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Characterization of Unbound Pavement Materials From Virginia Sources for Use in the New Mechanistic-Empirical Pavement Design Procedure

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The results of other tests were analyzed for correlation with the results of the resilient modulus test to determine their use in estimating resilient modulus values. The results of the triaxial compression test, referred to as the quick shear test in AASHTO T 307, correlated favorably with the resilient modulus. Although the complexity of such a test is similar to that of the resilient modulus test for cohesionless coarse soil and base aggregate, fine cohesive soil can be tested with a simpler triaxial test: the unconfined compression test. In this study, a model was developed to estimate the resilient modulus of fine soil from the initial tangent modulus produced on a stress-strain diagram from an unconfined compression test.

The following recommendations are made to VDOT's Materials Division: (1) implement the use of the resilient modulus test for pavement design along with the implementation of the MEPDG; (2) use the universal constitutive model recommended by the MEPDG to generate the k-values needed as input to MEPDG Level 1 design/analysis for resilient modulus calculation; (3) develop a database of resilient modulus values (or k-values), which could be used in MEPDG design/analysis if a reasonable material match were to be found; (4) use the initial tangent modulus from an unconfined compression test to predict the resilient modulus values of fine soils for MEPDG Level 2 input and the 1993 AASHTO design; and (5) continue to collect data for the unconfined compression test and update the prediction model for fine soil in collaboration with the Virginia Transportation Research Council.

Implementing these recommendations would support and expedite the implementation efforts under way by VDOT to initiate the statewide use of the MEPDG. The use of the MEPDG is expected to improve VDOT's pavement design capability and should allow VDOT to design pavements with a longer service life and fewer maintenance needs and to predict maintenance and rehabilitation needs more accurately over the life of the pavement.

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FINAL REPORT

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INTRODUCTION

A pavement design requires characterization of the component materials in addition to the support soil. The pavement structure may consist of layers of aggregate or other modified soil known as subbase and base layer. The subgrade is the underlying soil, and its characterization allows for the design of a proper foundational support for the pavement. On the other hand, base/subbase materials provide structural capacity to the pavement. Therefore, both subgrade and base/subbase material characterization is needed to design an adequate pavement structure for expected traffic.

The currently used *Guide for Design of Pavement Structures*[1] developed by the American Association of State Highway and Transportation Officials (AASHTO) in 1972 and updated in 1986 and 1993 (hereinafter called the 1993 AASHTO design guide) is empirically based on the 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 and base/subbase aggregate. 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 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, a recent project of the National Cooperative Highway Research Program (NCHRP) (Project 1-37A) proposed a mechanistic-empirical pavement design procedure. VDOT is one of the leading states in implementing the resulting *Guide for the Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures* (MEPDG)[2] to replace the 1993 AASHTO design guide. Material characterization and local calibration are part of an ongoing implementation effort for the MEPDG.

The resilient modulus test is the test recommended to characterize subgrade soil in the 1993 AASHTO design guide and both subgrade soil and aggregate base for pavement design in the MEPDG. This test requires significant resources including a high level of technical capability. VDOT uses a simple correlation with the CBR test results to estimate resilient modulus for its current AASHTO design methodology.

In a recent study,[3] the Virginia Transportation Research Council (VTRC) evaluated fine soils used as subgrade material with regard to resilient modulus values. The researcher found that the results of AASHTO's quick shear test correlated better than the results of the CBR test with the resilient modulus value of fine soils. The quick shear test is a static triaxial compression test described in AASHTO T 307 (the resilient modulus test). Similar correlations with the results of the unconfined compression test have been found in other studies[4,5]; this test is simply the triaxial (quick shear) test without confinement. The unconfined compression test is a simple and relatively inexpensive test compared to the resilient modulus test. During the Phase 1 study,[3] VTRC also characterized coarse soils but the typical resilient modulus values were found to be lower than the MEPDG-recommended values.

The MEPDG also recommends the resilient modulus test to characterize base course materials for pavement design and analysis. VDOT currently uses the 1993 AASHTO design guide, which specifies a structural layer coefficient to characterize the base course material. VDOT mainly uses two grades of materials for its base course, designated 21A and 21B, depending on specified gradation characteristics. A study to obtain resilient modulus values for these base aggregates is warranted.

The seasonal variation of moisture content also affects the resilient modulus value for soils and aggregates. Therefore, studying the effect of moisture content on resilient modulus is warranted for these construction materials.

There are three levels of the MEPDG design procedure:

- *Level 1.* In this level, actual laboratory resilient modulus testing is conducted to characterize the subgrade soil.
- *Level 2.* In this level, resilient modulus values are determined from other soil properties using correlations.
- *Level 3.* In this level, typical resilient modulus values are used based on soil classification.

The results of resilient modulus testing are required for Level 1 pavement design where a high volume of traffic is expected. Because of the complexity of resilient modulus testing, conducting the test for the other two levels of pavement design, for which traffic volume is relatively low and safety concerns are less intense, has not been recommended.

In Level 1 design/analysis, the MEPDG requires input of the regression constants of the stress-dependent constitutive equation for resilient modulus of a particular unbound material (subgrade soil or base aggregate). This ensures a more accurate assessment of the modulus during the analysis over the design period including seasonal variation and varying stress conditions. Constitutive equation coefficients (k-values) are usually obtained from the regression analysis of resilient modulus test data for an actual soil/aggregate sample.

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, further complicating the use of resilient modulus testing. Because of this, correlations are desired for estimating resilient modulus, especially for use (or verification of default values) associated with MEPDG Level 2 design/analysis. A common method to predict a resilient modulus (i.e., M_r) value is through the use of correlations with other soil test properties such as the CBR. Another approach is to use the stress-dependent constitutive equation with the k-values estimated from soil index properties through further regression equations. The use of soil properties to determine the regression constants presents the concern of multi-colinearity effects, in which a strong correlation exists among and between the explanatory variables. The use of physical properties to determine M_r may capture seasonal variation but not stress sensitivity.[6] A frequently cited problem with resilient modulus testing is selecting a representative value of M_r from the laboratory testing. Although M_r varies with stress state and seasonal changes of moisture and temperature, some literature has suggested using particular confining and deviator stress levels for selecting a resilient modulus value.[7]

MEPDG Level 3 design/analysis also requires a specific resilient modulus value as input. Although the MEPDG provides default values and correlations for Level 3 use, they are based on a limited number of tests and may not be applicable for Virginia soils and aggregates.

PURPOSE AND SCOPE

The purpose of this study was to investigate the mechanistic characterization of subgrade soil and common base course aggregate from Virginia sources in order to support the statewide implementation of the MEPDG. Three objectives of the study were:

1. Develop a predictive regression model for resilient modulus using unconfined compression test results for fine soils from Virginia sources.

2. Verify the low resilient modulus values for coarse soil found in an earlier study.[3]

3. Obtain typical resilient modulus values for VDOT base course aggregates 21A and 21B.

METHODOLOGY

Overview

To achieve the purpose of this study, four tasks were performed.

1. Since a comprehensive literature review was conducted in the previous study,[3] the literature was reviewed only to determine the state of the practice regarding the use of the base course resilient modulus in pavement analysis/design and the use of the unconfined compression test to predict resilient modulus values.

2. Soil and aggregate samples were collected from across Virginia.

3. The soil and aggregate samples were tested for resilient modulus in addition to index properties such as gradation, liquid limit, plastic limit, and specific gravity.

4. Fine (cohesive) soil samples were tested by the unconfined compression test to produce a stress-strain curve, and a model was developed to predict resilient modulus values.

Literature Review

The literature regarding the use of the resilient modulus in pavement design and previous work in investigating possible correlations between resilient modulus values and other soil testing results was identified using the resources of the VDOT Research Library and the University of Virginia library. Online databases searched included the Transportation Research Information System, the Engineering Index (EI Compendix), Transport, and WorldCat, among others. Information was also gathered from American Society of Testing and Materials (ASTM) standards for soils classification and testing and AASHTO materials specifications.

Sample Collection and Soil Classification

Soil and aggregate samples were collected from the nine VDOT construction districts. Six aggregate sources, six fine soils, and five coarse soils were selected from the nine districts for testing during this phase of the research. Each district was asked to send samples for this study from the predominantly used sources in the respective district. In addition to these, five coarse soil samples from a construction project on Battlefield Boulevard in the Hampton Roads District were included.

The soil samples were classified in accordance with AASHTO M 145,[8] Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes, and ASTM D 2487,[9] Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System [USCS]).

Laboratory Testing

The soil and aggregate samples were tested by an outside vendor to determine the resilient modulus. The VDOT Materials Division Soils Lab (VDOT Soils Lab) has the capability to conduct the resilient modulus test on only soil samples. Therefore, 24 fine soil samples were also tested at the VDOT Soils Lab. Tests conducted by the outside vendor and the VDOT Soils Lab included the resilient modulus test and the accompanying quick shear (triaxial) test. In addition, several tests were performed at the VTRC Lab, including standard soils properties tests to determine gradation, liquid limit, and plastic limit; the standard Proctor test; and the unconfined compression test.

Resilient Modulus Test

The *resilient modulus* (M_r) is the applied deviator stress divided by the resulting recoverable axial strain.

Different Standards for Determining Resilient Modulus

Many standards exist (and differ in their approach, methods, and results) for determining resilient modulus values for unbound materials, including the following:

- *AASHTO T 294-92*[10]*:* Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils
- *AASHTO T 292-91*[10]*:* Resilient Modulus of Subgrade Soils and Untreated Base/ Subbase Materials
- *AASHTO T 307-99*[8]*:* Determining the Resilient Modulus of Soils and Aggregate Materials
- *NCHRP 1-28*[11]*:* Laboratory Determination of Resilient Modulus for Flexible Pavement Design
- *NCHRP 1-28A*[11]*:* Harmonized Test Methods for Laboratory Determination of Resilient Modulus for Flexible Pavement Design (combines the four previous standards).

Each procedure determines the resilient modulus at different loading conditions or states of stresses. Measured resilient modulus values are used to fit universal constitutive models through regression analysis.

The universal constitutive equation to predict the resilient modulus has been extensively evaluated and generally provides a good fit to measured data. It takes a variety of forms:

$$M_r = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\sigma_d}{p_a}\right)^{k_3}$$

or the expanded

$$M_r = k_1 p_a \left(\frac{\theta - 3k_6}{p_a} \right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1 \right)^{k_3}$$

or the simplified

$$M_r = k_1 (\theta)^{k_2}$$

where

M_r = resilient modulus value
P_a = normalizing stress (atmospheric pressure, e.g., 14.7 psi)
σ_1, σ_2, and σ_3 = principal stresses, where $\sigma_2 = \sigma_3$
σ_d = deviator (cyclic) stress = $\sigma_1 - \sigma_3$
θ = bulk stress = $(\sigma_1 + \sigma_2 + \sigma_3) = (3\sigma_3 + \sigma_d)$
τ_{oct} = octahedral shear stress
$= \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} = \frac{\sqrt{2}}{3}\sigma_d$
k_i = elastic response coefficients.

With regard to the elastic response coefficients, k_1 is proportional to Young's modulus and should be positive, as M_r is always positive; k_2 must be positive, as an increase in bulk stress should stiffen the material; k_6 accounts for pore pressure or cohesion; and k_3 is usually negative, as increasing the shear stress (or deviator stress) will generally produce a softening of the material.[6]

Resilient Modulus Test Used in This Study

In this study, the resilient modulus test was performed in accordance with AASHTO T 307-99, Standard Method of Testing for Determining the Resilient Modulus of Soils and Aggregate Materials.[8] A recent NCHRP study[11] (1-28A) recommended a new test procedure for resilient modulus testing; the major change from the AASHTO T 307 procedure is the loading sequences. However, because of equipment and resource issues, the AASHTO T 307 procedure was used in this study. To investigate the effect of moisture content on the resilient modulus value, two additional sets of samples were compacted and tested for resilient modulus at approximately 20 percent higher moisture than the optimum moisture content (OMC) and 20 percent less than OMC. Instead of only ±20 percent, a wide range of the degree of saturation was considered for selecting the compaction moisture content.

A sample was compacted at OMC or another specified moisture content and maximum dry density (MDD) by use of a static compactor. The sample was loaded in accordance with AASHTO T 307, and the recoverable strains were measured using two external linear variable differential transducers. Resilient modulus values were calculated from the measured stress and recoverable strain values. The diameter of the soil and aggregate samples was 2.9 in (Type 2) and 6 in (Type 1), respectively, with the height to diameter ratio being approximately 2. A moisture content 20 percent higher than OMC was not achievable for the aggregate samples because of constructability and stability issues regarding the samples, so this set of aggregate samples was replaced with a soaked sample. Aggregate samples were compacted at OMC and soaked overnight, irrespective of the saturation level achieved. For most samples, the saturation level did not increase significantly.

Microsoft Excel was used to perform regression analysis for two other models in addition to the one already being performed by the VDOT Soils Lab.

Resilient Modulus Calculation/Prediction

Several constitutive models are available in the literature for resilient modulus calculation/prediction. The input required in MEPDG Level 1 design/analysis is the regression coefficients (k-values) determined from laboratory test results. The following three models were considered in this study:

Model 1 (used by the VDOT Soils Lab). This is the default model used by the data reduction program at the VDOT Soils Lab in its resilient modulus testing setup. This model is referenced by Andrei et al [11]:

$$M_r = k_1(\sigma_3)^{k_2}(\sigma_d)^{k_5}$$

where

M_r = resilient modulus value
σ_3 = confining stress
σ_d = cyclic (deviator) stress
k_1, k_2, and k_5 = regression coefficients.

Model 2 (suggested for the 1993 AASHTO design). Von Quintus and Killingsworth[12] recommended this model for estimating the resilient modulus value required by the 1993 AASHTO design guide.

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\sigma_d}{P_a}\right)^{k_3}$$

where

M_r = resilient modulus value
P_a = atmospheric pressure (e.g., 14.7 psi)
σ_1, σ_2, and σ_3 = principal stresses, where $\sigma_2 = \sigma_3$
σ_d = deviator (cyclic) stress = $\sigma_1 - \sigma_3$
θ = bulk stress = $(\sigma_1 + \sigma_2 + \sigma_3) = (3\sigma_3 + \sigma_d)$
k_1, k_2, and k_3 = regression coefficients.

Model 3 (recommended by the MEPDG). This model is recommended by the MEPDG[2] to calculate k-values for use as analysis input.

$$M_r = k_1 P_a \left(\frac{\theta}{P_a} \right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_3}$$

where

M_r = resilient modulus value
P_a = normalizing stress (atmospheric pressure e.g., 14.7 psi)
σ_1, σ_2, and σ_3 = principal stresses, where $\sigma_2 = \sigma_3$
σ_d = deviator (cyclic) stress = $\sigma_1 - \sigma_3$
θ = bulk stress = $(\sigma_1 + \sigma_2 + \sigma_3) = (3\sigma_3 + \sigma_d)$
τ_{oct} = octahedral shear stress
$= \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} = \frac{\sqrt{2}}{3}\sigma_d$
k_1, k_2, and k_3 = regression coefficients.

Quick Shear Test

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

Soil Index Properties and Standard Proctor Tests

Soil index properties including gradation (AASHTO T-87 and T-88),[8] specific gravity (AASHTO T-100),[8] liquid limit (AASHTO T-89),[8] and plastic limit (AASHTO T-90)[8] were determined. The OMC and MDD were determined using the standard Proctor test (AASHTO T-99).[8] The degrees of saturation of the tested samples were calculated using compaction moisture content, compaction density, and the specific gravity values. The measured specific gravity values were used for soil samples only; aggregate specific gravity values were used from the VDOT list of approved aggregate sources.

Unconfined Compression Test

Fine cohesive soils samples were tested in accordance with AASHTO T 208[8] (unconfined compression test), but data collection was not limited to compressive strength. A continuous stress-strain response was recorded to produce a complete stress-strain diagram. Samples were prepared in three ways: using the static compactor (static), the Proctor hammer (Proctor), and the Harvard miniature compactor (Harvard). The static and Proctor samples were approximately 3 in by 6 in cylindrical. The Harvard samples were 1.3 in by 2.8 in cylindrical. Three samples from each source at three moisture contents similar to the resilient modulus test samples were prepared using the Proctor hammer and Harvard compactor; however, only one set of samples was prepared, at OMC only, for the static compactor. The rate of loading was 1 percent strain per minute, similar to the quick shear (triaxial) test.

RESULTS AND DISCUSSION

Literature Review

Flintsch et al.[13] compared the resilient moduli of a VDOT 21B granular subbase used at the Virginia Smart Road as measured by laboratory testing and backcalculation from falling weight deflectometer (FWD) testing. The backcalculated moduli demonstrated clear stress sensitivity, with an exponential response to the bulk stress in the center of the layer. The correlation between the two methods was strong. Various models were evaluated to describe the laboratory data, all had good fit characteristics; the simplest model was chosen for comparison with the field measured moduli (similar to the universal constitutive model with $k_3 = 0$). The authors found that the effect of deviator stress was small for granular material. The bulk stress was computed at the middle of the base layer for use in the constitutive model. The backcalculated and laboratory results correlated very well with an apparent linear shift. The authors postulated that the shift may occur as a result of the backcalculated moduli representing an average value of the layer modulus whereas the stress at the mid-depth of the layer (which is input to the model with laboratory-determined coefficients) is not the average stress. They speculated that the shift was both geometry and material dependent. The average regression coefficients from 10 samples of VDOT 21B were $k_1 = 7{,}304$ (range of 3,846 to 15,346) and $k_2 = 0.6$ (range of 0.489 to 0.703) for the K-θ model.

Nazarian et al.[14] unsuccessfully attempted to compare the resilient modulus as measured in the laboratory to those as measured by the FWD and seismic pavement analyzer. The laboratory tests were performed on quarry samples of various aggregates, and the nondestructive tests (FWD and seismic) were measured in-situ. The authors found differences in the k_2 between the two sources and attributed them to possible changes in gradation in service (in-service materials were coarser), variations in moisture content, and different Atterberg limits.

Lee et al.[4] represented a simple relationship between conventional unconfined compression and the resilient modulus for fine cohesive soils. Three Indiana clayey soils, including AASHTO classifications A-4/A-6, A-6, and A-7-6, were tested. For comparison purposes, the representative stress state was selected to be a 6 psi deviator stress with a 3 psi confining pressure. The M_r value and stress at 1 percent strain ($S_{u1\%}$) from an unconfined compression test showed similar trends with the variation of moisture content. The following correlation between M_r and $S_{u1\%}$ was developed independent of actual moisture content or compaction density:

$$M_r = 695.4*(S_{u1\%}) - 5.93*(S_{u1\%})^2$$

The strength of this correlation was very high, with $R^2 = 0.97$.

Thompson and Robnett[5] identified the soil properties that influence the resilient behavior of soil from Illinois. The study was focused mainly on fine soil. The important soil properties considered in the study were soil classification including soil index properties, CBR, and static stress-strain behavior from the unconfined compression test. Correlations were found between the resilient behavior and soil properties such as degree of saturation, unconfined compressive strength, and the initial tangent modulus of the stress-strain curve. The degree of saturation was found to be one of the most statistically significant factors controlling the resilient behavior of the soil. Regression equations using these properties were developed for Illinois soil and could be used to predict probable resilient properties of soil. One of the regression equations using the initial tangent modulus value was as follows:

Resilient modulus (ksi) = 3.49 + 1.9 * Initial tangent modulus

Typical standard errors of estimate were in the range of 1.5 ksi to 3.5 ksi.

Sukumaran et al.[15] constructed a finite element analysis of a fine clay soil using von Mises shear strength idealization by means of the HKS 2000 element method in ABAQUS. Using this methodology, they performed a theoretical analysis of the unconfined compressive strength test, CBR test, and the resilient modulus test. Three analytic approaches were performed: (1) use of the ultimate shear strength input, (2) use of the stress-strain data input, and (3) an elastic model using the stress-dependent elastic modulus. A plot of stress versus displacement showed that the second analytical approach most closely represented field test data, with error on the conservative side. The model perfectly predicted the stress-strain relationship of a soil and was used to show that a suitable estimate of resilient modulus values could be obtained from the unconfined compressive strength test. It was also shown that the commonly used CBR overpredicted the resilient modulus values.

Soils Classification and Laboratory Tests

Index Properties and Proctor Tests

Soil classification, specific gravity, and standard Proctor test results for fine and coarse soil samples are presented in Tables 1 and 2, respectively. The six base aggregate samples were classified with the VDOT designation of 21A or 21B as produced by the manufacturer. The

Table 1. Fine Soil Sources and Index Properties Including Proctor Test Results

Soil Source	AASHTO and USCS Classification	Specific Gravity	Optimum Moisture Content (%)	Maximum Dry Density (lb/ft^3)
FS-1 Amherst	A-7-5 CH	2.74	23.6	101.1
FS-2 Culpeper	A-4 ML	2.83	16.5	109.8
FS-3 Salem	A-7-6 CH	2.77	33.75	86.4
FS-4 NOVA	A-7-5 MH	2.81	28.2	91.25
FS-5 Stadium	A-4 SC	2.86	21.5	102.7
FS-6 Hampton	A-6 CL	2.63	15.9	112.1

AASHTO = American Association of State Highway & Transportation Officials; USCS = Unified Soil Classification System; NOVA = Northern Virginia District.

Table 2. Coarse Soil Sources and Index Properties Including Proctor Test Results

Soil Source	AASHTO and USCS Classification	Specific Gravity	Optimum Moisture Content (%)	Maximum Dry Density (lb/ft^3)
CS-1 Richmond	A-2-4 SM	2.66	9.6	123.1
CS-2 Lynchburg	A-2-4 SM-ML	2.75	16.0	111.0
CS-3 Bristol	A-2-7 SC	2.79	22.1	101.2
CS-4 Fredericksburg	A-2-4 SP-SM	2.70	11.5	119.8
CS-5 NOVA	A-2-6 SC with cobbles	2.73	14.5	115
CS-6 Battlefield Blvd. 9-77-08	A-2-4 SP-SM	2.661	10.4	111.7
CS-7 Battlefield Blvd. 9-82-08	A-2-4 SM	2.644	9.5	126.8
CS-8 Battlefield Blvd. 9-85-08	A-3 SP-SM	2.651	10.7	114.2
CS-9 Battlefield Blvd. 9-101-08	A-3 SW-SM	2.641	8.8	119.2
CS-10 Battlefield Blvd. 9-107-08	A-2-4 SM	2.636	8.25	118.8

AASHTO = American Association of State Highway & Transportation Officials; USCS = Unified Soil Classification System; NOVA = Northern Virginia District.

standard Proctor test was used to determine OMC and MMD. Specific gravities of aggregate sources were collected from the VDOT list of approved aggregate sources, and mineralogy was identified visually at the VTRC Lab. Aggregate test results are summarized in Table 3.

Table 3. Base Aggregate Sources and Proctor Test Results

Soil Source	VDOT Classification and Mineralogy	Specific Gravity	Optimum Moisture Content (%)	Maximum Dry Density (lb/ft^3)
AGG-1 Shelton	21A Granite gneiss	2.75	8	134.2
AGG-2 Mt. Athos	21A Schist	3.01	7.25	154
AGG-3 Bristol	21B Dolomitic limestone	2.82	5.6	144.3
AGG-4 Frazier North	21B Limestone	2.71	7.1	139.4
AGG-5 NOVA	21B Diabase	2.82	7.65	142.5
AGG-6 Richmond	21B Marble	2.75	8.16	133.4

VDOT = Virginia Department of Transportation; NOVA = Northern Virginia District.

Resilient Modulus Test Results

All samples were tested in accordance with AASHTO T 307 (resilient modulus test) with 15 combinations of various confining and deviator stresses. The compacted dry densities for these samples were above 95 percent of the MDD in the Proctor test but the moisture content was varied. The three models discussed previously (i.e., Model 1, used by the VDOT Soils Lab; Model 2, suggested for use for the 1993 AASHTO design by Von Quintus and Killingsworth[12]; and Model 3, recommended by the MEPDG[2]) were tried to fit the data, and respective regression coefficients (k-values) were calculated using Microsoft Excel as described in the "Methods" section. The samples with an R^2 greater than 0.9 are considered acceptable by the MEPDG. Although all three models were tried, the data from only Model 3 are presented here since the main focus of the study is the MEPDG.

Fine Soil

Table 4 lists the k-values for Model 3 (MEPDG) and the respective R^2 for fine soil samples. Each source was tested as Type 2 material (3 in by 6 in sample) at three moisture contents by both the VDOT Soils Lab and an outside vendor. There were no replicate samples except for one source tested by the VDOT Soils Lab. The data from the two labs could not be compared directly because of differences in compaction moisture content and dry density in addition to lab variability; it was very difficult to replicate both properties. Typical resilient modulus values were calculated at a confining stress of 2 psi and a deviator stress of 6 psi using this fitted Model 3 and are presented in the last column of Table 4. Although individual k-values cannot be compared, the typical resilient modulus values were comparable between the two labs. Most samples have an R^2 greater than or very close to 0.9 except the source from Culpeper (FS-2), which had a consistently low R^2 for both laboratories. However, the R^2 value was 0.9 or higher with Model 1 and Model 2 for all samples from Culpeper. Therefore, it might be a good practice to keep all three models in the data analysis/calculation process for VDOT.

Coarse Soil

The coarse soils were also tested as Type 2 material. The five sources selected from the districts were tested by an outside vendor for resilient modulus at three moisture contents. The VDOT Soils Lab tested an additional 30 soil samples from a project on Battlefield Boulevard in the Hampton Roads District. Three replicate samples were tested at OMC and 20 percent more than OMC for samples from five locations in the project. The regression coefficient values (k-values) for Model 3, R^2, and calculated typical resilient modulus values at 2 psi confining pressure and 6 psi deviator stress are presented in Table 5. Typical resilient modulus values were comparable to the Phase 1 values[3] but were consistently low compared to MEPDG-recommended values. Since the small size of the sample (3-in diameter) might have contributed to such low values, three 6-in-diameter samples were tested for verification purposes. All three samples were compacted at OMC and 100 percent MDD for this test. The sample from the Northern Virginia (NOVA) District had larger size particles, so a correction was applied to the Proctor test results for +No. 4 materials. As a consequence, this sample was compacted at a higher density and had larger particles than did the small-size sample. The results from these three samples are presented in Table 6. The typical resilient modulus values were similar to those of the small-size samples and were low compared to MEPDG-recommended values.

Table 4. Fitting of MEPDG Model to Resilient Modulus Test Data for Fine Soil

Soil Source	Testing Laboratory	Compaction Moisture Content (%)	Regression Coefficients for Resilient Modulus Constitutive Model (MEPDG)				Calculated Resilient Modulus Value (psi)[a]
			k_1	k_2	k_3	R^2	
FS-1 Amherst	VDOT Soils Lab	18	1107.6	0.297	-0.418	0.97	14243.5
		18.2	997.3	0.272	-1.270	0.97	11094.3
		22.7 (OMC)	942.9	0.302	-1.240	0.96	10481.5
		23.8 (OMC)	969.7	0.322	-1.648	0.95	9990.9
		26.9	780.7	0.249	-3.860	0.98	5531.2
		30.3	604.9	0.317	-4.718	0.93	3635.3
	Outside vendor	18.2	1056.3	0.247	0.962	0.99	17494.9
		23.6 (OMC)	1006.2	0.231	0.770	0.96	16162.4
		28	757.2	0.131	-1.407	0.88	8461.9
FS-2 Culpeper	VDOT Soils Lab	16.3 (OMC)	472.7	0.453	2.649	0.84	3976.0
		20.1	492.7	0.487	3.214	0.86	3726.9
		21.4	403.7	0.505	2.793	0.85	3276.4
	Outside vendor	16.5 (OMC)	319.7	0.620	3.133	0.82	2388.1
		20	348.8	0.412	2.219	0.75	3191.8
		21.5	337.4	0.614	3.040	0.81	2564.4
FS-3 Salem	VDOT Soils Lab	27.9	977.1	0.207	0.752	0.99	15718.7
		34.5 (OMC)	1096.6	0.180	-0.088	0.96	15305.0
		36.6	867.3	0.169	0.093	0.95	12521.8
	Outside vendor	27	943.1	0.247	-1.023	0.97	11014.6
		33.8 (OMC)	819.7	0.138	-0.272	0.84	11170.1
		36	817.9	0.199	-2.203	0.96	7836.0
FS-4 NOVA	VDOT Soils Lab	22.4	807.6	0.201	-0.728	0.89	10026.4
		27.8 (OMC)	930.8	0.203	-1.578	0.98	9946.6
		31.6	704.3	0.230	-2.352	0.98	6532.2
	Outside vendor	23	809.5	0.245	-2.654	0.98	7096.8
		28.2 (OMC)	598.8	0.231	-3.141	0.96	4832.6
		32	620.0	0.319	-3.635	0.95	4505.7
FS-5 Stadium	VDOT Soils Lab	17.3	591.1	0.250	-2.029	0.94	5779.8
		21.3 (OMC)	667.5	0.268	-2.641	0.95	5838.1
		24.6	466.5	0.325	-2.894	0.93	3858.0
	Outside vendor	18	525.8	0.349	-3.134	0.93	4148.9
		21.5 (OMC)	317.2	0.419	-3.285	0.87	2402.5
		25.5	399.6	0.429	-3.390	0.9	2964.5
FS-6 Hampton	VDOT Soils Lab	11.7	1107.5	0.242	0.992	0.97	18459.5
		15.4 (OMC)	1366.8	0.210	0.062	0.97	19463.3
		16.8	981.5	0.267	0.826	0.98	15806.0
	Outside vendor	12.5	1162.0	0.240	-0.410	0.93	15134.6
		15.9 (OMC)	1010.9	0.178	0.617	0.91	15977.6
		17.5	1188.1	0.208	-1.812	0.95	12170.5

MEPDG = Mechanistic-Empirical Pavement Design Guide; VDOT Soils Lab = VDOT Materials Divisions Soils Lab; NOVA = Northern Virginia District; OMC = optimum moisture content.

[a] Confining pressure = 2 psi, and cyclic deviator stress = 6 psi.

Table 5. Fitting of MEPDG Model to Resilient Modulus Test Data for Coarse Soil

Soil Source	Testing Entity	Compaction Moisture Content (%)	Regression Coefficients for MEPDG Constitutive Model				Calculated Resilient Modulus Value (psi)[a]
			k_1	k_2	k_3	R^2	
CS-1 Richmond	Outside vendor	9.6	539.4	0.657	-0.769	0.95	6061.5
		11.5	401.8	0.662	-0.123	0.96	5053.3
		13	302.3	0.502	0.687	0.91	4529.5
CS-2 Lynchburg	Outside vendor	14	907.5	0.238	-1.281	0.96	10145.9
		16	813.5	0.231	-1.995	0.97	8032.6
		19.5	543.0	0.312	-3.664	0.91	3931.4
CS-3 Bristol	Outside vendor	18	1152.5	0.239	1.019	0.99	19309.6
		22.1	1036.0	0.244	0.739	0.99	16507.6
		25.5	863.4	0.230	-0.866	0.94	10401.3
CS-4 Fredericksburg	Outside vendor	9.5	719.7	0.500	-0.928	0.94	8118.6
		11.5	614.3	0.595	-0.672	0.98	7110.4
		13	625.5	0.550	-0.565	0.97	7446.0
CS-5 NOVA	Outside vendor	11.6	1139.8	0.196	-0.130	0.89	15737.4
		14.5	867.5	0.226	-2.360	0.97	8040.4
		17.4	364.5	0.261	-2.392	0.52	3336.4
CS-6 Battlefield Blvd.	VDOT Soils Lab[b]	11.9	612.3	0.585	-0.734	0.97	7026.1
		10.0	589.9	0.543	-0.344	0.96	7311.7
CS-7 Battlefield Blvd.	VDOT Soils Lab[b]	11.1	508.1	0.560	-0.619	0.96	4931.4
		10.0	780.4	0.615	-2.446	0.94	6584.3
CS-8 Battlefield Blvd.	VDOT Soils Lab[b]	12.1	587.6	0.581	-0.550	0.98	6963.3
		10.1	588.5	0.530	-0.413	0.94	7222.5
CS-9 Battlefield Blvd	VDOT Soils Lab[b]	10.2	628.1	0.645	-0.706	0.98	7151.6
		8.5	608.3	0.588	-0.528	0.98	7231.4
CS-10 Battlefield Blvd.	VDOT Soils Lab[b]	10.3	592.7	0.603	-0.794	0.97	6703.4
		8.5	611.1	0.575	-0.844	0.96	6887.6

MEPDG = Mechanistic-Empirical Pavement Design Guide; VDOT Soils Lab = VDOT Materials Divisions Soils Lab; NOVA = Northern Virginia District.

[a] Confining pressure = 2 psi, and cyclic deviator stress = 6 psi.

[b] Average of three replicate samples.

Table 6. Effect of Sample Size on Resilient Modulus Test Results for Coarse Soil

Soil Source	AASHTO and USCS Soil Type	Small Sample (3 in by 6 in)		Large Sample (6 in by 12 in)	
		Degree of Saturation, S (%)[a]	Model 3 (MEPDG) Resilient Modulus Value (psi)[b]	Degree of Saturation, S (%)[a]	Model 3 (MEPDG) Resilient Modulus Value (psi)[b]
CS-1 Richmond	A-2-4 SM	80.6	5053	70.9	4199
CS-2 Lynchburg	A-2-4 SM-ML	74.9	8033	83.8	6802
CS-5 NOVA[c]	A-2-6 SC	80.9	8040	82.8	12629

AASHTO = American Association of State Highway & Transportation Officials; USCS = Unified Soil Classification System; MEPDG = Mechanistic-Empirical Pavement Design Guide; NOVA = Northern Virginia District.

[a] Both samples were prepared at optimum moisture content and 100% maximum dry density, but both properties were off target a little.

[b] Confining pressure = 2 psi, and cyclic deviator stress = 6 psi.

[c] Because of the large number of particles retained on the No. 4 sieve, a modification of the Proctor density test was done in accordance with AASHTO T 224, i.e., the sample was compacted at a higher density than would have been the case for a sample with smaller particles.

Base Aggregate

Two types of VDOT aggregate, 21A and 21B, were tested as Type I material (6 in by 12 in sample) by an outside vendor. Two sources were 21A, and the other four were 21B. They all had different mineralogy. Although three samples at three moisture contents were planned, a sample at a higher moisture than optimum was not possible because of internal instability. So this set of samples was compacted at OMC and then soaked overnight. The saturation was checked after the resilient modulus test, and it showed a minor change in saturation level from OMC. All three constitutive models were fitted to the data, and the results for Model 3 are presented in Table 7.

A typical resilient modulus value was calculated using 3 psi confinement and 24 psi deviator stress. For soil samples, measured values were selected at a confining pressure of 2 psi and a deviator stress of 6 psi as was done in Phase 1 of this study.[3] For base aggregate, it was different because the typical stress condition would be different at this layer of the pavement than at the subgrade. A layered elastic analysis for a typical pavement section showed a confining pressure of 1.3 to 3.3 psi along with a deviator stress of 10 to 24.6 psi at the middle of the base layer. Rada and Witczak[16] found a typical bulk stress of 20 to 40 psi at the base layer. Therefore, a confining stress of 3 psi and a deviator stress of 24 psi were selected for this study; the calculated bulk stress would be 33 psi. There were no measured resilient modulus values at this stress combination, so values were calculated using Model 3 for the aggregate base. These values are presented in the last column of Table 7. Although there was no consistent pattern in

Table 7. Fitting of MEPDG Model to Resilient Modulus Test Data for Base Aggregate

Soil Source	VDOT Classification	Compaction Moisture Content (%)	Regression Coefficients for MEPDG Constitutive Model				Calculated Resilient Modulus Value (psi)[a]
			k_1	k_2	k_3	R^2	
AGG-1 Shelton	21A	6	796.5	0.529	0.207	1.00	19215.0
		8 OMC	441.0	0.656	0.372	0.99	12800.8
		8 soaked[b]	623.4	0.552	0.229	0.99	15488.6
AGG-2 Mt. Athos	21A	5.3	976.7	0.558	0.072	1.00	22265.4
		7.3 OMC	920.5	0.637	-0.066	0.99	20517.8
		7.3 soaked[b]	774.2	0.640	-0.022	0.99	17733.3
AGG-3 Bristol	21B	3.6	1325.2	0.567	0.109	1.00	31064.5
		5.6 OMC	986.3	0.567	0.073	1.00	22657.7
		5.6 soaked[b]	1277.9	0.551	-0.047	0.99	27092.3
AGG-4 Frazier North	21B	5.1	1369.2	0.481	0.262	1.00	32956.6
		7.1 OMC	1241.6	0.492	0.330	0.99	31297.2
		7.1 soaked[b]	1676.9	0.489	0.160	1.00	38258.2
AGG-5 NOVA	21B	5.7	836.6	0.581	0.399	1.00	23360.5
		7.7 OMC	729.4	0.695	0.043	1.00	18040.0
		7.7 soaked[b]	686.7	0.587	0.305	1.00	18259.1
AGG-6 Richmond	21B	6.2	918.2	0.541	0.263	1.00	23071.5
		8.2 OMC	849.7	0.665	0.091	1.00	21150.0
		8.2 soaked[b]	844.1	0.615	0.133	1.00	20765.5

VDOT = Virginia Department of Transportation; MEPDG = Mechanistic-Empirical Pavement Design Guide; OMC = Optimum Moisture Content; NOVA = Northern Virginia District.

[a] Confining pressure = 2 psi, and cyclic deviator stress = 24 psi.

[b] Sample was compacted at OMC and soaked overnight irrespective of saturation level achieved.

the values for 21A or 21B aggregates, in general, the values for the 21B aggregates were higher (18,259 to 31,297 psi) than those for the 21A aggregates (12,800 to 20,518 psi). Both 21A and 21B aggregates were on the finer side of the range. Moreover, none of the 21B aggregate samples complied with VDOT's gradation requirement[17]; they were marginally finer than required on particles larger than 3/8 in. It is also important to note that the 21A aggregate samples did have a higher percentage than the 21B aggregate of material passing the No. 200 sieve as allowed in the VDOT specification.[17]

Influence of Moisture and Density on Resilient Modulus

Three samples from each source were compacted to MDD with three moisture contents and tested for resilient modulus. The achieved densities were above 95 percent of MDD in most of the cases, and the moisture contents were measured within 1 percent of the target. Moisture and density affect the resilient modulus. Since the degree of saturation incorporates moisture and density into one parameter, a value was calculated for each sample to investigate the influence. Tables 8 through 10 summarize the degree of saturation and the measured resilient modulus at certain stress conditions for fine soil, coarse soil, and base aggregate, respectively.

The expected trend of lower resilient modulus values for a higher degree of saturation was seen with all cases, but some showed a stronger correlation than others. Figure 1 shows the trend for fine soils; all samples had a very strong correlation expect those from one source. The correlation was similar for coarse soil samples, as shown in Figure 2. The samples from Battlefield Boulevard were not considered in Figure 2 because only two points per sample were available, but they showed the similar trend of reduced resilient modulus value for a higher degree of saturation as is obvious from Table 8. The aggregate samples also had two points per sample since the third moisture sample could not be constructed. The data in Table 10 confirm the expected influence of moisture. A sample could not be prepared at a moisture content higher than OMC, but the sample prepared at lower moisture showed a higher resilient modulus.

Correlation of Resilient Modulus and Quick Shear Test Results

The quick shear (triaxial) test was performed on all samples at the end of the resilient modulus test and the stresses at 0.1 percent strain from the quick shear test were strongly correlated with the resilient modulus values, similar to the Phase 1 study.[3] These correlations for fine soil, coarse soil, and base aggregate are shown in Figures 3, 4, and 5, respectively. The strong correlations indicate a good possibility that the resilient modulus can be predicted from an independently run static triaxial test similar to the quick shear (triaxial) test.

There are several reasons the triaxial test could not be pursued for coarse soil and base aggregate:

- *For coarse soil and base aggregate, a triaxial testing device would have to be used.* Although the device would be much less expensive than the dynamic loading facility required for the resilient modulus test, the complexity of the triaxial test and the resources needed would be similar to those required for the resilient modulus test.

Table 8. Resilient Modulus and Quick Shear Test Results for Fine Soil

Soil Source	Testing Lab	Compaction Moisture Content (%)	Density % MDD	Degree of Saturation S (%)	Measured Resilient Modulus Value (psi)[a]	Stress at 0.1% Strain (psi)[b]
FS-1 Amherst	VDOT Soils Lab	18	97.6	67.4	13989	10
		18.2	97.3	67.6	13989	9.5
		22.7	98.1	86.0	10938	8
		23.8	97.3	88.4	10445	8
		26.9	95.6	96.0	9974	4.2
		30.3	89.6	93.6	5714	5.1
	Outside vendor	18.2	98.4	69.4	17081	18
		23.6	98.6	90.5	15826	15
		28	93.5	94.8	8748	7
FS-2 Culpeper	VDOT Soils Lab	16.3	95.2	66.9	3473	4.1
		20.1	94.4	80.9	2125	3.5
		21.4	93.6	84.4	2264	3.7
	Outside vendor	16.5	96.5	70.1	3717	4.5
		20	95.6	83.0	3068	4.2
		21.5	95.4	88.8	2897	4.1
FS-3 Salem	VDOT Soils Lab	27.9	97.1	72.9	15072	12.4
		34.5	97.6	91.0	11050	8.8
		36.6	96.6	94.7	8206	6.4
	Outside vendor	27	100.0	74.7	15401	15.8
		33.8	98.6	91.0	12452	11.4
		36	98.4	96.5	11243	9.6
FS-4 NOVA	VDOT Soils Lab	22.4	97.5	97.5	10011	8.4
		27.8	97.1	97.1	7176	5.9
		31.6	95.7	95.7	4464	4.5
	Outside vendor	23	98.0	98.0	10019	8.4
		28.2	97.7	97.7	6648	6
		32	97.0	97.0	4860	5
FS-5 Stadium	VDOT Soils Lab	17.3	96.2	61.4	5794	5.3
		21.3	98.6	80.0	4045	4.2
		24.6	94.6	84.2	2830	3.6
	Outside vendor	18	97.0	65.0	5631	5.1
		21.5	96.4	76.6	3851	4.1
		25.5	94.8	87.6	2266	3.3
FS-6 Hampton	VDOT Soils Lab	11.7	99.1	64.5	19212	16
		15.4	98.9	84.4	15243	11.9
		16.8	99.0	92.3	12590	9.3
	Outside vendor	12.5	98.6	67.8	18096	17.6
		15.9	99.1	87.6	15461	15.8
		17.5	98.9	95.9	15894	12.8

MDD = maximum dry density; VDOT Soils Lab = VDOT Materials Division Soils Lab; NOVA = Northern Virginia District.

[a] Confining pressure = 2 psi, and cyclic deviator stress = 6 psi.

[b] Stress from quick shear test performed at end of resilient modulus test.

Table 9. Resilient Modulus and Quick Shear Test Results for Coarse Soil

Soil Source	Testing Lab	Compaction Moisture Content (%)	Density % MDD	Degree of Saturation S (%)	Measured Resilient Modulus Value (psi)[a]	Stress at 0.1% Strain (psi)[b]
CS-1 Richmond	Outside vendor	9.6	98.8	70.0	5714	7.4
		11.5	97.7	80.6	5005	6.15
		13	98.4	93.3	4648	5.55
CS-2 Lynchburg	Outside vendor	14	99.6	65.4	10077	8.7
		16	99.7	74.9	8049	6.9
		19.5	98.3	87.9	3876	4.4
CS-3 Bristol	Outside vendor	18	99.0	68.1	18952	20.45
		22.1	99.5	84.6	16264	16
		25.5	98.3	94.9	10486	8.7
CS-4 Fredericksburg	Outside vendor	9.5	97.2	57.3	7534	9.1
		11.5	97.6	70.4	6712	7.9
		13	97.1	78.2	6997	8.55
CS-5 NOVA	Outside vendor	11.6	99.7	65.1	15766	12.5
		14.5	99.5	80.9	8170	6.8
		17.4	97.9	92.6	2884	4.55
CS-6 Battlefield Blvd.	VDOT Soils Lab[c]	11.9	97.7	60.6	6656	7.77
		10.0	96.6	49.4	6901	7.90
CS-7 Battlefield Blvd.	VDOT Soils Lab[c]	11.1	96.5	84.4	4593	5.9
		10.0	95.3	72.5	6179	6.98
CS-8 Battlefield Blvd.	VDOT Soils Lab[c]	12.1	96.8	64.7	6704	7.80
		10.1	96.8	53.8	6796	7.92
CS-9 Battlefield Blvd.	VDOT Soils Lab[c]	10.2	98.3	66.4	6873	7.93
		8.5	96.8	52.3	6926	8.20
CS-10 Battlefield Blvd.	VDOT Soils Lab[c]	10.3	97.3	64.0	6313	7.82
		8.5	96.9	52.0	6470	7.87

MDD = maximum dry density; VDOT Soils Lab = VDOT Materials Division Soils Lab; NOVA = Northern Virginia District.

[a] Confining pressure = 2 psi, and cyclic deviator stress = 6 psi.

[b] Stress from quick shear test performed at end of resilient modulus test.

[c] Average of three replicate samples.

Table 10. Resilient Modulus and Quick Shear Test Results for Base Aggregate

Soil Source	VDOT Classification	Compaction Moisture Content (%)	Moisture Content at End of Test (%)	Density % MDD	Degree of Saturation, S (%) (at end)	Model 3 Resilient Modulus Value (psi)[a]	Stress at 0.1% Strain (psi)[b]
AGG-1 Shelton	21A	6	5.9	100	58.0	19215.0	11.1
		8 OMC	7.7	100	76.5	12800.8	7.2
		8 soaked[c]	9.1	100	90.1	15488.6	6.69
AGG-2 Mt. Athos	21A	5.3	5.2	100	71.3	22265.4	12.8
		7.3 OMC	5.8	100	79.5	20517.8	14.86
		7.3 soaked[c]	6.1	100	83.6	17733.3	10.77
AGG-3 Bristol	21B	3.6	3.3	100	42.4	31064.5	21.1
		5.6 OMC	5.1	100	65.5	22657.7	15
		5.6 soaked[c]	6	100	77.1	27092.3	18.5
AGG-4 Frazier North	21B	5.1	5	100	63.6	32956.6	21.56
		7.1 OMC	6.7	100	85.2	31297.2	22
		7.1 soaked[b]	5.5	100	69.9	38258.2	23.84
AGG-5 NOVA	21B	5.7	5.6	100	67.2	23360.5	14.5
		7.7 OMC	6.9	100	82.8	18040.0	11.76
		7.7 soaked[c]	6.8	100	81.6	18259.1	10.7
AGG-6 Richmond	21B	6.2	5.9	100	56.7	23071.5	14.2
		8.2 OMC	7.5	100	72.0	21150.0	13.5
		8.2 soaked[c]	6.1	100	58.6	20765.5	11.4

VDOT = Virginia Department of Transportation; MDD = maximum dry density; NOVA = Northern Virginia District.

[a] Confining pressure = 3 psi, and cyclic deviator stress = 24 psi.

[b] Stress from quick shear test performed at end of resilient modulus test.

[c] Sample was compacted at OMC and soaked overnight irrespective of saturation level achieved.

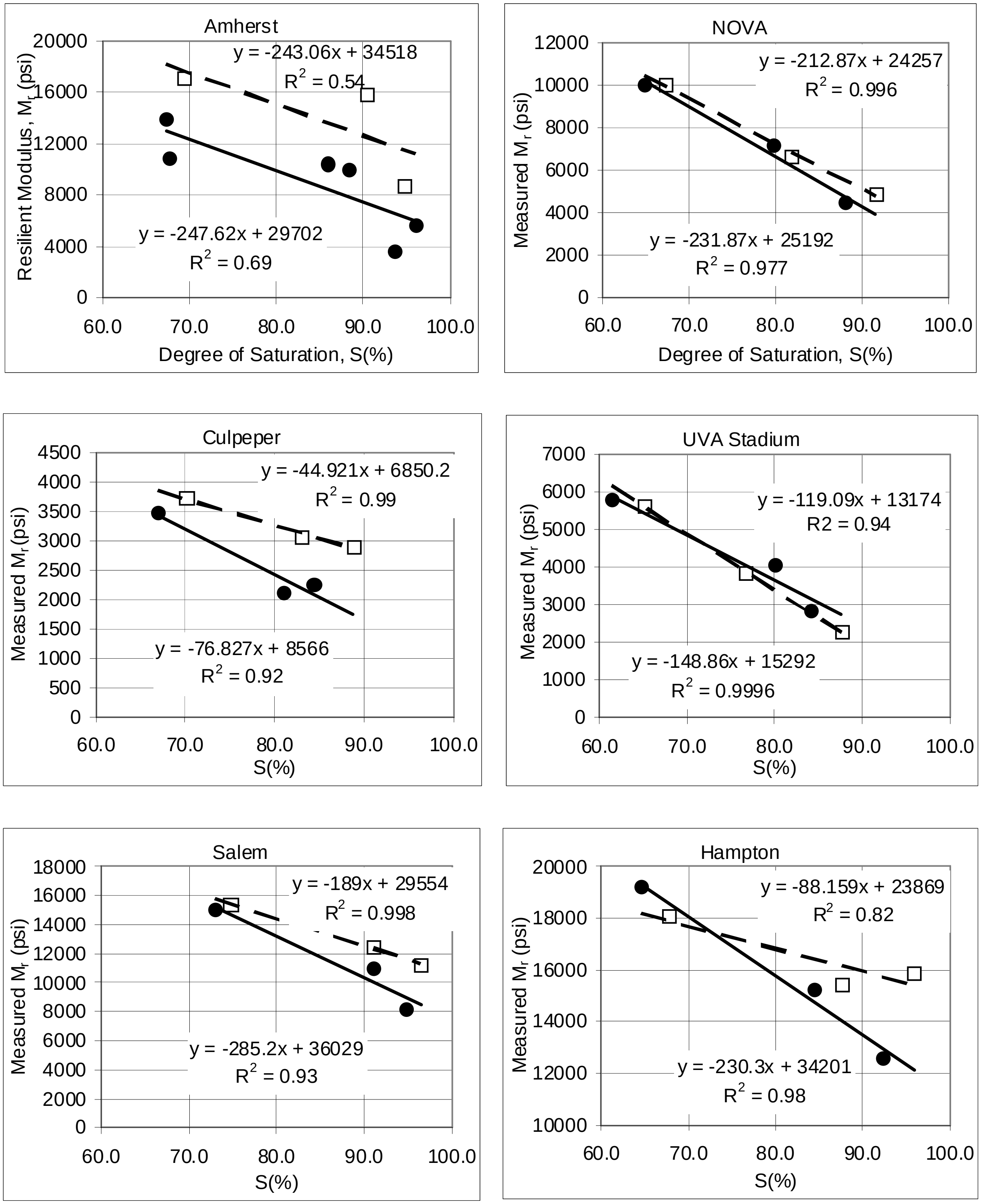


Figure 1. Influence of Moisture Content on Resilient Modulus Value for Fine Soil. Solid line = values measured by Virginia Department of Transportation; dotted line = values measured by outside vendor.

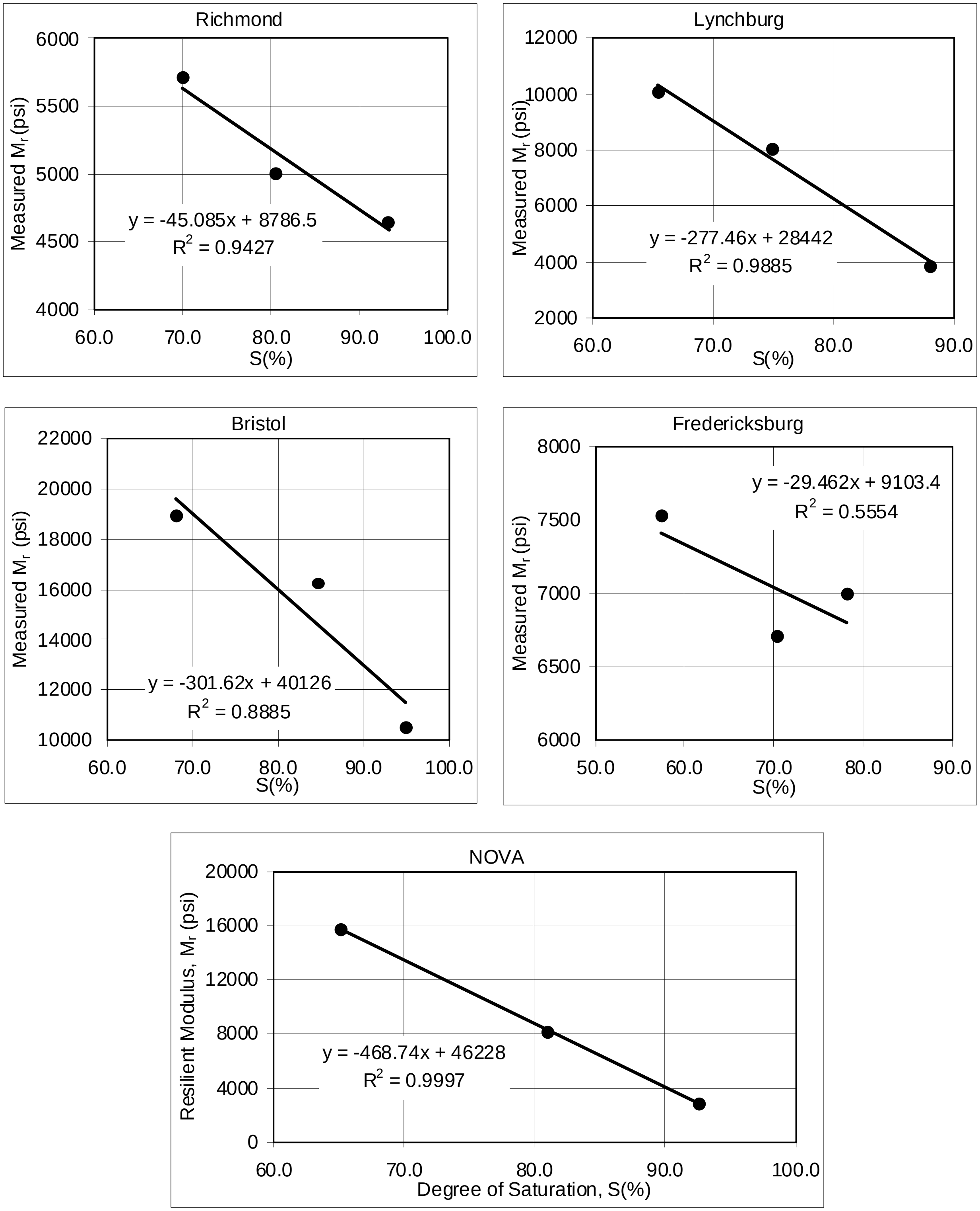


Figure 2. Influence of Moisture Content on Resilient Modulus Values for Coarse Soil

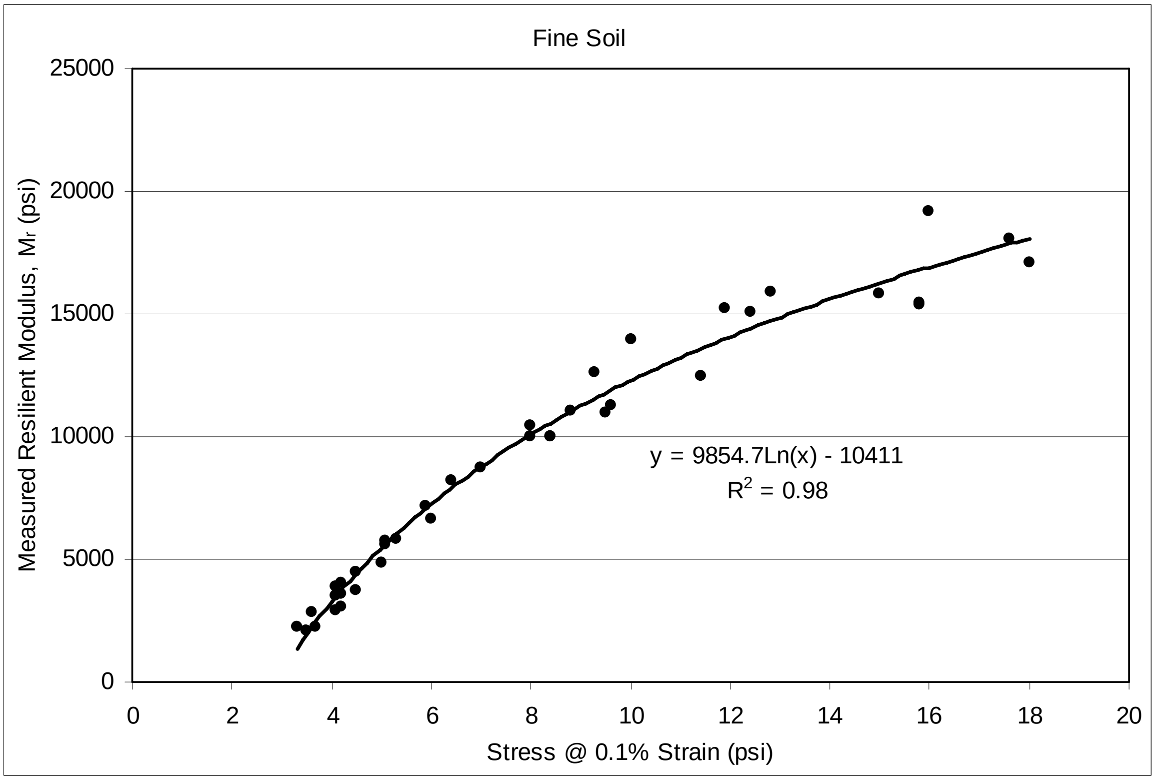


Figure 3. Correlation of Resilient Modulus and Stress at 0.1% Strain From Quick Shear Test for Fine Soil

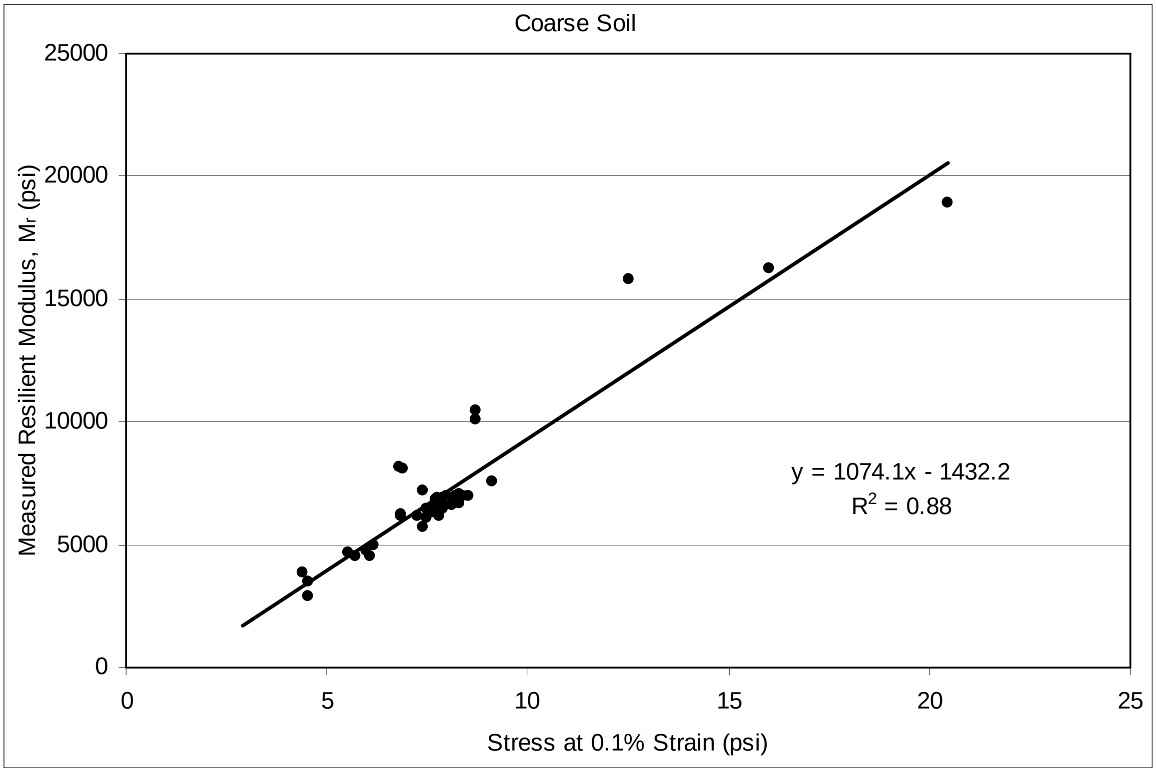


Figure 4. Correlation of Resilient Modulus and Stress at 0.1% Strain From Quick Shear Test for Coarse Soil

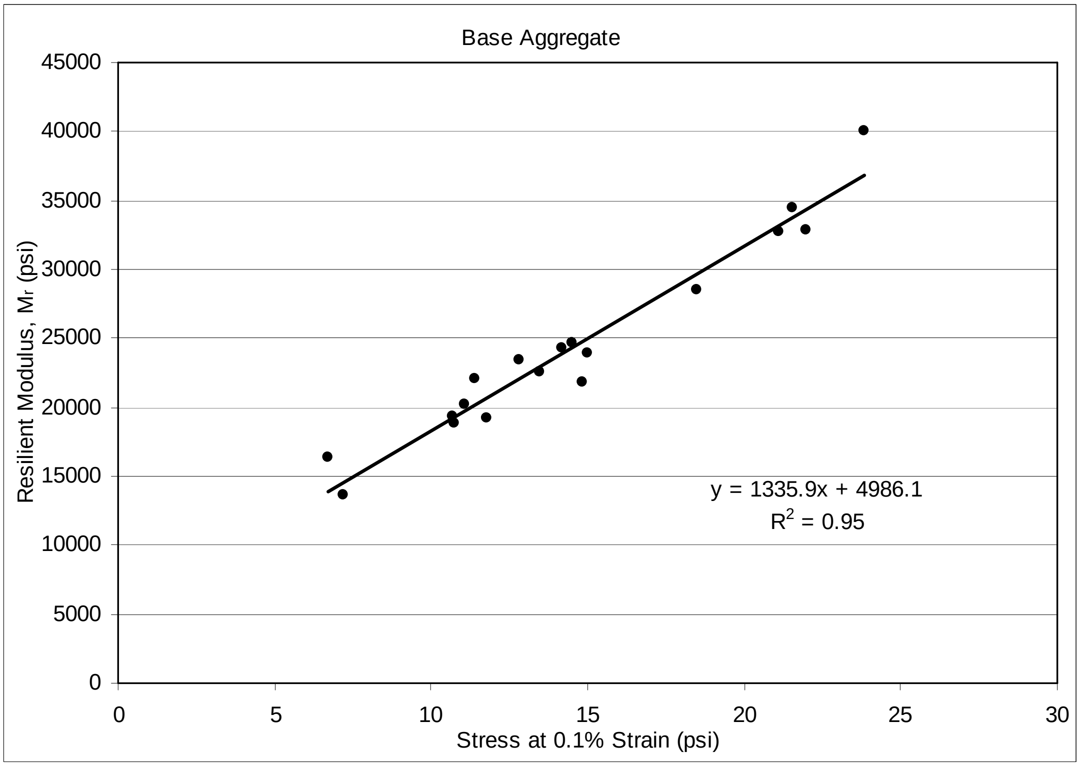


Figure 5. Correlation of Resilient Modulus and Stress at 0.1% Strain From Quick Shear Test for Base Aggregate

Moreover, the expense of this test is comparable to that of the resilient modulus test by an outside vendor.

- *The reliability of the data from a static triaxial test is questionable.* The stress at 0.1 percent strain represents the initial portion of the stress-strain curve similar to the initial tangent modulus, and this portion of the curve is usually affected by many factors such as the sample preparation, seating load, and irregular loading surface. Although a correction could be applied, it would be subjective. On the contrary, samples were well conditioned by many cycles of loading from the resilient modulus test before the quick shear (triaxial) test so none of these conditions existed.

- *In order to develop a prediction model, both the resilient modulus test and triaxial test need to be conducted on the same sample or replicate samples.* It is not practical to conduct both tests on the same sample, and it would also be very difficult to produce a replicate sample.

On the other hand, a fine soil is usually cohesive and an unconfined compression test, the simplest form of a static triaxial test, could easily be performed on them. The resources needed for this test are much less than those needed for a resilient modulus test or a full triaxial test. A stress-strain diagram could easily be generated from an unconfined compression test. Of course, a correction (similar to the CBR test) needs to be applied for the initial portion of the curve but the test itself is simple to conduct in-house.

Use of Unconfined Compression Test to Predict Resilient Modulus for Fine Soil

As mentioned earlier, the unconfined compression test was conducted only on fine soil samples. A stress-strain diagram was produced as part of the results. The VDOT Soils Lab used the same static compactor as in the resilient modulus test to prepare samples at OMC and 100 percent MMD. The VTRC Lab produced three samples for each source using the Proctor hammer and three using the Harvard miniature compactor. These samples were prepared at three moisture contents but at the same 100 percent MMD to produce a range of degree of saturation from 50 to 100 percent. The actual moisture content and density and the unconfined compression test results are presented in Table 11. The stress-strain diagram was corrected for the initial concave portion of the curve, 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 correct curve drawn through the origin. The secant modulus at 1 percent strain was calculated as the slope of the line drawn from the origin to the 1 percent strain point on the stress-strain plot. Finally, the failure strength is noted as the conventional result of a standard unconfined compression test. The stress-strain behavior was influenced by the sample preparation method/ technique, so all three sets (static, Proctor, and Harvard) were considered and analyzed separately.

The effect of degree of saturation was evaluated for samples prepared using the Proctor hammer and the Harvard miniature compactor. The variation of initial tangent modulus with degree of saturation was investigated and is presented in Figures 6 and 7 for the Proctor hammer and Harvard miniature compactor, respectively. In general, a linear decreasing value of initial tangent modulus with increasing degree of saturation was observed. The samples prepared with the Proctor hammer showed a fairly strong correlation for all six sources, whereas only four sources for the Harvard samples showed a similar correlation. The Harvard samples from Culpeper showed low strength irrespective of moisture content; these samples were very difficult to prepare as the soil was silty with very little cohesion. One sample from Hampton showed a very high strength compared to the other two, and no explanation for this was found except for the small size of the sample. Although a smaller sample usually would have fewer defects than a larger one, the smaller Harvard sample may not always be representative. It is obvious from Table 11 that the Harvard samples are always stronger than the Proctor or static samples. Both sample size and compaction method might have contributed to this finding.

The strong correlation of resilient modulus and the stress at 0.1 percent strain from the quick shear (triaxial) test indicates the possibility of predicting resilient modulus from the initial tangent modulus derived from an unconfined compression test of fine soil. In order to develop the prediction model, both tests must be done on the same sample or on replicate samples. Testing of the same sample was impractical, so replicate sample testing was tried with limited success. Since both the OMC and MDD of a soil sample depend on degree of saturation, replicate samples were prepared to match saturation levels as practical as possible. Where matching saturation levels was not achieved, an interpolated value of resilient modulus was used for the model development. The samples compacted only at OMC were used because the prediction model is expected to be used at OMC. Resilient modulus prediction models for the Proctor and static samples are presented in Figure 8. The initial tangent modulus of the stress-strain curve generated from the unconfined compression test is used as the only independent

Table 11. Unconfined Compression Test Results for Fine Soil

Soil Source	VDOT Lab[a]	Compaction Moisture Content (%)	Density % MDD	Degree of Saturation S (%)	Initial Tangent Modulus (psi)	Secant Modulus at 1% Strain (psi)	Failure Strength (psi)
FS-1 Amherst	Soils	23.4 OMC	97.7	87.8	56.4	40	65.8
	VTRC (Proctor)	18.2	99.8	92.3	58.8	32.8	33.3
		23.4 OMC	96.2	98.8	30	31	78
		27.3	97.5	68.0	8	8	39.2
	VTRC (Harvard)	17.4	97.3	64.6	270	n/a[b]	166
		21.7	99.3	84.6	86.7	90	132
		26.3	97.2	97.5	21	21	65.8
FS-2 Culpeper	Soils	15.8 OMC	95.4	65.2	6	7	14.7
	VTRC (Proctor)	16.7 OMC	98.2	74.1	8	8	17.5
		19.7	95.7	82.0	2.4	2.5	11.6
		21.1	94.4	85.0	1.4	1.5	8.7
	VTRC (Harvard)	16.2	97.2	69.9	5	5.4	16.8
		18.7	97.5	81.6	5.75	5.7	16.3
		19.3	98.0	85.0	4.8	4.8	16.6
FS-3 Salem	Soils	33.4 OMC	98.3	89.3	60	38.5	52.3
	VTRC (Proctor)	26.5	99.7	72.9	61	57.5	104.8
		32.6 OMC	102.5	95.0	33.3	29	65.5
		35.4	99.0	96.0	14.2	9.2	34.7
	VTRC (Harvard)	26.2	98.9	70.8	93	83	108
		32.5	100.3	90.4	53.3	38.5	67
		34.1	99.7	93.8	25.6	26	58
		34.9	98.7	94.0	24.5	22.5	48
FS-4 NOVA	Soils	29.1 OMC	96.1	81.6	16.7	19.5	33.4
	VTRC (Proctor)	22.8	101.9	72.1	32.2	32	51.7
		27.1 OMC	102.7	87.4	12.9	13	42
		30.8	99.0	92.0	3.9	4	20.6
	VTRC (Harvard)	21.6	99.4	65.0	26.7	26.2	38.2
		26.5	99.4	79.8	18.5	17	31.2
		31.1	98.4	91.5	8.2	8.2	22
FS-5 Stadium	Soils	21.1 OMC	95.5	73.7	16.6	12	24.6
	VTRC (Proctor)	18.5	98.0	68.4	27.5	16	25.7
		22.1 OMC	96.7	79.3	11.8	11	26.4
		24.6	95.5	85.9	4.03	4	17
	VTRC (Harvard)	17.6	99.1	66.7	18.2	18	34.4
		21.0	100.8	82.7	10.9	11	34
		24.3	97.5	89.0	4.8	4.8	19.5
FS-6 Hampton	Soils	15.0 OMC	99.1	82.7	70	43	53.3
	VTRC (Proctor)	12.0	92.3	53.9	87	65	66
		16.0 OMC	98.8	87.2	46.7	44	83.4
		17.5	98.4	94.3	19	19	60.1
	VTRC (Harvard)	12.0	96.6	61.1	93.6	90	101
		15.4	98.8	83.9	112.5	115	427
		16.9	98.5	91.4	31.25	31.5	57

VDOT = Virginia Department of Transportation; MDD = maximum dry density; NOVA = Northern Virginia District.

[a] All samples were prepared at the VDOT Materials Division Soils Lab (Soils) or the Virginia Transportation Research Council Lab (VTRC). The VDOT Soils Lab used a static compactor for 2.9 in by 5.8 in samples. The VTRC Lab used the Proctor hammer (Proctor) for 3 in by 6 in samples and the Harvard miniature compactor (Harvard) for 1.3 in by 2.8 in samples.

[b] The sample broke before reaching 1% strain.

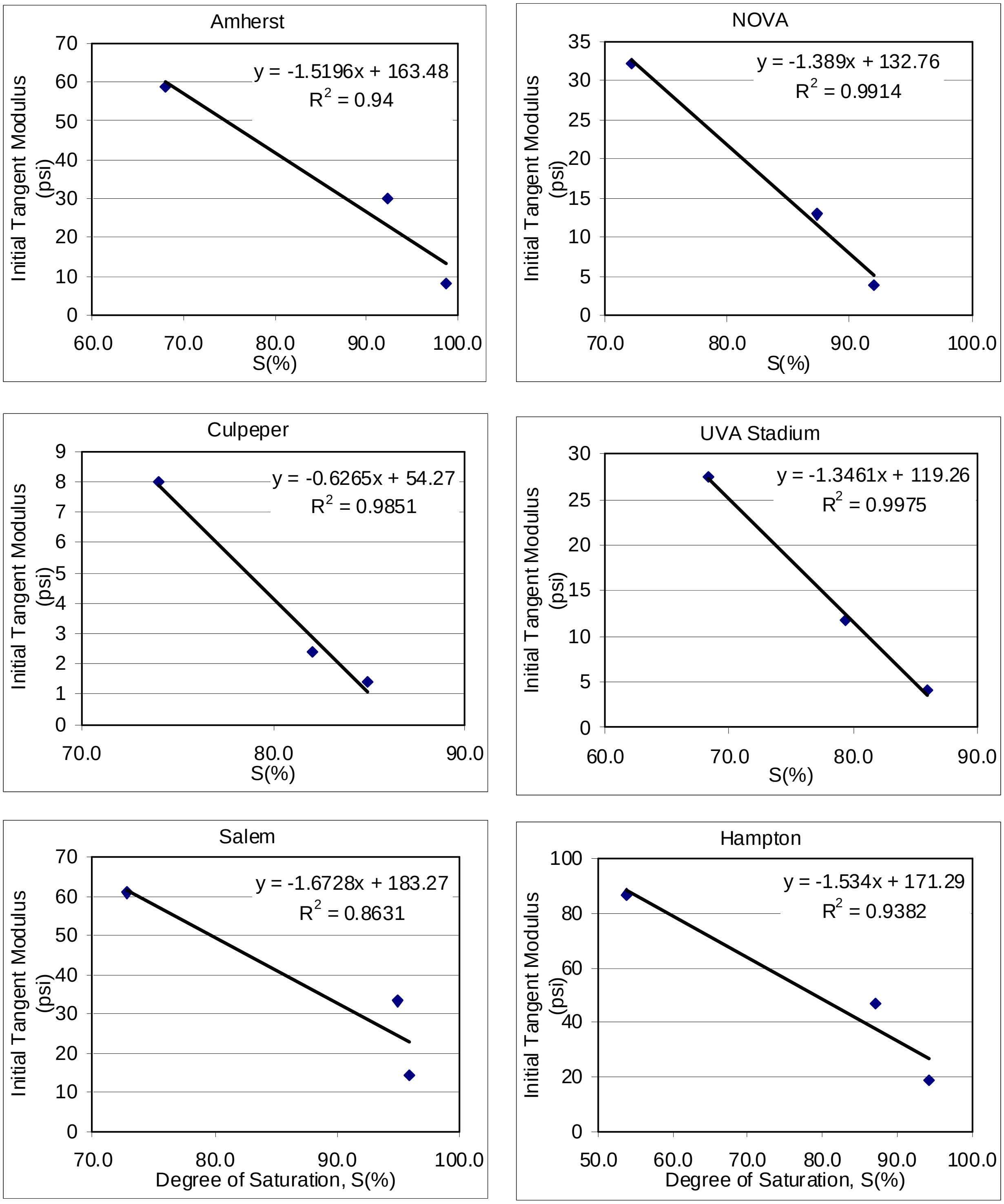


Figure 6. Influence of Moisture Content on Initial Tangent Modulus for Fine Soil Samples Prepared With Proctor Hammer

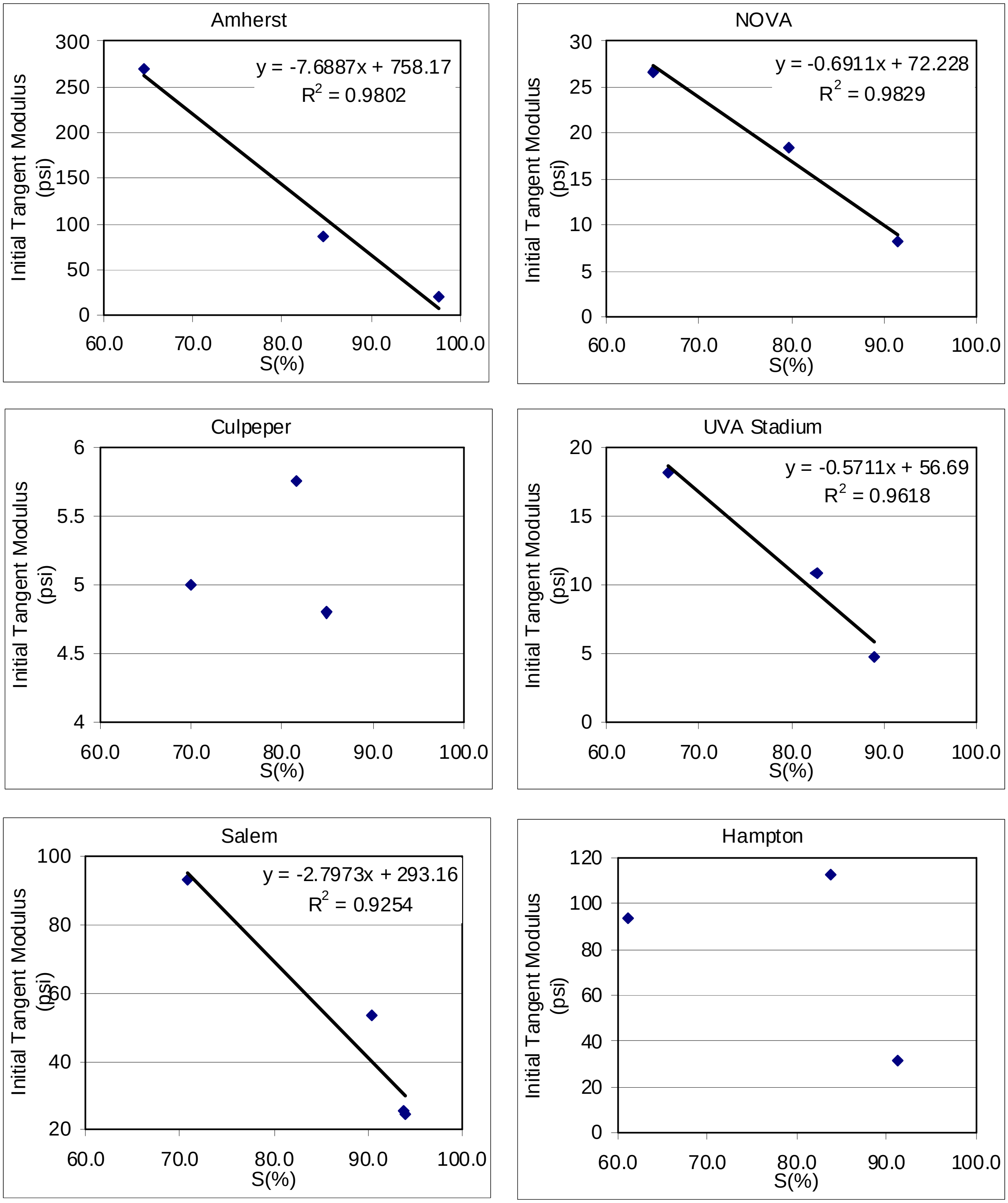
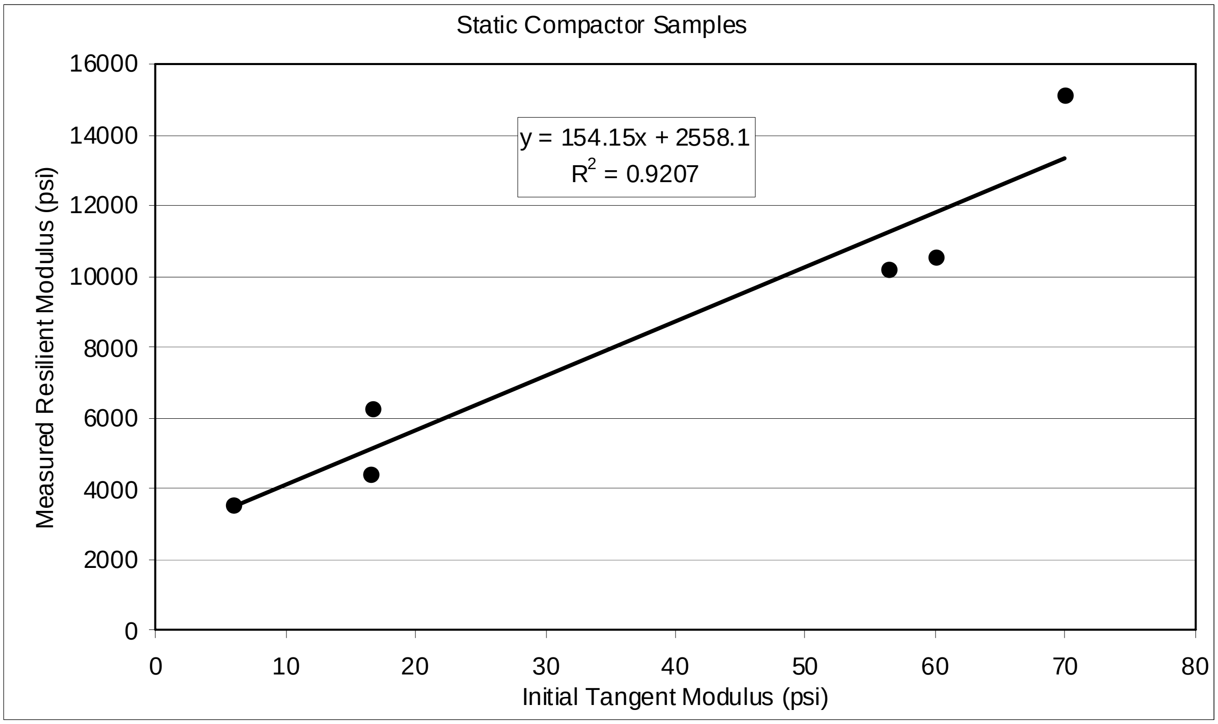


Figure 7. Influence of Moisture Content on Initial Tangent Modulus for Fine Soil Samples Prepared With Harvard Miniature Compactor



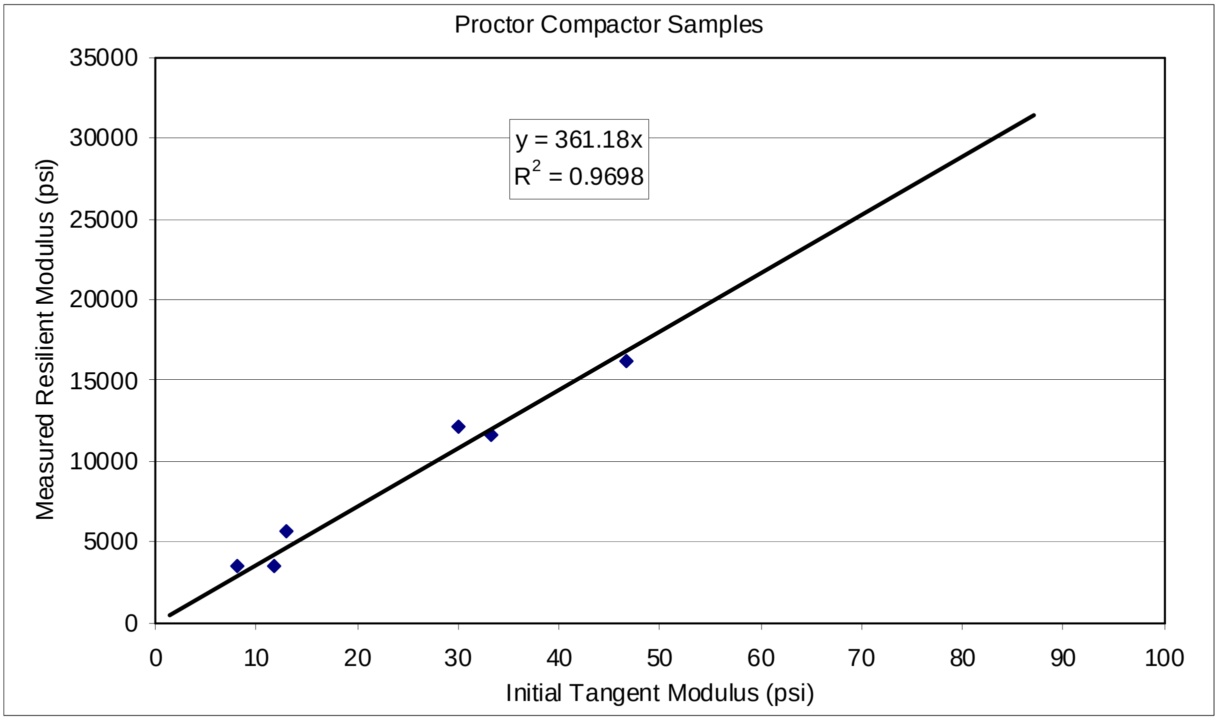


Figure 8. Models to Predict Resilient Modulus From Unconfined Compression Test for Fine Soil Samples

variable for the regression analysis to predict resilient modulus. The regression statistics are summarized in Table 12. Both models and the coefficients for the variables are significant at the 5 percent confidence level. The intercept for the static model is significant at 7 percent. The standard error for the static and Proctor models is 1,391 psi and 917 psi, respectively. The predicted value would be within ±1 standard error 68 percent of the time and ±2 standard errors 95 percent of the time. These values seem to be acceptable considering the variability of soil in terms of field moisture content, density, location, and soil type along a project. Only six points (sources) were used to develop the model, so these models need to be updated as more data points become available.

Table 12. Regression Statistics for Resilient Modulus Prediction Models

Regression Statistics		**Model: Static Compactor**	**Model: Proctor Hammer**
Dependent variable		Resilient modulus values (psi)	Resilient modulus values (psi)
Independent variable		Initial tangent modulus (psi)	Initial tangent modulus (psi)
Intercept		Non-zero	Zero
No. of observations		6	6
R^2		0.92	0.99
Adjusted R^2		0.90	0.79
Standard error		1391	917
F - value		46.4	707.2
F - significance		0.0024	0.000012
Intercept	Coefficient	2558.13	N/A
	t-statistic	2.5	N/A
	p-value	0.067	N/A
Variable 1	Coefficient	154.15	361.18
	t-statistic	6.81	26.59
	p-value	0.0024	0.0000014

CONCLUSIONS

- *The degree of saturation has a significant effect on the resilient modulus value but the nature of the effect is specific to a particular soil or aggregate.* This specific nature has been attributed to different pore structures and suction characteristics of soil or aggregate.

- *Resilient modulus values for fine soil, coarse soil, and base aggregate are determined from the dynamic resilient modulus test; however, a reasonable estimate can be obtained from a static triaxial test such as the quick shear (triaxial) test mentioned in AASHTO T 307.* 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 percent strain obtained from the stress-strain diagram of a quick shear (triaxial) test. Both the static and dynamic triaxial tests are difficult to conduct.

- *The resilient modulus values for coarse soils need to be measured or used from a catalog of values specific to VDOT.* No reasonable correlations with other soil properties except for the results of the quick shear (triaxial) test were found. Moreover, the measured resilient modulus values were low compared to the values suggested in the MEPDG range for both small (Type 2) and large (Type 1) samples.

- *Coarser base aggregate is stiffer than finer gradation materials.* In general, VDOT 21B aggregate is stiffer than 21A aggregate as 21B aggregate has a coarser gradation with less material passing the No. 200 sieve. The resilient modulus value ranged from 12,800 to 20,517 psi and 18,259 to 31,297 psi for 21A and 21B aggregates, respectively. It is important to note that the tested 21B aggregates were usually on the finer side of the specification limit, and in some cases large (+3/8 in) particles were marginally finer than specified.

- *The resilient modulus value for fine soil can be estimated from the initial tangent modulus of the stress-strain curve obtained from the unconfined compression test.* The correlation ($R^2 > 0.9$) was strong between the initial tangent modulus and resilient modulus values measured at a confining pressure of 2 psi and a deviator stress of 6 psi. An unconfined compression test is the simplest form of triaxial (quick shear) test and could be conducted for fine cohesive soils only.

RECOMMENDATIONS

1. *VDOT's Materials Division should use resilient modulus values for characterizing subgrade soils and base aggregate when MEPDG design/analysis is implemented.*

2. *VDOT's Materials Division should consider using the universal constitutive model recommended by the MEPDG (Model 3 in this study) to generate k-values needed as input to MEPDG Level 1 design/analysis for resilient modulus calculation.*

3. *VDOT's Materials Division should develop a database of resilient modulus values (or k-values), which could be used in MEPDG design/analysis when appropriate (if a reasonable material match were found).*

4. *VDOT's Materials Division should consider using a catalog of resilient modulus values or actual dynamic testing for all unbound (subgrade and base) materials.* However, the unconfined compression test, a simpler and less expensive test, could also provide similar results for fine soil. This test can easily be conducted in VDOT district labs.

5. *VDOT's Materials Division should use the initial tangent modulus from an unconfined compression test to predict the resilient modulus values of fine soils (AASHTO classifications A-4, A-5, A-6, and A-7) for MEPDG Level 2 input and the currently used 1993 AASHTO design.*

6. *VDOT's Materials Division should collect more data for the unconfined compression test and update the prediction model for fine soil in collaboration with VTRC.*

BENEFITS AND IMPLEMENTATION PROSPECTS

Implementing the recommendations provided in this study would support and expedite the implementation efforts currently under way by VDOT's Materials Division to initiate the statewide use of the MEPDG. The use of the MEPDG is expected to improve VDOT's pavement design capability and should allow VDOT to design pavements with a longer service life and fewer maintenance needs and to predict maintenance and rehabilitation needs more accurately over the life of the pavement.

VDOT can readily implement the use of the resilient modulus test in place of the conventional CBR test in the current AASHTO 1993 pavement design and enhance its reliability. VDOT's Materials Division is capable of conducting resilient modulus testing, which usually takes less time and soil compared to CBR testing.

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