Final Report VTRC 09-R4

Virginia Transportation Research Council

research report

Characterization of Subgrade Resilient Modulus for Virginia Soils and Its Correlation with the Results of Other Soil Tests

http://www.virginiadot.org/vtrc/main/online_reports/pdf/09-r4.pdf

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Standard Title Page - Report on Federally Funded Project

1. Report No. FHWA/VTRC 09-R3	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Assessment of Soil and Wash Water Quality Beneath Salt-Spreader Racks		5. Report Date July 2008 6. Performing Organization Code
7. Author(s) Megan Fuller, G. Michael Fitch, and James A. Smith		8. Performing Organization Report No. VTRC 09-R3
9. Performing Organization and Address Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 81142
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

The Virginia Department of Transportation's (VDOT) winter maintenance program hinges primarily on the use of granular NaCl for deicing. On average, VDOT applies more than 300,000 tons of NaCl each winter season. The majority of this salt is spread by way of salt-spreaders attached to dump trucks. The spreaders require cleaning and lubricating after each use. The purpose of this research was to determine if VDOT should provide an impermeable surface beneath the spreaders to prevent potential contamination resulting from lubrication and, if so, to determine if washing could occur on the same impermeable surface, thus reducing the number of times the spreaders are handled by providing a single location for washing and lubricating.

The results showed that potentially significant volumes of excess lubricants can be generated by way of the spreader lubrication process and that this excess should, therefore, be captured. In the majority of cases, this could be done by means of a drip pan or similar device. Because of dilution, if washing and lubrication were to occur at the same location and the wash water and lubricant mixture were contained and conveyed to the nearby salt ponds, lubricant concentrations found in the pond water would be relatively low. Although laboratory results indicate that these concentrations could be reduced even further by way of an in-line organoclay filter, this method of lubricant capture would be more expensive and labor intensive than the simple use of drip pans.

Although paving beneath existing spreader racks was not advised unless other provisions for washing at the spreader racks are also made available, proposed best management practices were developed for three different site conditions that are likely to be found at VDOT's maintenance facilities. The benefits of following these practices include decreased potential for soil contamination beneath spreader racks and decreased potential for wash water runoff contamination and associated salt pond contamination.

17. Key Words Spreader racks, spreader lubricants, runoff, wash water	18. Restrictions No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 22	22. Price

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

FINAL REPORT

CHARACTERIZATION OF SUBGRADE RESILIENT MODULUS FOR VIRGINIA SOILS AND ITS CORRELATION WITH THE RESULTS OF OTHER SOIL TESTS

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(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

August 2008
VTRC 09-R4

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ABSTRACT

In 2004, the *Guide for the Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures* (MEPDG) was developed under NCHRP Project 1-37A to replace the currently used 1993 *Guide for Design of Pavement Structures* by the American Association of State Highway and Transportation Officials, which has an empirical approach. Implementation of the MEPDG requires the mechanistic characterization of pavement materials and the calibration of performance prediction models by the user agencies.

The purpose of this study was (1) to determine the resilient modulus values for Virginia's subgrade soils for input into MEPDG design/analysis efforts, and (2) to investigate the possible correlation of the resilient modulus with other soil properties. Although the MEPDG provides default values and correlations for resilient modulus, they are based on a limited number of tests and may not be applicable for Virginia soils and aggregates. The possible correlation of the resilient modulus with other soil properties was investigated because such correlations could be used for smaller projects where costly and complex resilient modulus testing is not justified. More than 100 soil samples from all over Virginia representing every physiographic region were collected for resilient modulus, soil index properties, standard Proctor, and California Bearing Ratio testing.

Resilient modulus values and regression coefficients (*k*-values) of constitutive models for resilient modulus for typical Virginia soils were successfully computed. There were no statistically significant correlations between the resilient modulus and all other test results, with the exception of those for the quick shear test, for which the correlation was very strong (R^2 = 0.98). The study recommends that the Virginia Department of Transportation's Materials Division (1) implement resilient modulus testing for characterizing subgrade soils in MEPDG Level 1 pavement design/analysis, and (2) use the quick shear test to predict the resilient modulus values of fine soils using the relationships developed in this study for MEPDG Level 2 design/analysis.

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INTRODUCTION

As with any other structure, a pavement structure is supported by the underlying soil. The design of the entire pavement structure depends on the condition of the soil. Therefore, characterizing the soil layer, also known as the subgrade, is a critical component for pavement design and, thus, the performance and life of the pavement structure. The traffic load is not usually very high, but the dynamic and repetitive nature of the load complicates pavement design. Although the California Bearing Ratio (CBR) comprises a static approach, it is widely used by the transportation community to characterize subgrade soil for pavement design. Such a design concept is empirical and is based on previous performance and experience.

Material characterization is an essential part of any pavement design procedure. Subgrade 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 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 from the AASHO road test, which were limited to a particular soil and environmental condition.

To overcome the limitations of empirical design, a recent NCHRP project (1-37A) proposed a new 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.

Resilient Modulus

The *resilient modulus* (M_r) is the ratio of the applied deviator stress to the resulting recoverable axial strain. Many standards exist (and differ in approach, methods, and results) for determining resilient modulus values for unbound materials, including the following:

- *AASHTO T 294-92[3]:* Resilient Modulus of Unbound Granular Base/ Subbase Materials and Subgrade Soils
- *AASHTO T 292-91[3]:* Resilient Modulus of Subgrade Soils and Untreated Base/ Subbase Materials
- *AASHTO T 307-99[4]:* Determining the Resilient Modulus of Soils and Aggregate Materials
- *NCHRP 1-28[5]:* Laboratory Determination of Resilient Modulus for Flexible Pavement Design
- *NCHRP 1-28A[5]:* 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; k_3 is usually negative, as increasing the shear stress (or deviator stress) will generally produce a softening of the material.[6]

MEPDG Design/Analysis

There are three levels of design for the MEDPG 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 from resilient modulus testing are required for Level 1 pavement design where a high volume of traffic is expected. Because of the complexity of the 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 allows for input of the regression constants of the constitutive model for a specific subgrade soil. This ensures a more accurate assessment of the modulus during the analysis over the design period including seasonal variation and varying stress conditions. Constitutive model coefficients from similar soils and test specimen conditions can also be combined to obtain "pooled" *k*-values for use in MEPDG Level 1 design/analysis.

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 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 an M_r value is through the use of correlations with other soil test properties such as the CBR. Another approach is to use the 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-co-linearity 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 (1) to determine the resilient modulus for Virginia's subgrade soils for input into the MEPDG design/analysis, and (2) to investigate the possible correlation of the resilient modulus with other soil properties. The possible correlations with other soil properties were investigated because such correlations, if they exist, could be used for smaller projects where costly and complex resilient modulus testing is not justified.

The scope of this study was limited to subgrade soils. A follow-up study will focus on coarse soils and base/subbase aggregates.

METHODOLOGY

Overview

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

1. The literature was reviewed to determine the state of the practice regarding the use of the resilient modulus in pavement analysis/design.

2. Soil samples from across Virginia were collected and classified according to both the AASHTO and the Unified Soil Classification System (USCS) systems.

3. Laboratory testing was conducted on all soil samples to characterize specific physical and mechanical properties. Testing 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.

4. All test results were compared to those of the resilient modulus test to determine any possible correlations.

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 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, 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.

Soil Selection and Classification

Soil samples were collected at the existing construction projects in the nine VDOT construction districts by the respective district staff over a 2-year period in 2003 and 2004. A total of 124 soil samples were collected. Their distribution is shown in Figure 1 on a physiographic map of Virginia. Although adequate representation from all five physiographic provinces of Virginia was not planned, it was verified by this plot. All soil samples were classified in accordance with both AASHTO M 145,[4] Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes, and ASTM D 2487,[8] Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).

Laboratory Testing

Soil samples were tested at the VDOT Materials Division Soils Lab. Testing 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.

Resilient Modulus Test

Description of Test

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.[4] A recent NCHRP study[5] (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 performed. In order to investigate the effect of moisture content on the resilient modulus value, another set of samples was compacted and tested for resilient modulus at 20 percent more moisture than the optimum moisture content (OMC).

A sample 2.9 in in diameter was compacted at OMC and maximum dry density (MDD) using 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.

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

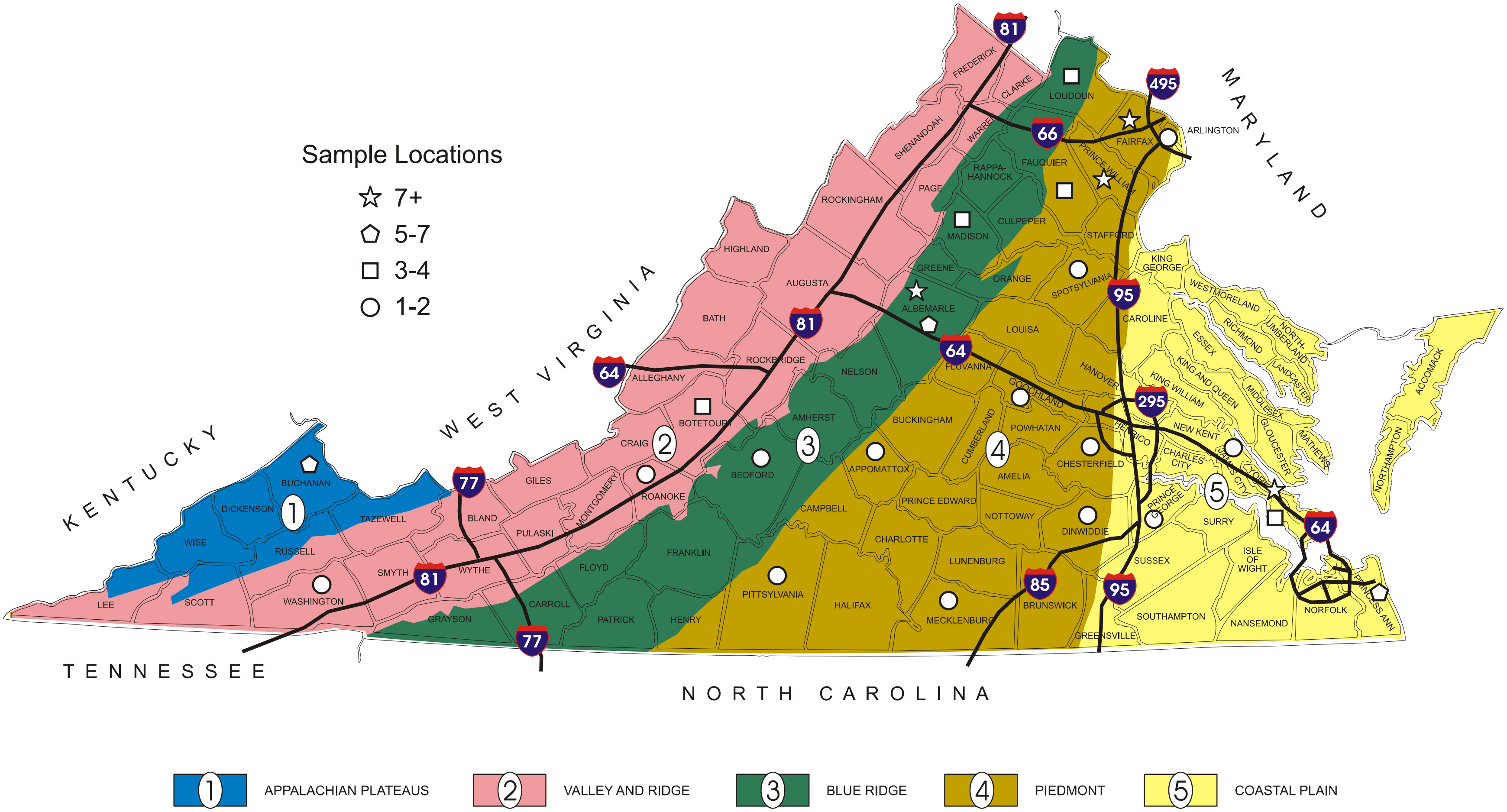


Figure 1. Physiographic Distribution of Soil Samples Tested

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 Materials Division Soils Lab). This is the default model used by the data reduction program at the VDOT Materials Division Soils Lab in its resilient modulus testing setup. This model is referenced by Andrei et al.:[5]

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

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 1993 AASHTO design). Von Quintus and Killingsworth[9] 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 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 loading for the shear test 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),[4] liquid limit (AASHTO T-89),[4] and plastic limit (AASHTO T-90)[4] were determined. The OMC and MDD were determined using the standard Proctor test (AASHTO T-99).[4] The degrees of saturation of the tested samples were calculated assuming a specific gravity value of 2.65; a few measured values were also available. A value of 2.7 to 2.85 was used for a few samples to avoid negative void ratios during calculation of degrees of saturation.

California Bearing Ratio Test

Most soil samples were tested to determine the soaked and unsoaked CBR in accordance with Virginia Testing Method-8: Conducting California Bearing Ratio Test.[10] The VTM-8 test procedure is similar to that specified in AASHTO T 193,[4] and the results are comparable.

A cylindrical soil sample 6 in by 6 in was compacted in a mold at OMC and MDD. The CBR value was calculated as the ratio of load needed to have an 0.1-in penetration of a circular spindle of 3 in^2 in area to 3,000 lb. A soaked CBR was also determined after the sample was soaked for 96 hr under water.

RESULTS AND DISCUSSION

Literature Review

Rahim[11] discussed two correlation equations to predict M_r for fine and coarse (sand) soils. The soils used in the study were selected to represent a range of typical subgrade materials found in Mississippi. A consistent trend was noted: for fine soils, the deviator stress had a significant effect on M_r, whereas confining pressure only had a slight effect. For coarse soils, the resilient modulus significantly increased with increased confinement and had a varied response to changes in deviator stress. The author postulated that the varied deviator stress response might be attributable to physical properties of the sample such as percent passing the No. 200 sieve and/or moisture content. A representative value of M_r was defined as occurring under a 2 psi lateral confining pressure and a 5.4 psi deviator stress. Regression models were then developed for each soil class (fine vs. coarse). For fine soils, M_r was a function of liquid limit, water content, dry density, MDD, and percent passing the No. 200 sieve. For coarse soils, M_r was a function of dry density, water content, uniformity coefficient (C_U), and percent passing the No. 200 sieve. The R^2 for each model varied between 0.7 and 0.77.

Yau and Von Quintus[6] analyzed the M_r data in the Federal Highway Administration's Long-Term Pavement Performance (LTPP) Program database as of October 2000. The results of 2,014 tests were extracted (1,920 of which were analyzed); all results passed all levels of the quality control checks (Level E status). Of those results, 212 were found to have a poor fit to the universal constitutive model; all were attributed to testing error and were removed from the dataset. For analysis, the data were parsed into base/subbase materials and subgrade materials, with further division in each category based on more distinct material descriptions. The authors found that for all categories, the sampling technique affected the M_r results. They found that the physical properties correlated to M_r varied between material and soil types and no property was included for all types. Because of this, the authors thought that the M_r of the universal constitutive equation could not be accurately predicted from the physical properties (of those included in the LTPP database).

Andrei et al.[5] presented a summary of the harmonized procedure for determining M_r developed under NCHRP Project 1-28A. The key differences between the harmonized procedure and the original NCHRP 1-28 protocol included changes in material type definitions, specimen sizes, compaction methods, loading time, stress sequences, and predictive equation. Loading time for subgrade soils was increased because of the stress distribution effect with depth. The deeper in the pavement structure, the larger the area over which a wheel load is distributed, and for moving wheel loads, this leads to an increased loading duration with depth. The original stress sequence, with constant levels of confining pressure, led to stress paths that rapidly approached the Mohr-Coulomb failure line; in the revised harmonized procedure, the stress ratio is held constant, thus protecting the specimen from premature failure. Similarly, the range of stresses was modified to represent in-situ conditions more accurately; subgrade materials experience lower traffic-induced stresses than base materials. The authors evaluated various predictive equations and determined that the expanded universal constitutive model was the best compromise among accuracy, complexity, and computational stability.

Ping et al.[7] compared the falling weight deflectometer (FWD) backcalculated modulus, laboratory measured resilient modulus, and limerock bearing ratio values (analogous to CBR) for a variety of soils typically found in Florida (i.e., AASHTO classifications A-3, A-2-4). They also presented a case study on the use of laboratory resilient modulus data for pavement design using the 1993 AASHTO design guide. They found that the laboratory resilient modulus at optimum compaction condition was on an average 1.1 times higher than the modulus at in-situ conditions. For granular materials, the FWD modulus was on average 1.8 times higher than the laboratory resilient modulus. Resilient modulus was determined under the state of stress of materials under an FWD test (lateral confinement attributable to self-weight of material added to the horizontal component of stress induced by the applied load, with vertical stress as the deviator stress) and at a fixed confining pressure of 2 psi (thought by the authors to be adequately representative of the resilient behavior of granular materials) with a 5 psi deviator stress. No relationship was found between the laboratory resilient modulus and the limerock bearing ratio.

In a continuation of the previous study, Ping and Ge[12] discussed the calibration of the laboratory-measured resilient modulus to field performance data, specifically to the plate load test. Through the laboratory program, they found a significant difference between M_r values obtained with half-length deformation measurements vs. full-length deformation measurements. They speculated that the full-length measurements would be susceptible to significant errors introduced by end effects (including air gaps between the specimen and accessories, alignment problems, and bedding problems). Moduli from the half-height measurement were consistently higher than those for the full-height measurement. Bulk stress was found to influence the modulus of granular materials significantly, and under isotropic confining pressure conditions, the modulus generally increased as confining pressure increased. The modulus of granular materials was found to increase slightly with increasing deviator stress for a confinement pressure of less than 10 psi; the reverse was true for higher confining pressures. The resilient modulus test (AASHTO T 292) was found to be repeatable. The authors stated that one of the most important considerations for evaluating resilient modulus is a sound understanding of the field state of stress.

Khazanovich et al.[13] reviewed the characterization of unbound materials by the MEPDG; k_i parameters were collected for a range of Minnesota fine soils, and the interpretation of the resilient modulus test to provide input to MEPDG Level 2 design/analysis was discussed. The recommended ranges for Level 3 design/analysis (modulus correlated to soil classification) were found to be reasonable. They were unable to find typical values for the k_i parameters (even for soils with the same classification in the same state); instead, ranges of each value were suggested: k_1 = 1,000 to 5,000; k_2 = 0.01 to 0.35; k_3 = -6 to -1.5. The authors pointed out that the singular modulus value required for Level 2 design/analysis must represent the state of stress in the unbound layer attributable to both vehicular and overburden stress. A multilayer elastic analysis (MEA) could be used to determine the stress distribution, which is then used to determine the modulus of the layer. However, MEA requires the modulus values of each pavement layer as input. To determine the Level 2 subgrade input from the k_i universal constitutive model, the following procedure is recommended in the MEPDG:

1. Assume the initial moduli.
2. Compute the stress state at critical points within unbound layers.
3. Use Step 2 pressures to compute the total stress state including the overburden pressure.
4. Use the Step 3 stress state to compute the predicted M_r.
5. Compare M_r from Step 4 with the assumed moduli and iterate if necessary.

As the procedure is cumbersome and may require multiple MEAs, a database of 600,000 combinations of structure and moduli was developed to allow for the rapid determination of the stress condition. Using that database, a sensitivity analysis was performed from which the following were observed:

- Increased asphalt thickness significantly reduced the predicted base modulus while moderately increasing the modulus of the subgrade.
- An increase in base thickness led to a less severe reduction in base moduli, again with a moderate increase in the subgrade modulus.
- An increase in subbase thickness did not appreciably affect the modulus of the base or subbase but, again, modestly increased the subgrade modulus.

When the k_i values of the base were varied, the modulus of the base changed but did not significantly affect the subbase and subgrade; varying the k_i of the subbase may have affected the moduli of the base and the subbase; and varying the k_1 of the subgrade affected all layers, but the effect of varying k_2 and k_3 was much less apparent.

Khazanovich et al.[13] found that the recommendations for the MEPDG Level 3 subgrade resilient modulus were reasonable but that soil with the same soil classification may have a wide range of modulus values. Even for the same soil material, the range of predicted modulus values from the constitutive model can be wide: the influence of the overlaying layers can greatly affect the modulus. The modulus of a subgrade under thick, stiff asphalt may be much higher than in a system under a thin, soft asphalt layer; the subgrade resilient modulus correlated well with the effective structural thickness of the pavement system. A second implication of this relationship is that seasonal variations in subgrade modulus should also be attributed to the change in pavement structure (e.g., the softening of the asphalt layer in the hotter summer months) in addition to the moisture conditions currently considered. The authors also noted the influence of the calculation depth for computing stress states.

Elias and Titi[14] developed correlations to predict the resilient modulus of subgrade soils native to Wisconsin from soil properties. When all soils were considered, no good correlations were found. However, when fine and coarse soils were separated, the correlation was good, with R^2 ranging from 0.58 to 0.84. The developed correlations were compared to those of the LTPP models; the LTPP models did not yield good results. The authors found that the effect of increased moisture content was significant: modulus values were lower. Samples compacted on the dry side of OMC had higher modulus values than those compacted at MDD and OMC. Equations were developed to relate the k_i parameters of the universal constitutive model to various soil properties. For fine soils, the k_i values were related to the plasticity index, dry density, MDD, moisture content, and OMC. For non-plastic coarse soils, the k_i values were related to percent passing the No. 4, No. 40, and No. 200 sieves; moisture content; OMC; dry density; and MDD. For plastic coarse soils, the k_i were related to percent passing the No. 200 sieve, percent silt, moisture content, liquid limit, plasticity index, OMC, dry density, and MDD.

Mikhail et al.[15] found significant differences in resilient moduli determined by backcalculation and laboratory testing and cited five research studies that reported similar trends. Because of these differences, the authors warned that pavement design can become dependent on the method by which design parameters are determined. For coarse materials, the simplified universal model is used; for fine soils, a model linear with respect to deviator stress is used.

Inputs to the constitutive models were computed using KENLAYER with a standard 40 KN FWD load and the pavement structure as found at the WesTrack site. The authors presented the following limitations and weaknesses of laboratory testing:

- Sample disturbance, particle orientation, non-homogeneous moisture content, and level of compaction of specimens may not accurately reflect in-situ conditions.
- In-situ stress states may not be accurately simulated with axial or triaxial testing.
- Limited sample volume may not be representative of an entire site area.
- Statistically adequate sampling is labor, time, and cost intensive.
- Equipment calibration and verification procedures for resilient modulus are poorly standardized.

Laboratory resilient modulus testing was performed using LTPP Protocol 46 procedures. Comparing the laboratory results and FWD moduli, the authors found significant differences between the two moduli for unbound granular materials but not for engineered fill and natural soils (clays, sands, and silts). They speculated that the difference might be explained by the fact that the FWD moduli are representative of surrounding conditions whereas laboratory samples are homogeneous specimens.

Hardcastle[16] presented a method for estimating seasonal variation of the subgrade resilient modulus of Idaho soils via adjustment coefficients (based on moisture content, temperature, soil type, and geographic location) to a reference modulus determined at OMC and 10 psi bulk stress for coarse and 8 psi for fine soils. Reference moduli were presented separately for coarse soils (USCS classifications SW, SP, SM, SC, GW, GP, GM and GC) and fine soils (USCS classifications ML, MH, CL and CH) as a function of median grain size and plasticity index, respectively. The ranges of resilient modulus values reported were 8,000 to 19,000 psi for coarse soil and 6,000 to 12,000 psi for fine soil. By dividing Idaho into six climate zones, Hardcastle established transition dates and durations for typical seasonal subgrade states (summer, winter-frozen, thaw softened, winter-spring wet) that allowed for continuous evaluation of subgrade moduli for pavement design.

Maher et al.[17] presented a statistical model to predict the resilient modulus of subgrade soil as a function of moisture content and stress ratio. Laboratory testing was performed on eight soils typical for New Jersey. Design procedures were presented for utilizing resilient modulus parameters with MEA and the effect of seasonal subgrade modulus variation.

Janoo et al.[18] sought to establish a range of typical resilient modulus values for subgrade types found around New Hampshire. Samples were constructed to MDD at OMC using a kneading compactor. Samples were tested at two temperatures, room temperature and freezing, to establish a yearly effective recommended resilient modulus value with the use of relative damage theory. The typical yearly effective resilient modulus values found were as follows:

- *A-1-a (SP):* 38,500 psi
- *A-1-b (SP):* 3,800 psi
- *A-2-4 (SM):* 9,000 psi
- *A-4 (SM):* 6,500 psi

- *A-7-5 (ML):* 3,000 psi.

George[19] evaluated the correlation equations to determine resilient modulus values without the need for costly laboratory testing for subgrade soils (including AASHTO classifications A4, A6, and A-2-4) in Mississippi. The equations developed from the LTPP studies were found to work well; however, for certain fine soils, specific equations developed by the Mississippi Department of Transportation worked even better. To establish a representative stress state at which to evaluate resilient modulus, George suggested a deviator stress of 7.4 psi with a confining pressure of 2 psi after performing a MEA using KENLAYER. From a literature review, George summarized the factors affecting resilient modulus as follows:

- Stress state
- Soil type and structure
- For fine soils:
  - Decrease in water content yields increased resilient modulus.
  - Increase in unit weight yields increased resilient modulus.
  - Increase in deviator stress yields decreased resilient modulus.
- For coarse soils:
  - A rapid decrease in resilient modulus values occurs for degrees of saturation above 85 percent.
  - An increase in density usually yields an increase in resilient modulus.
  - An increase in confinement yields an increase in resilient modulus.

Rahim and George[20] assessed the validity of using FWD backcalculated moduli for pavement design and evaluation. The commonly suggested correction factor for backcalculated moduli of 0.33 to match laboratory values was questioned. Laboratory resilient modulus was determined in accordance with AASHTO T P46, and FWD moduli were measured both when tested directly on a prepared subgrade and after (sometimes partial) construction of the pavement section (some sections when tested directly on the subgrade produced unrealistic basins or exceeded the sensor limits and had to be discarded). Soil types represented a range of typical Mississippi soils including AASHTO classifications A-6, A-2-4, and A-3. The authors concluded that subgrade conditions are non-uniform, with more variation spatially than vertically. FWD measurements performed directly on the subgrade were generally in agreement with laboratory values, which was attributed to increased confinement because of the overlying pavement structure; backcalculated moduli increased by 40 percent for fine and 100 percent for coarse soils after construction of the pavement section.

Lee et al.[21] 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 $R^2 = 0.97$.

Soils Classification and Laboratory Tests

Resilient Modulus

A total of 124 soil samples were tested at OMC 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 by the Proctor test. The three models discussed previously (i.e., Model 1, used by the VDOT Materials Division Soils Lab; Model 2, suggested for use for the 1993 AASHTO design by Von Quintus and Killingsworth;[9] 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 previously described in the "Methods" section. The samples with an R^2 greater than 0.9, a criterion set by the MEPDG, were considered for further analysis; the numbers of samples satisfying the criterion were as follows:

- *Model 1:* 101 samples
- *Model 2:* 80 samples
- *Model 3:* 90 samples.

All three models are stress dependent. Therefore, in-situ stress values are required to calculate the resilient modulus. However, the resilient modulus is needed to compute the in-situ stress values in the pavement layers using layered elastic analysis or finite element analysis. Therefore, the resilient modulus calculation is an iterative process, which is conveniently done by the MEPDG software[2] for Level 1 design/analysis. The only input values required in Level 1 design/analysis are regression coefficients (*k*-values: k_1, k_2, and k_3). The VDOT Materials Division Soil Lab was able to conduct resilient modulus testing with a fair amount of success. More than 70 percent (90 of 124) of the samples were tested with an R^2 more than 0.9 using Model 3. It is important to note that all three models have limitations and are not expected to fit the results of every laboratory test. If the R^2 value is less than 0.9, the MEPDG suggests checking for possible problems with the equipment or sample disturbance. If no irregularity is found, the use of another model is recommended. VDOT's success rate was much higher when fitting at least one of the three models was considered; i.e., more than 85 percent (106 of 124). The samples satisfying the R^2 requirement in at least one model are summarized in Table 1.

Stress Dependency of Constitutive Models

As stated previously, all constitutive models for subgrade resilient modulus are stress dependent and stress calculation is dependent on the pavement structure and subgrade resilient modulus. 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 and the 1993 AASHTO design guide require a specific resilient modulus value as an input. Therefore, it

Table 1. Sample Locations and Soil Classifications of Soils with $R^2 > 0.9$ in at Least One Model

County or City	No. of Samples	AASHTO Soil Classification	USCS Soil Classification
Albemarle	8	A-4 (0): 5 A-7-5 (15, 16, 20): 3	ML: 4 and SM: 1 ML: 1 and MH: 2
Alexandria	1	A-6 (8)	CL
Appomattox	1	A-4 (1)	ML
Bedford	2	A-4 (0) A-5 (4)	SM ML
Botetourt	3	A-5 (13): 1 A-7-6 (23): 2	ML CL
Buchanan	6	A-4 (1, 4): 2 A-6 (1, 2): 4	ML SC
Charlottesville	5	A-4 (0): 5	ML
Chesterfield	2	A-7-5 (25) A-7-6 (8)	MH ML
Dinwiddie	2	A-6 A-7-6	CL
Fairfax	15	A-1-b (0) A-2-4 (0) A-2-6 (0,1,2): 4 A-4 (0,2): 3 A-6 (0,2,5): 4 A-7-5 (19) A-7-6 (4)	SM: 4 SC: 7 ML: 1 MH: 1 CL: 2
Fauquier	3	A-6 (3,4,9)	SC: 2 and CL: 1
Goochland	1	A-7-5 (19)	MH
James City	1	A-4 (2)	CL
Loudoun	4	A-4 A-6 (10): 2 A-7-6 (8)	ML CL: 2 ML
Madison	4	A-4 (0)	ML
Mecklenburg	1	A-5 (3)	ML
Newport News	3	A-4 (1,2): 2 A-6	CL and CL-ML CL
Pittsylvania	2	A-2-4 (0) A-4 (0)	SM ML
Prince George	1	A-7-6 (12)	CL
Prince William	21	A-2-4 (0): 3 A-2-7 (2): 3 A-6 (6,10,10): 3 A-7-6 (7 -56): 12	SC SC CL CL: 3 and CH: 9
Roanoke	2	A-7-5 (6) A-7-6 (16)	ML CL
Spotsylvania	1	A-2-5 (0)	SM
Virginia Beach	6	A-2-4 (0): 2 A-4 (0): 2 A-6 (7, 20): 2	SM: 2 ML: 2 CL: 2
Washington	1	A-7-5 (12)	MH
York	10	A-2-4 (0): 4 A-4: 1 A-6 (2,3,4,5,6): 5	SC: 2 and SC-SM: 2 CL SC: 2 and CL: 3

is necessary to estimate stresses to calculate the resilient modulus for further analysis/ comparison of laboratory test results for the benefit of using them 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. This iterative procedure was outlined by Von Quintus and Killingsworth[9] for use with the AASHTO 1993 design guide.

Previous researchers have used different combinations of stresses for such calculation. The recommended stress states from the literature for input in resilient modulus constitutive models are summarized in Table 2. For the relative comparison, a confining pressure of 2 psi and a deviator stress of 6 psi were used in this study.

The effect of stress on the constitutive model is further illustrated in Figure 2 using Model 3 for AASHTO classification A-7-6 soil as an example. The average regression coefficients (explained later in the report) from this study were used in the illustration.

Table 2. Input Stresses for Resilient Modulus Constitutive Models

Reference	Pavement Layer	Confining Stress, psi	Deviator or Cyclic Stress, psi	Reference No.
Asphalt Institute (as cited in Ping et al.)	Subgrade	2	6	7
Daleiden et al. (as cited in Ping et al.)	Subgrade	2	2	7
Rahim	Subgrade	2	5.4	11
George	Subgrade	2	7.4	19
Lee et al.	Subgrade	3	6	21
Ping et al.	Subgrade	2	5	7
Jones and Witczak	Subgrade	2	6	22
Rada and Witczak	Granular subbase	Bulk stress	10	23
	Granular base	Bulk stress	20-40	

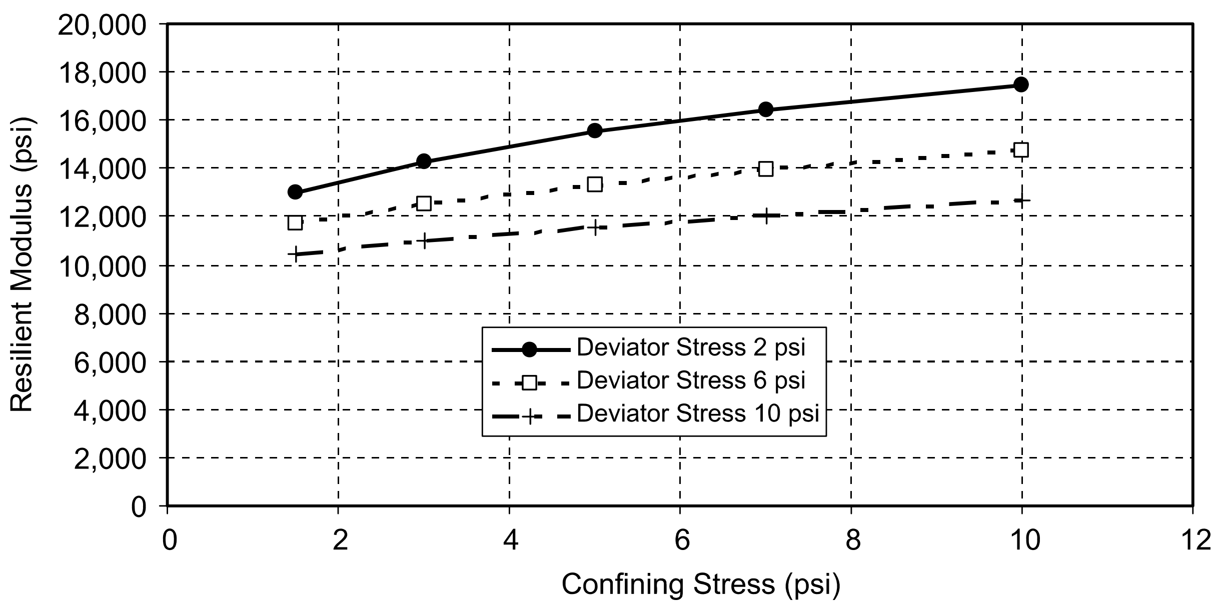


Figure 2. Variation of Resilient Modulus with State of Stress

Resilient Modulus Parameters (k-values) for Different Types of Soil

In general, coarser materials are stiffer than finer materials. Therefore, coarse soils will have higher resilient modulus values than fine soils at a specified stress level. The resilient modulus tests conducted during this research covered a wide range of soil types, as summarized in Table 1. The average k-coefficients for each model were calculated according to soil classification and are presented in Tables 3 through 5. These values could easily be used for

Table 3. Average Regression Coefficients for Model 1 Based on Soil Classification

Soil Type AASHTO	Statistics	Model 1					
		k_1		k_2		K_5	
		Statistics	Average	Statistics	Average	Statistics	Average
A-1-b (0)	N	1	8667	1	-0.18285	1	0.32415
	Maximum	8667		-0.18285		0.32415	
	Minimum	8667		-0.18285		0.32415	
	Standard deviation	-		-		-	
A-2-4 (0)	N	11	7752	11	-0.11718	11	0.30045
	Maximum	14716		-0.24246		0.03891	
	Minimum	3867		0.06437		0.44339	
	Standard deviation	3373		0.09268		0.12309	
A-2-5 (0)	N	1	3108	1	-0.09816	1	0.54439
	Maximum	3108		-0.09816		0.54439	
	Minimum	3108		-0.09816		0.54439	
	Standard deviation	-		-		-	
A-2-6 (0-2)	N	4	13249	4	-0.14797	4	0.16484
	Maximum	16059		-0.11844		0.27496	
	Minimum	9624		-0.18033		0.08425	
	Standard deviation	2869		0.03236		0.08197	
A-2-7 (2)	N	3	12618	3	-0.23185	3	0.23931
	Maximum	16405		-0.20925		0.34931	
	Minimum	7927		-0.26152		0.16850	
	Standard deviation	4311		0.02684		0.09657	
A-4 (0-4)	N	29	9850	29	-0.20314	29	0.22638
	Maximum	15825		0.08185		0.43784	
	Minimum	3427		-0.36449		0.05681	
	Standard deviation	3383		0.10983		0.09081	
A-5 (3,4,13)	N	3	13899	3	-0.15637	3	0.07867
	Maximum	16086		-0.06311		0.09911	
	Minimum	12078		-0.25219		0.04271	
	Standard deviation	2029		0.09457		0.03124	
A-6 (0-20)	N	23	14388	23	-0.11437	23	0.16200
	Maximum	23478		0.08751		0.55622	
	Minimum	2818		-0.40564		0.02548	
	Standard deviation	4914		0.13481		0.11042	
A-7-5 (6-45)	N	8	14423	8	-0.03943	8	0.12968
	Maximum	18783		0.06727		0.34151	
	Minimum	7072		-0.31901		0.02485	
	Standard deviation	4001		0.15158		0.09533	
A-7-6 (4-56)	N	18	13717	18	-0.11729	18	0.12156
	Maximum	18081		0.10337		0.24784	
	Minimum	6344		-0.56628		0.08854	
	Standard deviation	3761		0.18575		0.04009	

Model 1 is used by the VDOT Materials Division Soils Lab.

Table 4. Average Regression Coefficients for Model 2 Based on Soil Classification

Soil Type AASHTO	Statistics	Model 2					
		k_1		k_2		K_3	
		Statistics	Average	Statistics	Average	Statistics	Average
A-1-b (0)	N	1	448.1	1	0.46469	1	-0.31388
	Maximum	448.1		0.46469		-0.31388	
	Minimum	448.1		0.46469		-0.31388	
	Standard deviation	-		-		-	
A-2-4 (0)	N	10	433.3	10	0.47954	10	-0.25197
	Maximum	775.1		0.66601		-0.11360	
	Minimum	298.0		0.24332		-0.35595	
	Standard deviation	136.1		0.14043		0.07656	
A-2-5 (0)	N	1	230.1	1	0.81020	1	-0.32808
	Maximum	230.1		0.81020		-0.32808	
	Minimum	230.1		0.81020		-0.32808	
	Standard deviation	-		-		-	
A-2-6 (0-2)	N	3	619.4	3	0.26833	3	-0.23135
	Maximum	685.2		0.39019		-0.22713	
	Minimum	574.4		0.17118		-0.23895	
	Standard deviation	58.3		0.11158		0.00660	
A-2-7 (2)	N	3	540.9	3	0.34312	3	-0.32810
	Maximum	697.1		0.50314		-0.27609	
	Minimum	337.7		0.23774		-0.40224	
	Standard deviation	184.2		0.14089		0.06592	
A-4 (0-4)	N	25	431.9	25	0.34497	25	-0.31934
	Maximum	1426.7		0.64458		0.04522	
	Minimum	106.4		0.12936		-0.47835	
	Standard deviation	255.8		0.11850		0.11555	
A-5 (3,4,13)	N	3	682.8	3	0.10919	3	-0.18685
	Maximum	950.2		0.13737		-0.08040	
	Minimum	445.8		0.06140		-0.28804	
	Standard deviation	235.6		0.04161		0.10392	
A-6 (0-20)	N	19	823.9	19	0.24205	19	-0.19926
	Maximum	1663.1		0.81246		0.03728	
	Minimum	173.8		0.03644		-0.47404	
	Standard deviation	463.4		0.17286		0.15406	
A-7-5 (6-25)	N	3	495.5	3	0.30459	3	-0.26420
	Maximum	643.4		0.50813		-0.11751	
	Minimum	329.0		0.15760		-0.38670	
	Standard deviation	158.0		0.18197		0.13622	
A-7-6 (4-32)	N	12	729.2	12	0.180944	12	-0.21808
	Maximum	1333.0		0.34695		-0.01970	
	Minimum	116.3		0.12063		-0.65412	
	Standard deviation	444.2		0.06698		0.20165	

Model 2 is recommended for the AASHTO 1993 design guide.

Table 5. Average Regression Coefficients for Model 3 Based on Soil Classification

Soil Type AASHTO	Statistics	Model 3					
		k_1		k_2		K_3	
		Statistics	Average	Statistics	Average	Statistics	Average
A-1-b (0)	N	1	953.6	1	0.46371	1	-2.52227
	Maximum	953.6		0.46371		-2.52227	
	Minimum	953.6		0.46371		-2.52227	
	Standard deviation	-		-		-	
A-2-4 (0)	N	10	825.9	10	0.45643	10	-1.9205
	Maximum	1427.8		0.65301		-0.88081	
	Minimum	482.8		0.05546		-2.84003	
	Standard deviation	268.4		0.17772		0.694216	
A-2-5 (0)	N	1	496.4	1	0.79365	1	-2.48712
	Maximum	496.4		0.79365		-2.48712	
	Minimum	496.4		0.79365		-2.48712	
	Standard deviation	-		-		-	
A-2-6 (0-2)	N	4	1124.4	4	0.23480	4	-1.7637
	Maximum	1223.8		0.39117		-1.31585	
	Minimum	998.7		0.12551		-1.98978	
	Standard deviation	106.8		0.11537		0.31077	
A-2-7 (2)	N	3	1172.6	3	0.34603	3	-2.69832
	Maximum	1473.6		0.49911		-2.31857	
	Minimum	886.2		0.24464		-3.22475	
	Standard deviation	294.0		0.13488		0.47056	
A-4 (0-4)	N	23	904.4	23	0.30349	23	-2.50299
	Maximum	1264.9		0.63734		-0.83199	
	Minimum	335.4		0.07847		-3.83883	
	Standard deviation	219.0		0.11604		0.89668	
A-5 (3,4,13)	N	3	1038.0	3	0.11412	3	-1.58431
	Maximum	1158.4		0.14301		-0.67806	
	Minimum	906.2		0.06367		-2.43908	
	Standard deviation	126.5		0.04385		0.88164	
A-6 (0-20)	N	25	1215.3	25	0.23243	25	-1.51822
	Maximum	1963.6		0.80760		0.27564	
	Minimum	458.2		0.03899		-3.90792	
	Standard deviation	358.3		0.15376		1.14528	
A-7-5 (6-25)	N	3	851.1	3	0.31089	3	-1.97817
	Maximum	1050.9		0.50813		-0.11751	
	Minimum	643.4		0.16741		-3.34331	
	Standard deviation	203.9		0.17660		1.66901	
A-7-6 (4-56)	N	17	1104.0	17	0.18602	17	-1.68214
	Maximum	1485.0		0.37421		-0.07017	
	Minimum	456.7		0.09073		-5.69048	
	Standard deviation	321.2		0.07812		1.53970	

Model 3 is recommended for use by the MEPDG.

pavement design under the 1993 AASHTO design guide and MEPDG Level 2 design/analysis provided the state of stress is known from layered elastic analysis or some other means.

MEPDG Level 3 design/analysis requires the input of resilient modulus values based on soil classification or local experience; such values are provided in the MEPDG from the LTPP database. In order to compare these values with those for Virginia soils, resilient modulus values were calculated using the average coefficients presented in Tables 3 to 5 with confining and deviator stresses of 2 and 6 psi, respectively. The calculated resilient modulus values are presented in Table 6; for relative comparison, CBR correlated values and MEPDG recommended values are also included. The values for the fine aggregate were well within the MEPDG range, but the coarse aggregate values were low compared to the MEPDG recommendation. There is no apparent reason for this finding other than the fact that the sample size was small compared to the particle size. The data population for coarse soils was also small.

Table 6. Average Resilient Modulus Values Based on Soil Classification

Soil Type AASHTO	Resilient Modulus Value (psi)				CBR Correlation	
	MEPDG Recommended Range	Model 1[a]	Model 2[a]	Model 3[a]	MEPDG: $2,555*(CBR)^{0.64}$	VDOT: 1,500*CBR
A-1-b (0)	38,500-40,000	7,819	7,941	8,185	39,453	10,800
A-2-4 (0)	28,000-37,500	7,738	7,242	7,893	18,161	32,133
A-2-5 (0)	24,000-33,000	3,802	3,850	4,010	17,822	31,200
A-2-6 (0-2)	21,500-31,000	11,394	10,609	11,529	17,712	30,900
A-2-7 (2)	21,500-28,000	9,831	9,951	9,994	18,864	34,100
A-4 (0-4)	21,500-29,000	8,008	7,881	8,047	10,331	13,309
A-5 (3,4,13)	17,000-25,500	11,092	11,607	11,281	9,765	12,188
A-6 (0-20)	13,500-24,000	13,115	13,785	13,046	12,614	18,181
A-7-5 (6-45)	8,000-17,500	14,703	8,676	8,293	9,737	12,133
A-7-6 (4-56)	5,000-13,500	12,095	12,563	11,623	6,650	6,687

MEPDG = *Guide for the Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures;* CBR = California Bearing Ratio; VDOT = Virginia Department of Transportation.
[a]Confining stress = 2 psi; deviator stress = 6 psi.

Influence of Moisture on Resilient Modulus

The MEPDG[2] has an Enhanced Integrated Climatic Model (EICM) to include the effect of environment on the performance of pavement. Moisture and temperature can significantly affect pavement performance and the strength of subgrade soil. As the water in the soil freezes, the resilient modulus could rise to values 20 to 120 times higher than the value of the modulus before freezing. When thawing occurs, the strength of the soil is greatly reduced, thereby weakening the pavement structure. MEPDG software calculates the strength changes according to the environmental condition from the input values of resilient modulus parameters at OMC and MDD. The effect of moisture change is estimated internally by the MEPDG program using the following model as a function of the degree of saturation of the subgrade soil.

$$Log\left(\frac{M_r}{M_{r-opt}}\right) = \left(a + \frac{b-a}{1+EXP[\beta + k_m * (S - S_{opt})]}\right)$$

where

M_r = modulus at any degree of saturation
S = current degree of saturation (decimal)
$M_{r\text{-}opt}$ = modulus at OMC and MDD
S_{opt} = degree of saturation at OMC (decimal)
a = minimum of $\log(M_r/M_{r\text{-}opt})$
b = maximum of $\log(M_r/M_{r\text{-}opt})$
β = location parameter as a function of a and b = ln(-b/a)
k_m = regression parameter

with the following MEPDG recommended values:

a = -0.5934 for fine and -0.3123 for coarse materials
b = 0.4 for fine and 0.3 for coarse materials
k_m = 6.1324 for fine and 6.8157 for coarse materials.

In this study, the resilient modulus parameters were calculated for soil samples at OMC and 20 percent more than OMC. Data were analyzed to compare the moisture effect model for Virginia soils. The laboratory data were used to calculate the resilient modulus values according to Model 3 at the stress condition (confining stress = 2 psi and deviator stress = 6 psi) mentioned earlier. These values were compared with the predicted values from the moisture effect model shown in Figure 3 for coarse and fine soils, respectively. The laboratory values did not show or follow any trend similar to that of the moisture effect model in the MEPDG.

Analysis for Correlation Between Results of Resilient Modulus Test and Those of Other Tests

The resilient modulus test requires significantly more resources than conventional soil tests. Therefore, it may not be practical for use with every project. For smaller and low-impact projects, correlation with other soil properties could be used. The test results from this study were analyzed to develop correlations for Virginia soils. The correlation analysis involved estimation of the following parameters from soil index properties: (1) regression coefficients for the universal constitutive model, and (2) direct estimation of resilient modulus

As discussed in the “Methods” section, several factors were considered for correlation analysis. These included soil index properties and results of measurements of strength such as the CBR and quick shear tests:

1. liquid limit, plastic limit, and plasticity index
2. percent passing No. 4 and No. 200 sieves
3. OMC, compaction moisture content, and their ratio
4. MDD and compaction density
5. specific gravity and degree of saturation.

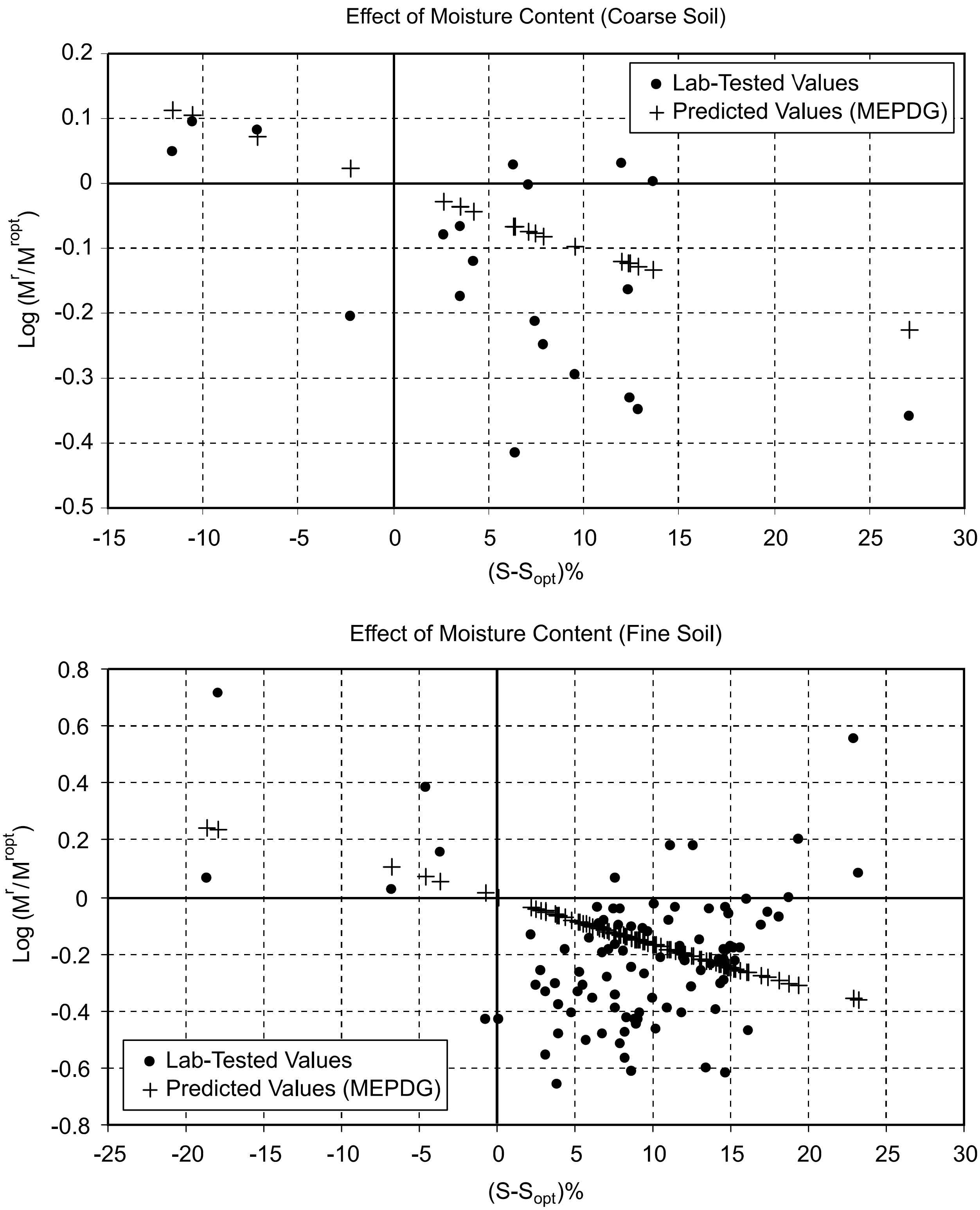


Figure 3. Effect of Moisture Content on Soil Resilient Modulus. MEPDG = *Guide for the Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures*.

Estimation of Regression Coefficients

Although the estimation of regression coefficients from soil index properties is not outlined in the MEPDG, several researchers[19, 24] have attempted to establish such a correlation using the LTPP database. The strength of such correlations is in general very poor. The data from this study were analyzed to determine similar correlations, and no strong correlations were found. It is important to note that the soil index properties used by other researchers (i.e., percent clay, percent sand, or percent passing No. 40 sieve, etc.) were not available for the study laboratory database; therefore, it was not possible to verify those relationships.

Only four types of soil (AASHTO classifications A-2-4, A-4, A-6, and A-7-6) had enough samples/data points to allow a meaningful correlation investigation. The correlation equation for A-4 soil is provided in Table 7 with the respective adjusted R^2 values ranging from 0.4 to 0.6.

Table 7. Correlation for Regression Coefficients of Model 3 for AASHTO A-4 Soil

Coefficient	Intercept	% Maximum Dry Density	Water Content (%)	% Passing No. 4 Sieve	Liquid Limit (%)	Specific Gravity	Degree of Saturation (decimal)	Moisture Content Ratio	R^2/ Adjusted R^2
k_1	-6497.58	92.145	-15.273	-13.943					0.64/0.59
k_2	4.399	-0.0713			-0.006	0.942	0.696		0.51/0.40
k_3	-45.833	0.4875						-4.1572	0.52/0.47

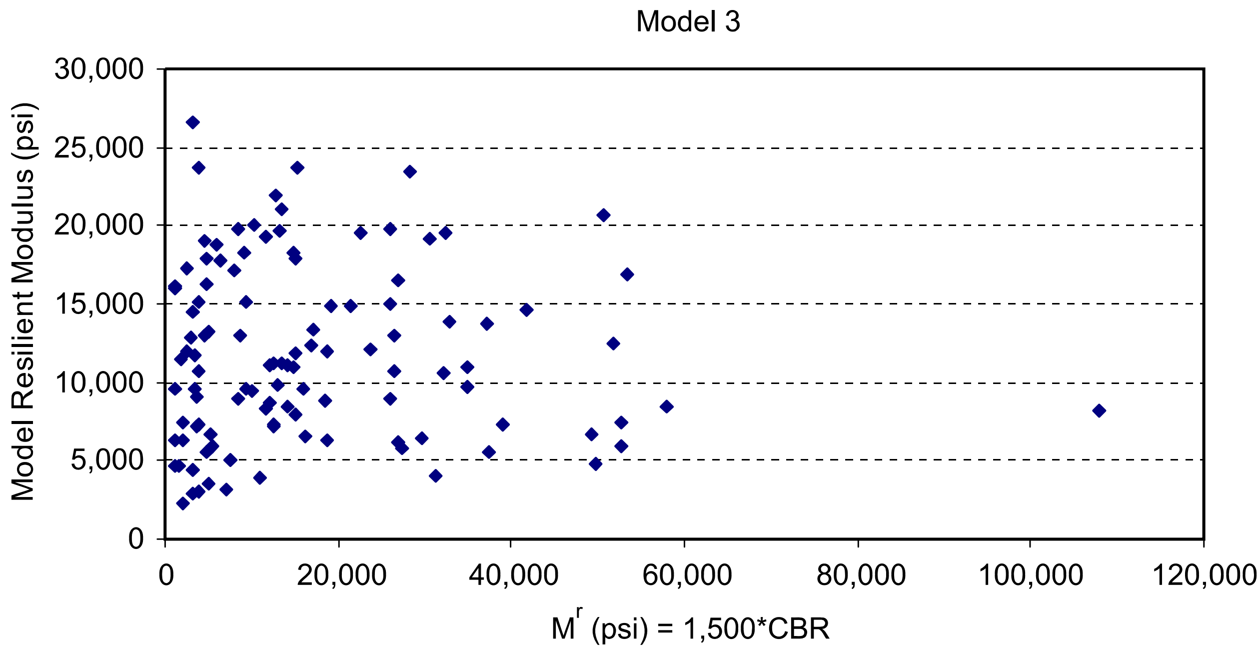
Model 3 is recommended for use in the MEPDG.

Direct Estimation of Resilient Modulus

MEPDG Level 2 design/analysis requires the input of resilient modulus values instead of regression parameters, and the MEPDG provides suggested correlations for its estimation. These correlations are mostly based on the CBR value. Since VDOT currently uses CBR as the basis for the design, soaked and unsoaked CBR were measured for most of the soil samples considered in this study. VDOT uses a simplified correlation of 1,500*CBR as an input resilient modulus value for 1993 AASHTO pavement design. This simplified relationship and the one provided in the MEPDG[2] [$M_r = 2{,}555*(CBR)^{0.64}$] were investigated for use in estimating resilient modulus values and comparing the results with laboratory-measured resilient modulus values.

As mentioned earlier, the resilient modulus test does not provide a single resilient modulus value; instead, it gives a series of values determined at different stress conditions; a suitable constitutive model can be fitted to the data using regression analysis. These regression coefficients can then be used to determine the resilient modulus value as a function of stresses in the pavement subgrade. As mentioned previously, the stress combination used for this correlation analysis was a confining stress of 2 psi and a deviator stress of 6 psi.

It was obvious from the scatter plots of CBR and resilient modulus values that there was no relationship between them. The scatter plot of resilient modulus values estimated from the soaked CBR and constitutive Model 3 is shown in Figure 4. Plots for other models were similar, with no trend.



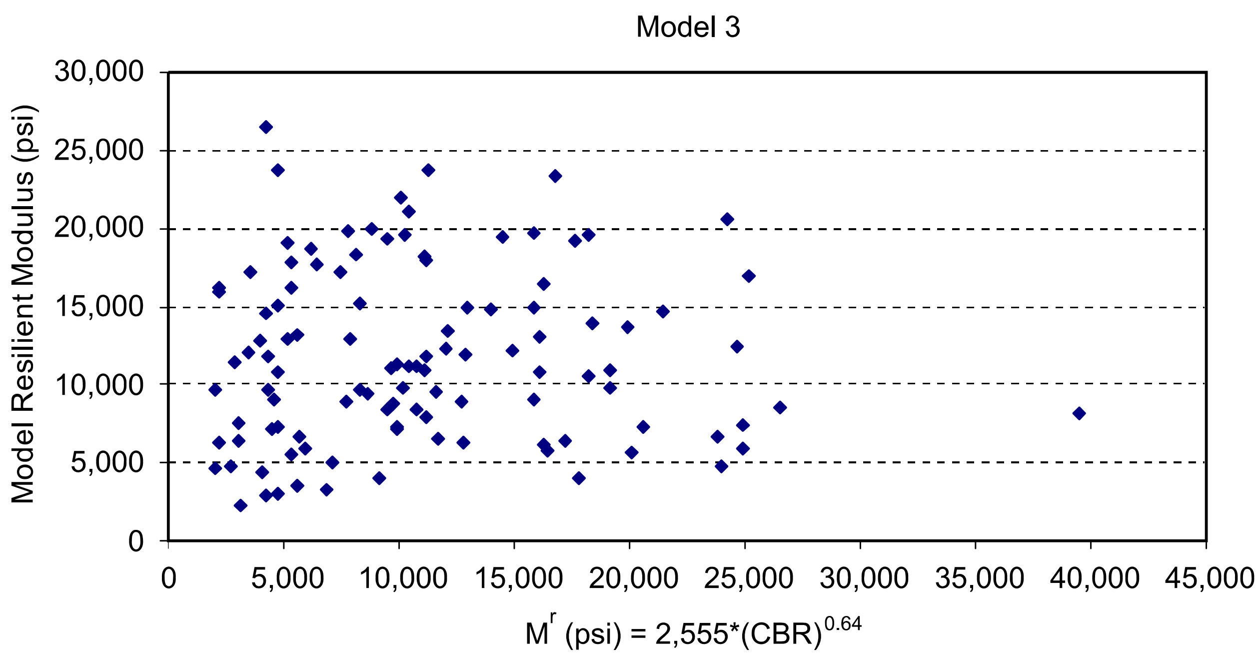


Figure 4. Scatter Plot of Resilient Modulus Estimated from CBR and Model 3. Model 3 is recommended for use in the MEPDG

As mentioned earlier, Lee et al.[21] found a very strong correlation between the resilient modulus of cohesive soil and the unconfined compressive stress at 1 percent strain. The unconfined compressive strength test (AASHTO T 208)[4] is one of the simplest soil strength tests, but it can be performed only with cohesive soils.

As mentioned previously, the soil samples from the current study underwent the quick shear test after the completion of the resilient modulus test. Unlike the unconfined compressive strength test, the quick shear test uses a confining pressure of about 5 psi and applies the axial load at a rate of 1 percent strain per minute. Because of the fast loading rate, the testing condition could be assumed to be undrained and should result in stress-strain behavior similar to that expected from a true unconfined compressive strength test. The stress values at 1 percent strain ($S_{u1\%}$) were recorded for all samples, including those with other than OMC, and correlated to the calculated resilient modulus values (M_r) at the stress level previously mentioned (confining pressure of 2 psi, deviator stress of 6 psi). All three constitutive models used in this study showed very strong linear correlations; the regression R^2 was 0.98 and 0.80 for fine and coarse soils, respectively. These correlations are summarized in Table 8 and are well suited for MEPDG Level 2 design/analysis input for fine soils. The scatter plots with regression lines are shown in Figures 5 and 6. The data points for coarse soils were only 39, compared to 176 for fine soils.

Table 8. Resilient Modulus Prediction Equations

Constitutive Model	Equation
Model 1	$M_r = 1625.5*S_{u1\%} – 2945.6$
Model 2	$M_r = 1635.6*S_{u1\%} – 2918.5$
Model 3	$M_r = 1622.8*S_{u1\%} – 2707.1$

M_r = resilient modulus; S_{u1} = stress at 1% strain.

Although the current 1993 AASHTO pavement design regularly uses the CBR to characterize subgrade soil, the CBR was not correlated with resilient modulus. The results of the quick shear test, however, showed a very strong correlation with the resilient modulus for fine soils. Moreover, the effect of moisture and compaction level is already incorporated in the quick shear test. Samples could be prepared and tested at different expected moisture levels during the year. These values could be used to calculate the effective resilient modulus in accordance with the 1993 AASHTO design guide. But determining the expected moisture during the year could be challenging. The relationship shown in Table 8 used strain values from a quick shear test that applied a confining pressure of 5 psi. Another simplification would be to use the unconfined compression test similar to that described by Lee et al.,[21] but a new correlation would need to be developed.

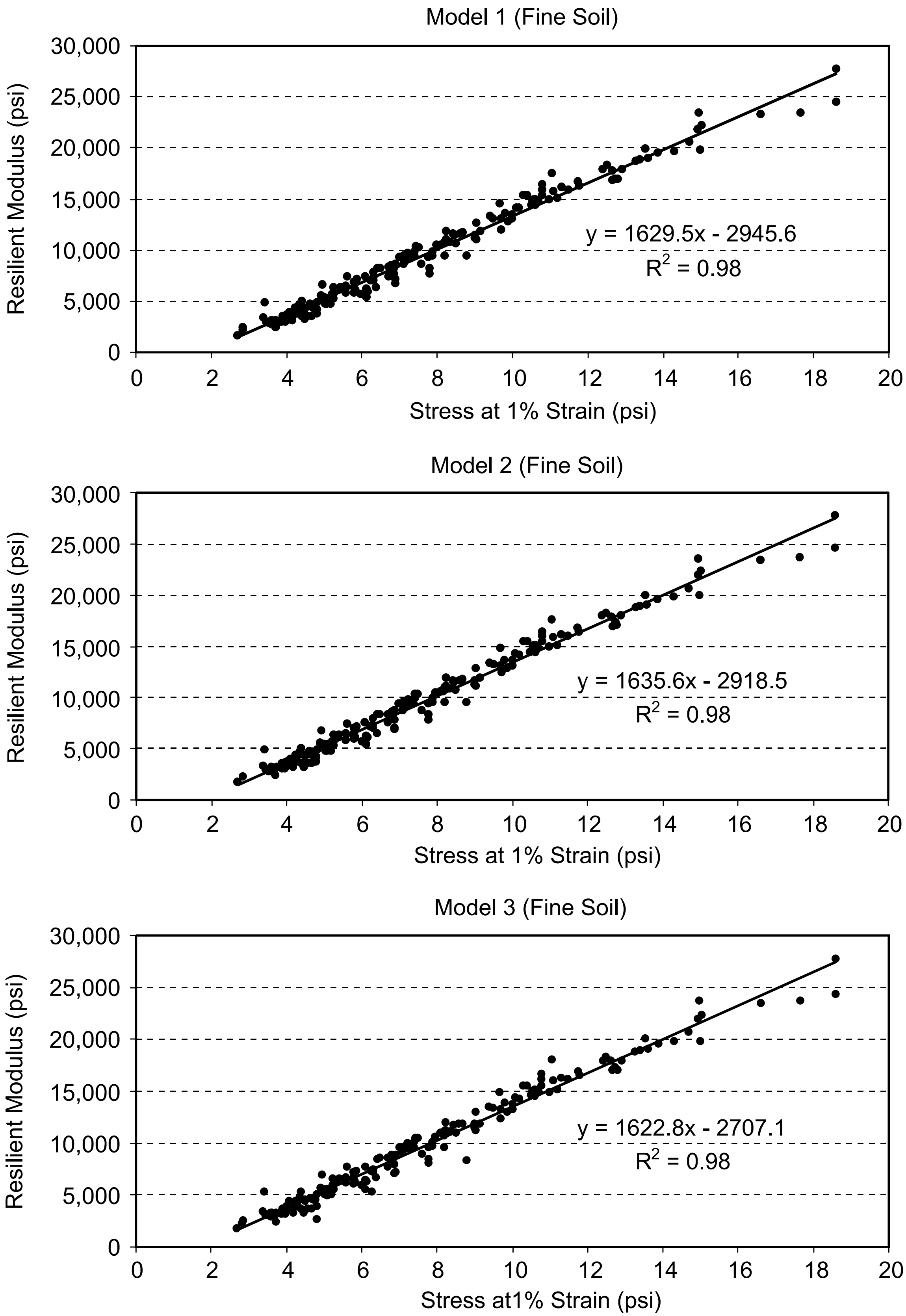


Figure 5. Correlation Between Resilient Modulus and Stress at 1% Strain for Fine Soil

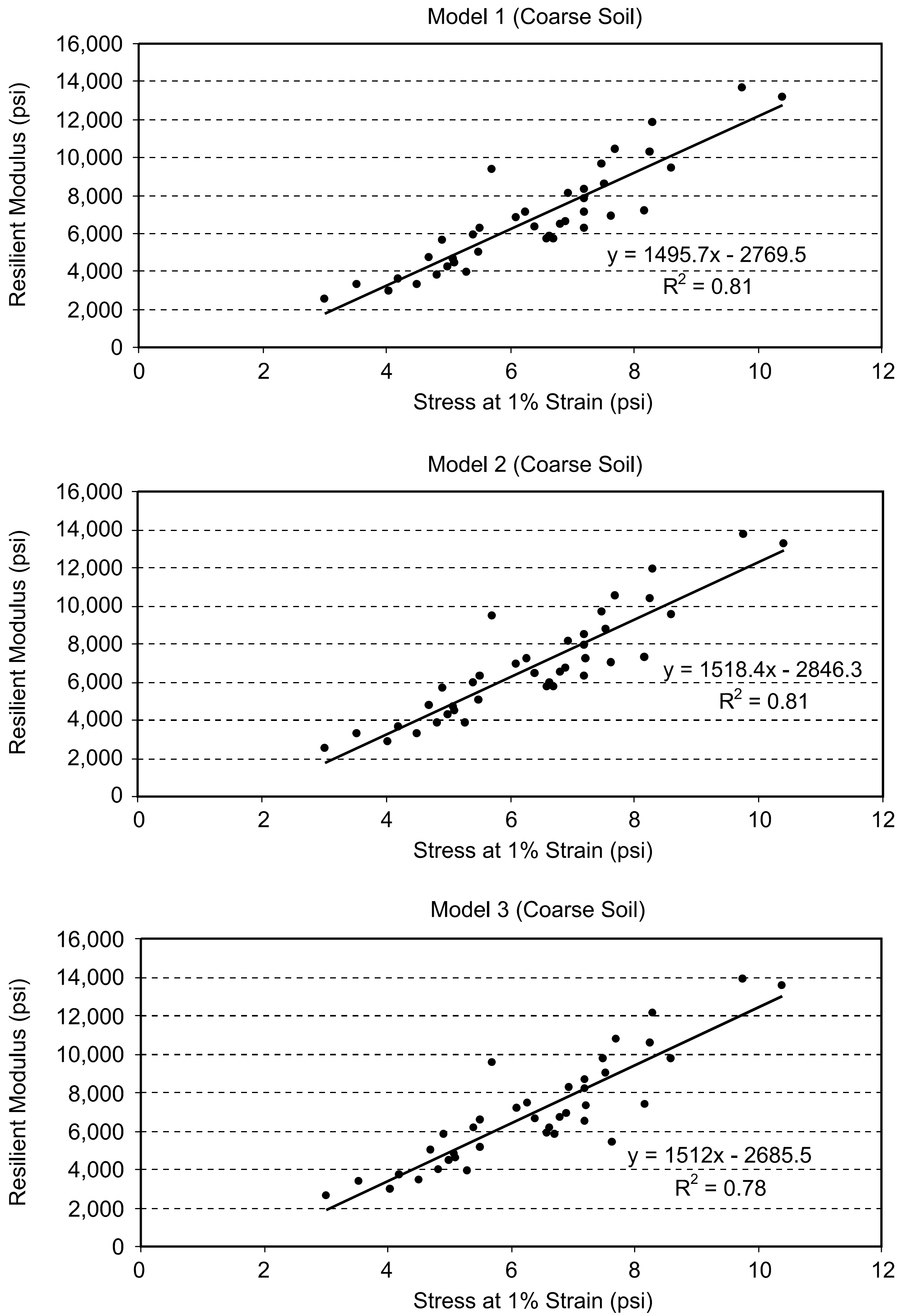


Figure 6. Correlation Between Resilient Modulus and Stress at 1% Strain for Coarse Soil

CONCLUSIONS

- *The VDOT Materials Division Soils Lab has the capability to conduct the resilient modulus test in accordance with AASHTO T 307.*

- *The current data reduction program used at the VDOT Materials Division Soils Lab can calculate k-values for one constitutive model (Model 1) only. These k-values can be used as the direct input to MEPDG Level 1 pavement design/analysis if the R^2 is greater than 0.9.*

- *Test data from the VDOT Materials Division Soils Lab also fit two other models (Models 2 and 3 in this study); Model 3 is recommended by the MEPDG.*

- *The average k-values for the three models used in this study, grouped according to the AASHTO classification of Virginia soils, could be used for MEPDG Level 2 or Level 3 design/analysis along with the stresses calculated from any layered elastic analysis program.*

- *The typical resilient modulus values, grouped according to the AASHTO classification of Virginia soils, calculated in this study (using average k-values at confining and deviator stresses of 2 and 6 psi, respectively) are comparable to the MEPDG suggested range for fine soils and are suitable for use in MEPDG Level 3 design/analysis. The values for coarse soils were low compared to the values in the MEPDG range. Further research is needed to address this issue.*

- *There are no statistically significant correlations between the results of the resilient modulus test and the results of the other tests used in this study, with the exception of stresses at 1 percent strain from the quick shear test. The correlation was very strong for fine soils (R^2 = 0.98) and fair for coarse soils (R^2 = 0.80). This correlation for fine soils can easily be used for MEPDG Level 2 or Level 3 design/analysis. The correlation for coarse soils requires further study.*

- *Because no correlation between the resilient modulus and CBR was found in this study, the current VDOT practice of converting a CBR value to a resilient modulus value (i.e., resilient modulus = 1,500*CBR) does not provide an accurate relationship.*

- *Since the unconfined compressive strength test can be expected to yield results similar to those of the quick shear test at a loading rate of 1 percent strain per minute, it may be used as a low-cost alternative to the resilient modulus test.*

- *The effect of moisture on the measured resilient modulus value from this study did not match the predicted values obtained from the model proposed by the MEPDG.*

RECOMMENDATIONS

1. *VDOT's Materials Division should implement resilient modulus testing for characterizing subgrade soils in MEPDG Level 1 design/analysis.*

2. *VDOT's Materials Division should consider using the model recommended by the MEPDG (Model 3 in this study) for resilient modulus calculation.*

3. *VDOT's Materials Division should use the quick shear test to predict the resilient modulus values of fine soils (AASHTO classifications A-4, A-5, A-6, and A-7) using the relationships developed in this study and shown in Table 8 for MEPDG Level 2 design/analysis.*

4. *VDOT's Materials Division should consider using the average k-values for fine soils provided in Tables 3, 4, and 5 of this report for MEPDG Level 2 design/analysis. Since Level 2 design/analysis requires inputting a resilient modulus value, the value should be calculated using the stresses determined from any layered elastic analysis program.*

5. *VDOT's Materials Division should use the average resilient modulus values provided in Table 6 of this report for fine soils or the MEPDG-recommended resilient modulus values for Level 3 design/analysis.*

SUGGESTIONS FOR FURTHER RESEARCH

- The Virginia Transportation Research Council (VTRC) and VDOT's Materials Division should further investigate resilient modulus testing for coarse soils along with completing the tests for base/subbase aggregate.

- VTRC should conduct research to develop the correlation between the results of the resilient modulus and unconfined compressive strength tests.

- VTRC should assist VDOT's Materials Division in developing guidelines to use the resilient modulus test rather than the current practice of converting CBR to resilient modulus (i.e., resilient modulus = 1,500*CBR).

COSTS AND BENEFITS ASSESSMENT

Implementing the recommendations provided in this study would support and expedite the implementation efforts currently underway 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 their 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.

ACKNOWLEDGMENTS

The author acknowledges the cooperation of VDOT's Materials Division in supplying soils and conducting the soils tests in their lab. The author also acknowledges Jason Bennett and Chris Gresham, technicians in VDOT's Materials Division, for their laboratory work. Thanks also go to Benjamin Schmidt, a University of Virginia graduate student, for conducting part of the literature review. Special thanks also go to Chaz Weaver, Staunton District Materials Engineer, for facilitating and directing some of the tests while he was at the VDOT Materials Division Soils Lab. The members of the technical advisory panel for the project are acknowledged for their contributions: Mohamed Elfino, Stan Hite, and Ed Hoppe. The author also acknowledges Randy Combs, Jim Gillespie, and Linda Evans of VTRC for their support in reviewing and preparing the report.

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