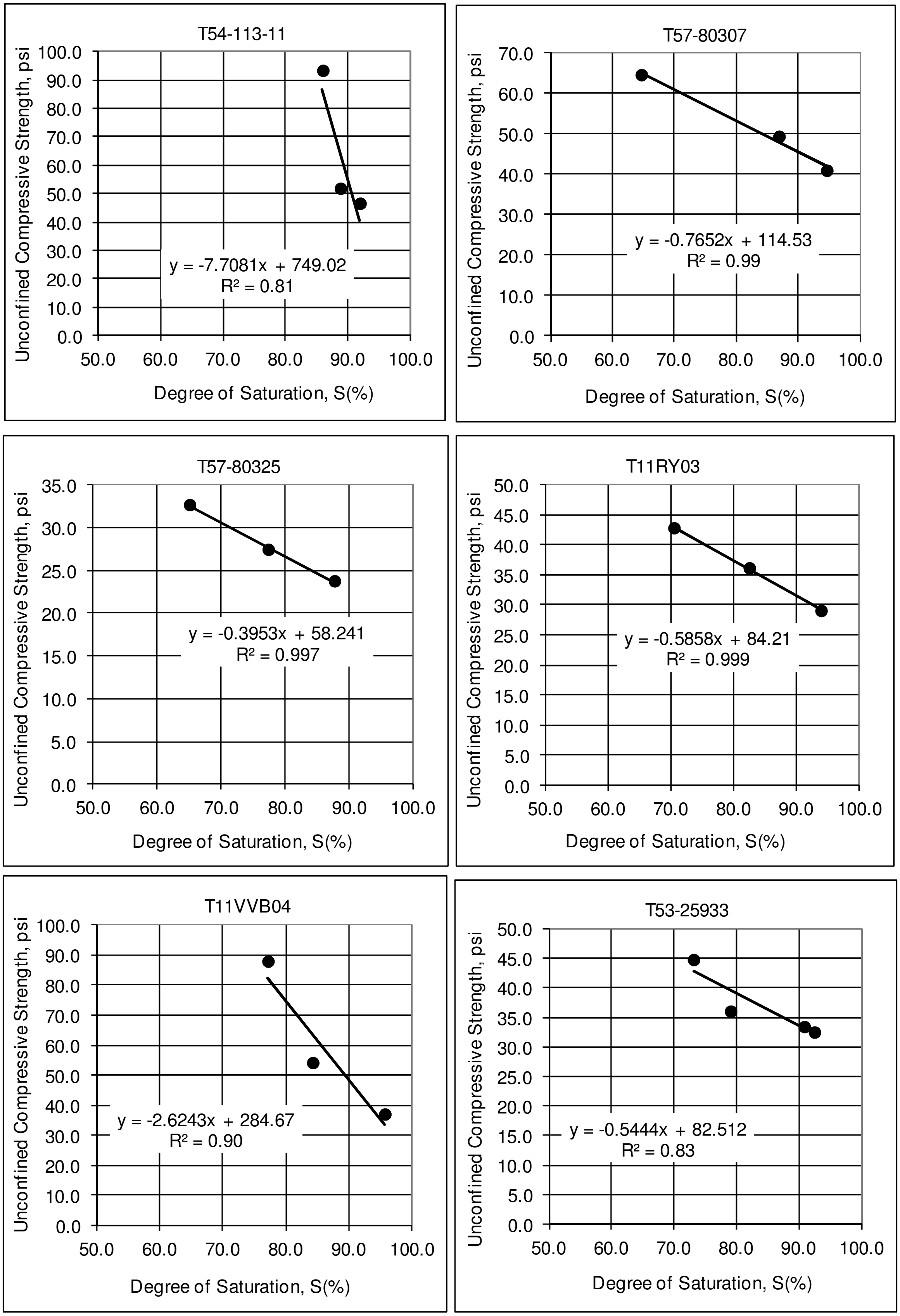

Figure A2. Influence of Moisture Content on Unconfined Compressive Strength (Impact Samples)

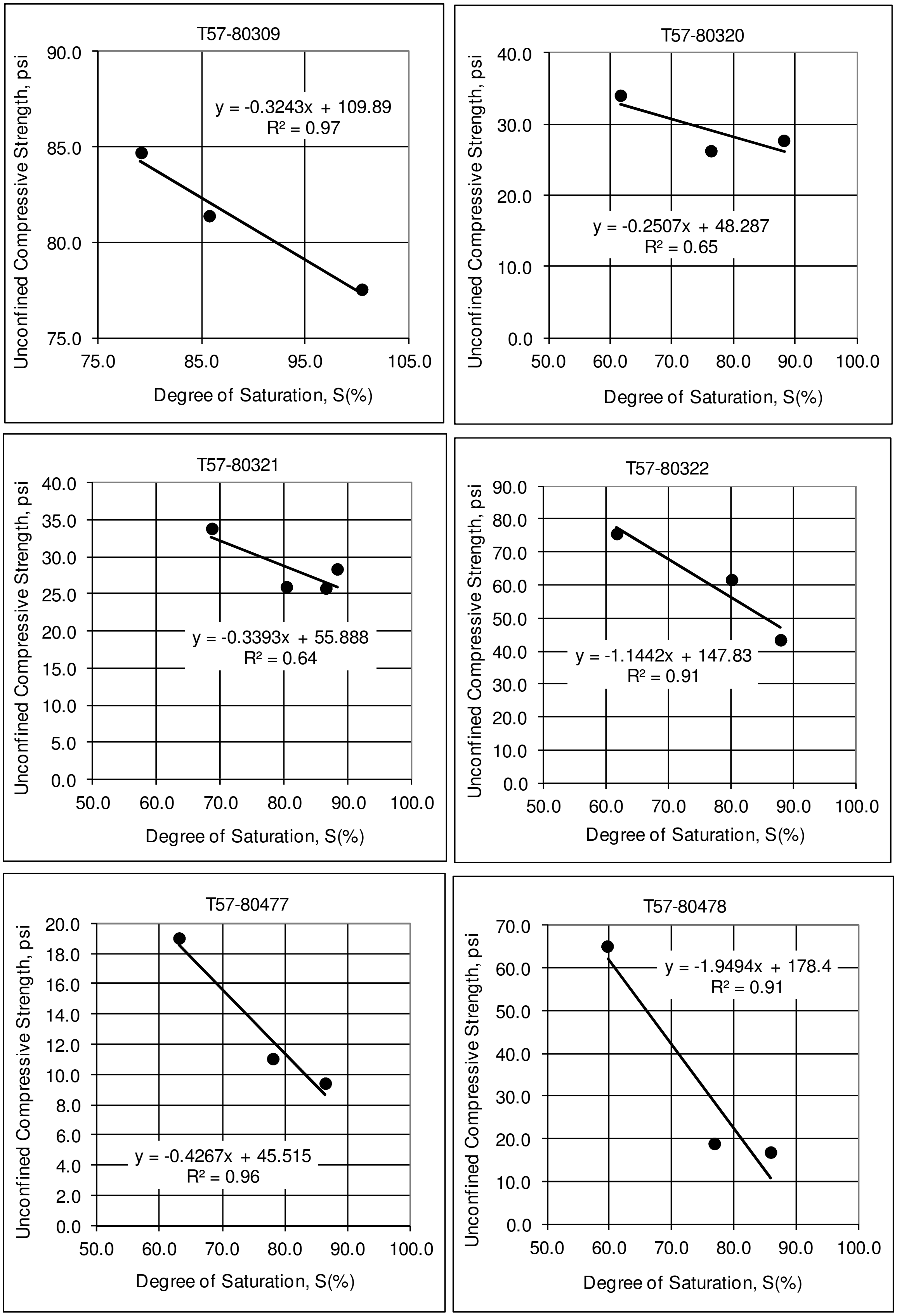

Figure A3. Influence of Moisture Content on Unconfined Compressive Strength (Impact Samples)

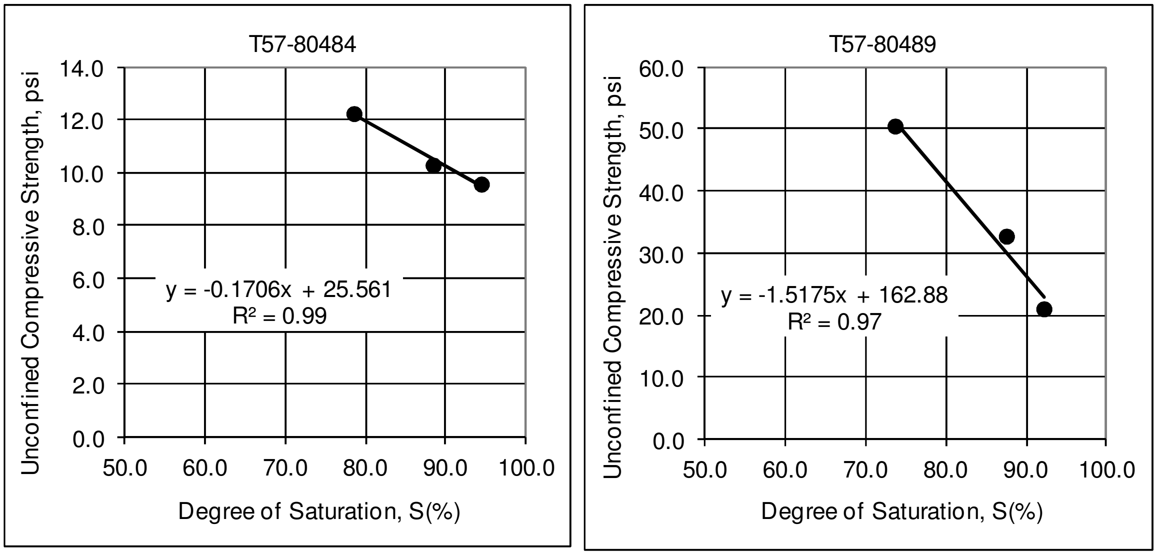

Figure A4. Influence of Moisture Content on Unconfined Compressive Strength (Impact Samples)