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Resilient Modulus of Coarse-Grained Subgrade Soils for Pavement Design

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M. SHABBIR HOSSAIN, Ph.D., P.E.
Associate Principal Research Scientist

HARIKRISHNAN NAIR, Ph.D., P.E.
Associate Director

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530 Edgemont Road, Charlottesville, VA 22903-2454
vtrc.virginia.gov

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As part of VDOT's MEPDG implementation efforts, the Materials Division Soils Lab collected both fine- and coarse-grained soil samples from around the state on which to perform M_r tests. For fine-grained soils (A-4, A-5, A-6, and A-7), a correlation with unconfined compression strength was developed in a Virginia Transportation Research Council study that is currently being used to estimate design M_r for high-volume projects (annual average daily traffic > 10,000) as an alternative to actual M_r testing. Also, enough fine-grained soils were tested to determine statewide average M_r values to be used in the design of low-volume roadways (annual average daily traffic < 10,000). However, no statewide average M_r values or correlations are currently available for coarse-grained soils (A-1, A-2, and A-3). Although some actual measured M_r values of coarse-grained soil are available, they are significantly less than AASHTO-recommended M_r values (MEPDG default), which needs to be further investigated.

During this study, six coarse-grained soil samples were tested for M_r at standard Proctor compactive effort: three A-2-4, one A-2-6, and two A-3. The M_r values at a confining pressure of 2 psi and a deviator stress of 6 psi were less than MEPDG-recommended default values, but they are comparable with measured values reported in the literature. Sample compaction density and moisture influenced the M_r values. The M_r value of any coarse-grained soil showed a decreasing trend with increasing degrees of saturation, a combining measure of compaction density and moisture. A few soil index properties showed good correlation with M_r values. A predictive model could not be recommended because of limited data points, that is, only six soil samples.

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FINAL REPORT

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M. Shabbir Hossain, Ph.D., P.E.
Associate Principal Research Scientist

Harikrishnan Nair, Ph.D., P.E.
Associate Director

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ABSTRACT

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As part of VDOT's MEPDG implementation efforts, the Materials Division Soils Lab collected both fine- and coarse-grained soil samples from around the state on which to perform M_r tests. For fine-grained soils (A-4, A-5, A-6, and A-7), a correlation with unconfined compression strength was developed in a Virginia Transportation Research Council study that is currently being used to estimate design M_r for high-volume projects (annual average daily traffic > 10,000) as an alternative to actual M_r testing. Also, enough fine-grained soils were tested to determine statewide average M_r values to be used in the design of low-volume roadways (annual average daily traffic < 10,000). However, no statewide average M_r values or correlations are currently available for coarse-grained soils (A-1, A-2, and A-3). Although some actual measured M_r values of coarse-grained soil are available, they are significantly less than AASHTO-recommended M_r values (MEPDG default), which needs to be further investigated.

During this study, six coarse-grained soil samples were tested for M_r at standard Proctor compactive effort: three A-2-4, one A-2-6, and two A-3. The M_r values at a confining pressure of 2 psi and a deviator stress of 6 psi were less than MEPDG-recommended default values, but they are comparable with measured values reported in the literature. Sample compaction density and moisture influenced the M_r values. The M_r value of any coarse-grained soil showed a decreasing trend with increasing degrees of saturation, a combining measure of compaction density and moisture. A few soil index properties showed good correlation with M_r values. A predictive model could not be recommended because of limited data points, that is, only six soil samples.

FINAL REPORT

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INTRODUCTION

In 2018, the Virginia Department of Transportation (VDOT) implemented the American Association of State Highway and Transportation Officials' (AASHTO) AASHTOWare-ME version 2.2.6 as the pavement design methodology for new, reconstruction, and lane-widening projects, including interstate, primary, and secondary routes with an annual average daily traffic (AADT) greater than 10,000. The *Mechanistic-Empirical Pavement Design Guide* (MEPDG) and the AASHTOWare Pavement ME (hereafter, Pavement ME) software provided an improved process for conducting pavement analysis and for developing pavement designs based on mechanistic-empirical (ME) principles (AASHTO, 2020). To facilitate the pavement design, MEPDG recommends the resilient modulus (M_r) to characterize the subgrade soils for calculating pavement responses attributable to traffic and environmental loading.

As part of the VDOT Pavement ME implementation efforts, the Materials Division Soils Lab collected both coarse- and fine-grained soil samples from around the state and performed M_r tests on them. VDOT's M_r database contains the M_r data (370 soils) and other soil property information, such as gradation, Atterberg limits, Proctor, and California Bearing Ratio (CBR). Of the 370 soils in the database, 301 soils (81%) were fine-grained soils (A-4, A-5, A-6, and A-7), and only 69 soils (19%) were coarse-grained soils (A-1, A-2, and A-3). It is important to note that class A-2 soil has four subgroups, and some variation of percent passing the No. 200 sieve and plasticity index is possible within the class range. Both percent passing the No. 200 sieve and plasticity index have a significant effect on the moisture sensitivity of subgrade soil, hence M_r. Moreover, the testing on coarse-grained soil was conducted on a smaller-sized (3-inch × 6-inch) sample, which could only accommodate the portion of the soil passing a 3/8-inch sieve.

For fine-grained soils, a sufficient number of test results allowed statewide average M_r values to be determined. These average values are currently used in the design of low-volume roadways (AADT less than 10,000 or annual average daily truck traffic [AADTT] less than 2,000). In addition, the correlations with the results of unconfined compression strength testing that were developed from a previous Virginia Transportation Research Council (VTRC) study are currently being used to estimate design M_r for high-volume projects (either 10,000 AADT or 2,000 AADTT, or greater) as an alternative to actual M_r testing (Hossain and Kim, 2014).

For coarse-grained soils, however, no statewide average M_r values or correlations are currently available. Many factors have contributed to this omission, including the limited number of measured M_r values for Virginia coarse-grained soils. Moreover, these measured M_r values of coarse-grained soil were consistently less than MEPDG-recommended M_r values (hereafter, default values) and even less than measured values for fine-grained soil. This trend warrants further investigation, and many factors might have contributed to it, such as test sample size versus maximum particle size, testing on only the portion passing a 3/8-inch sieve, stress condition, and moisture content of the sample. Although the exact backgrounds of the AASHTOWare Pavement ME-recommended or default values are not known, some information was gathered through a literature review.

VDOT currently uses the global default inputs for pavement design that AASHTOWare software provides for coarse-grained soils. Because M_r of subgrade soil is a key design parameter in Pavement ME, the default M_r values provided in AASHTOWare software should be used with utmost care. The default M_r input in Pavement ME software may be out of range for Virginia local soils, which may lead to unoptimized pavement designs as defaults are recommended for level 3 ME input.

This research study was planned to develop a comprehensive M_r database for local coarse-grained subgrade soils and to assess the data as appropriate input parameters in Pavement ME.

PURPOSE AND SCOPE

The purpose of this research was to investigate the discrepancies between MEPDG-recommended M_r values and actual laboratory-tested values for coarse-grained soils in Virginia. The objectives of the proposed research were to:

1. Develop a catalog of M_r values for Virginia coarse-grained subgrade soils.

2. Find correlations with other simple conventional soil tests to estimate M_r values for coarse-grained subgrade soils that can be used as a substitute, as necessary. It is important to note that the M_r test is resource intensive and too complex for daily operation.

METHODS

Literature Review and State Departments of Transportation Survey

Because many VTRC studies on M_r have documented previous research efforts, an extensive literature review was not conducted during this study. A few important research studies related to coarse-grained soil M_r were identified using VDOT Research Library resources. Online databases searched included Transportation Research International

Documentation, an integrated database of the Transportation Research Board; the Engineering Index; Transport; and WorldCat, among others.

In addition, a survey of other state departments of transportation (DOTs) was conducted to find the status of the use of measured M_r values in pavement design. A four-question survey, as shown in Figure 1, was sent to state DOT representatives through the AASHTO Research Advisory Committee.

Subgrade Modulus Input for pavement Design (MEPDG) - VDOT Survey

1. Does your agency use tested resilient modulus values for subgrade in pavement design?

    ◯ Yes

    ◯ No

2. Method of Test

    ◯ AASHTO T307

    ◯ NCHRP 1-28A

    ◯ Other

3. Sample preparation for Resilient Modulus Test: Density and Moisture

    ◯ Modified Proctor

    ◯ Standard Proctor

    ◯ Other

4. When a single value of resilient modulus is needed, what stress condition is used?

    ◯ Confining pressure 2 psi and deviator stress 6 psi

    ◯ Other

Figure 1. Survey Questions to State Departments of Transportation Regarding the Use of Measured Resilient Modulus for Pavement Design

Laboratory Testing

Laboratory testing of coarse-grained soils taken from various Virginia field project sites was planned to develop the catalog of M_r values for VDOT pavement design use. During the study period, VDOT districts did not encounter coarse-grained soils in their respective construction projects, although a few districts were able to help with some coarse-grained soils unrelated to actual pavement projects. Although it was planned to test 10 sources of coarse-grained soil, only six were considered because of the lack of availability of soil samples. Two sources were from Northern Virginia (NOVA), and two were from the Hampton Roads District. Two additional "sources" were made in the laboratory. A portion of the fine particles (passing a

No. 200 sieve) was removed from one of the NOVA sources to create another source. The Salem District provided a source that was marginally A-2-4 or A-4. Some No. 10 sieve screenings were blended with it to make a coarse-grain A-2-4 soil. All sources were tested for soil index properties, lightweight deflectometer (LWD), CBR, and M_r.

Soil index properties tests included gradation, liquid limit, plastic limit, and standard Proctor, following Virginia Test Method (VTM)-1 (VDOT, 2025), which is similar to AASHTO T99 method A (AASHTO, 2024). A moisture-density relationship was determined on materials passing a No. 4 sieve and corrected for particles retained on a No. 4 sieve according to VTM-1.

LWD tests were conducted on samples prepared in a 6-inch diameter Proctor mold at three different moistures but compacted to maximum dry density (MDD) to simulate varying degrees of saturation. The “scalp and replace” of CBR test standard AASHTO T193 was followed to prepare the samples (AASHTO, 2024). Some of the sources had particles retained on a ¾-inch sieve and that were replaced by an equal amount of materials passing a ¾-inch sieve but retained on a No. 4 sieve. A Dynatest LWD device with a 6-inch diameter plate was used for all testing (Appendix C includes a device setup picture). Three drop heights (5 inches, 16 inches, and 27 inches) were used to generate three drop loads to assess stress dependency. Each measurement consisted of three seating drops followed by six test drops. The average of the last six loads and deflection measurements was taken as the final reading. LWD testing was conducted following ASTM E3331 (ASTM, 2024), except for nine drops instead of six as mentioned previously. Soil modulus was calculated using Equation 1, as suggested by a Federal Highway Administration pooled fund study (Schwartz et al., 2017).

$$E = \left(1 - \frac{2\nu^2}{1-\nu}\right)\frac{4H}{\pi D^2}k \qquad \text{[Eq. 1]}$$

Where:
ν = Poisson’s ratio (assumed 0.35 for this study).
H = height of the mold (4.584 inches for this study).
D = the diameter of the plate or mold (6 inches for this study).
k = soil stiffness = (load/deflection) as calculated by the LWD device.

After LWD testing, samples were broken and recompacted to the same density and tested for unsoaked CBR according to the loading requirement of AASHTO T193, 0.05 inches per minute. CBR values were calculated at 0.1-inch penetration. A few samples were prepared with fresh materials, and a few were tested under soaked conditions of 96 hours.

All sources of material were tested for M_r, the focus of this study. Materials were tested at optimum moisture content (OMC) and maximum density as required for Pavement ME design. In addition, samples were tested at two other moisture contents but compacted at MDD to achieve a range of degrees of saturation. Samples were prepared according to AASHTO T307 and tested by a private laboratory (AASHTO, 2024). Some samples were tested following the loading sequences of AASHTO T307, and others were tested following National Cooperative Highway Research Program (NCHRP) 1-28A test protocol (Transportation Research Board, 2004). The NCHRP study developed a new loading sequence to prevent samples from premature failure. NCHRP 1-28A had 20 loading cycles, but the testing facility at the private laboratory could only accommodate 15 cycles, so it was modified to skip a few cycles (Table 1). Other recommendations in NCHRP 1-28A, such as use of an internal Linear Variable Differential Transformer (LVDT), were not used—only loading protocol was followed.

Table 1. Modified National Cooperative Highway Research Program 1-28A Loading Sequence

Loading Sequence	Confining Pressure (psi)	Maximum Axial Stress (psi)	Cyclic Stress (psi)	Constant Stress (psi)	No. of Load Applications
Conditioning	4	8.9	8	0.9	1000
1	2	1.1	1	0.1	100
2	4	2.2	2	0.2	100
3	6	3.3	3	0.3	100
4[a]	8		4		Skipped
5	12		6		Skipped
6	2	2.2	2	0.2	100
7	4	4.4	4	0.4	100
8	6	6.7	6	0.7	100
9[a]	8		8		Skipped
10	12	13.3	12	1.3	100
11	2	4.4	4	0.4	100
12	4	8.9	8	0.9	100
13	6	13.3	12	1.3	100
14	8	17.8	16	1.8	100
15	12	26.7	24	2.7	100
16	2	6.7	6	0.7	100
17	4	13.3	12	1.3	100
18	6	20	18	2.0	100
19[a]	8		24		Skipped
20[a]	12		36		Skipped

[a] Shaded cycles (4,5, 9, 19, and 20) were skipped, and constant stress was modified to match American Association of State Highway and Transportation Officials T307 (10% of maximum axial stress).

Measured M_r values from each cycle of loading are used to fit the universal constitutive model (Equation 2) recommended in MEPDG (ARA, Inc., 2004). The k-values were calculated through regression analysis. The coefficient of determination, R^2, of the regression equation was above 0.90 for all tests considered in the study, and the regression coefficients, k-values, were also significant at 5%.

$$M_r = k_1 P_a \left(\frac{\theta}{P_a} \right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_3} \quad \text{[Eq. 2]}$$

Where:
M_r = resilient modulus value.
k_1, k_2, and k_3 = regression coefficients.

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

The model presented in Equation 2 was used to calculate the M_r value at a confining stress of 2 psi and a deviator stress of 6 psi. This calculated M_r value was used in the subsequent analysis, such as correlation in which a single value of modulus was needed.

Factors Influencing Resilient Modulus Values

The moisture content usually influences M_r values, and they are also dependent on the actual stress condition of the subgrade. Each source was tested at two or three different moisture contents. The laboratory tests included LWD, M_r, and CBR. The effect of moisture was assessed by observing the trend of measured properties with the change in degree of saturation for three samples. Different loading levels were considered in both M_r and LWD testing to assess the stress dependency of the measured modulus values. All samples were prepared at standard Proctor densities, but higher compactive effort, such as modified Proctor, would produce stiffer soil fabric and should produce higher M_r values, but this direction was not investigated during this study.

Typical Resilient Modulus Value for Coarse-Grained Soil

In the context of ME pavement design, MEPDG suggests that typical M_r values be used as level 3 design input. Many correlations are used for level 2 input. A correlation with CBR is the most prominent, as suggested in MEPDG. Many researchers have conducted M_r tests on coarse-grained subgrade soil and have reported the results in published literature. Some of those values were gathered for reference. For relative comparison, an M_r value for each source is reported at a confining pressure of 2 psi and a deviator stress of 6 psi.

Correlation Analysis

Because an M_r test is resource intensive in terms of both time and expense, a reasonable correlation with simpler and routine test results would benefit VDOT. A few correlations are available in the literature, but most of them are specific to those studies and may not have universal applicability. Therefore, several predictive models were tried with tested values of M_r from this study.

Direct estimation of M_r was tried from soil index properties, CBR, and LWD test values. M_r values used in correlation analysis were at a confining pressure of 2 psi and a deviator stress of 6 psi.

Inputs to Pavement Mechanistic-Empirical and Sensitivity Analysis

The M_r input for subgrade in Pavement ME is required to be at OMC and MDD. Both moisture and stress conditions would affect the M_r value of the subgrade soil. The effect of moisture is incorporated through the Enhanced Integrated Climatic Model in the Pavement ME software. Pavement ME needs a single value as an input but did not specify the stress condition. To investigate the effect of different M_r values on pavement performance, a few simulations were run on two representative pavement structures (Table 2). Section 1 structure represents an actual site from VDOT's MEPDG calibration effort, whereas layer thicknesses were reduced in section 2 to make a slightly thinner structure.

Table 2. Flexible Pavement Structures for *Mechanistic-Empirical Pavement Design Guide* Sensitivity Analysis

Layer Materials	Properties	Layer Thickness, inch	
		Section 1	Section 2
VDOT SM	VDOT Default Value	2.0	2.0
VDOT IM	VDOT Default Value	2.0	2.0
VDOT BM	VDOT Default Value	8.0	6.0
Aggregate Base VDOT 21A/B	VDOT Default Value	12.0	8.0
Subgrade A-2-4	8,000 to 21,000 psi	Semi Infinite	Semi Infinite

BM = base mixture; IM = intermediate mixture; SM = surface mixture.

Two levels of traffic and four levels of subgrade M_r were considered for simulation. Four subgrade M_r values were 8,000, 11,250, 16,500, and 21,000 psi. Truck counts for high and low traffic levels were 2,000 and 1,170 AADTT, respectively. Additional simulation at very high traffic, with 2,500 AADTT on section 2 (thinner), was also investigated.

RESULTS AND DISCUSSION

Literature Review and State DOT Survey

The M_r value of subgrade is an essential input parameter for ME pavement design. Numerous studies were conducted to measure and estimate such values for use by different state agencies. In addition to the subgrade physical properties, these values are dependent on moisture condition and state of stress at the subgrade level. Repeated load triaxial test is used to determine M_r value in the laboratory at different stress levels, and stress-dependent models are developed to calculate the modulus at the field stress condition. These processes are complex and require a highly skilled operator. Moreover, this test is time consuming, and equipment is expensive. Many researchers have developed correlation with soil index properties, such as gradation, Atterberg limit, moisture content, and compaction density. These correlations were developed using the Long-Term Pavement Performance (LTPP) database or local subgrade soil, so their universal applicability is limited (Hassan et al., 2019; Rahman et al., 2023).

Yau and Von Quintus (2004) analyzed the M_r data found in the LTPP database as of October 2000. The results of 2,014 tests were extracted, 1,920 of which were analyzed, and all passed all levels of the quality control checks, or level E status. They concluded that the universal constitutive model parameters (k-values) cannot be accurately predicted from the physical properties of the soils included in the LTPP database. The average k-values from the LTPP database were as follows:

- Base and subbase: k_1 = 873; k_2 = 0.626; and k_3 = -0.170.
- Coarse-grained soil: k_1 = 802; k_2 = 0.452; and k_3 = -1.140.
- Fine-grained soil: k_1 = 896; k_2 = 0.282; and k_3 = -1.576.

New Mexico DOT developed prediction models for estimating the M_r of aggregate base and non-cohesive subgrade soil to be used in mechanistic pavement design (Hasan et al., 2019). Materials were collected from seven different project sites and tested in the laboratory for M_r following AASHTO T307. The universal constitutive model provided in MEPDG was used to fit the data, and respective k-values were determined. Samples were prepared at OMC and MDD according to modified Proctor results. Prediction models were developed to estimate k-values using multiple regression analysis based on physical properties of soil, such as percent passing various sieve sizes, OMC, and MDD. Regression equations for k coefficients were established for both base aggregate and subgrade soil with strong predictive capability as indicated by high R^2 values.

Ahmed et al. (2016) studied stress-depending behavior of unbound pavement layers using both a field falling weight deflectometer (FWD) test and a laboratory M_r test. The stiffness in the aggregate base layers increased with stress, showing consistent stress-hardening behavior. On the other hand, subgrade soils exhibited both stress-hardening and stress-softening, depending on the soil type and condition. A conversion factor was developed to relate back-calculated M_r from FWD testing to laboratory-measured value at field stress condition. Such conversion would be useful for stiffness-based construction monitoring of the subbase and subgrade layer.

Rahman et al. (2023) discussed the effect of moisture on the subgrade modulus and its implication on predicting rutting in a flexible pavement using MEPDG. Bulk samples were collected from three field projects in South Carolina and tested for M_r according to AASHTO T307 at different moisture contents. In addition, soil index properties and CBR values were also measured. Good correlation was observed between unsoaked CBR and laboratory-measured M_r values. The generalized constitutive M_r model parameters (k_1, k_2, and k_3) were correlated to soil index properties, such as percent passing a No. 4 sieve, liquidity index, OMC, and MDD. Each of the field sites was tested for FWD, and the subgrade M_r was back calculated. Laboratory-measured M_rs were correlated to the field measured values. Undisturbed soil samples (Shelby tube) were also collected from field projects and tested for M_r according to AASHTO T307. The M_r values were different between the field undisturbed sample and laboratory-remolded sample. The effect of M_r on undisturbed soil samples in predicting rutting was investigated (Rahman and Gassman, 2017).

Mississippi DOT also conducted extensive testing of base, subbase, and subgrade to develop a library of typical M_r values to be used in MEPDG (James et al., 2010). They used NCHRP 1-28A testing protocol and standard compactive effort. Most of their subgrade soil was classified as A-4 and A-6. Only a few coarse-grained soils were included in the testing program:

five A-2-4, three A-2-6, and two A-3. The ranges of M_r values calculated at 2 psi confining pressure and 6 psi deviator stress were as follows:

- A-2-4: 10,500–23,000 psi.
- A-2-6: 8,800–13,600 psi.
- A-3: 9,300–13,700 psi.

These values were below the MEPDG-recommended values, and their suggested reasoning was unspecified stress condition and use of modified Proctor compaction in MEPDG values.

When measured values are unavailable, MEPDG provides recommended subgrade M_r values based on established correlations (ARA, Inc., 2001) but independent of stress condition. This process involved first collecting typical CBR values for Unified Soil Classification System and AASHTO soil classes from the U.S. Army Corps of Engineers and Asphalt Institute, respectively. These values were then used to estimate M_r via the correlation, $M_r = 2555*CBR^{0.64}$. To simplify the estimation further, CBR was correlated with key soil index properties D_{60} (particle diameter corresponding to 60% finer), and the product of percent passing the No. 200 sieve and plasticity index ($P200 \cdot PI$) for coarse-grained soils and fine-grained soils, respectively. MEPDG documents list the typical ranges for these soil index properties and the corresponding M_r values for each of AASHTO and Unified Soil Classification System soil classes (ARA, Inc., 2001).

These MEPDG-recommended M_r values were further refined using field back-calculated values from FWD tests and incorporated in AASHTOWare Pavement ME manual of practice as default values (Witczak et al., 2006). FWD back-calculated values from the LTPP database were grouped by soil class and converted to the optimum laboratory condition using established correlation equations. Back-calculated values were adjusted to correspond with laboratory-measured values under in situ field conditions by applying a factor of 0.6 for coarse-grained soils and 0.5 for fine-grained soils. Another correlation of M_r (at optimum) = 1.1* M_r (in situ) was used to convert this in situ laboratory value to optimum condition. This correlation was developed from a Florida study in which samples were tested at modified Proctor conditions (Ping et al., 2001), and values were calculated at specific stress states (2 psi confining and 5 psi deviator). The M_r test in the Florida study was conducted following an older AASHTO T292 standard (AASHTO, 2024), and internal LVDT was used. The range of recommended values for each soil class was established by adding and subtracting 1 standard deviation from the average value.

Chowdhury and Kassem (2025) explored correlation between M_r values and two other tests: CBR and LWD for base aggregate in Idaho. An M_r test was conducted following AASHTO T307, and both external and internal LVDTs were used. The M_r was calculated at 5 psi confining and 15 psi deviator stresses for correlation analysis. Although the M_r from internal LVDT measurements were higher than external measurements as observed by other researchers (Camargo et al., 2012; Ping et al., 2003), both CBR and LWD correlated better with external measurements. The M_r of Idaho unbound granular materials showed fair correlation with unsoaked CBR and good correlation with LWD modulus.

A survey of state DOTs indicated that most DOTs currently do not use measured M_r values for their pavement design—most use some sort of correlations. Only six DOTs out of 23 respondents have the option for using measured M_r values. All six DOTs follow AASHTO T307 protocol for testing, but some use modified Proctor, and others use standard Proctor compaction. Mississippi DOT does not use measured values yet, but they have developed a catalog of values using NCHRP 1-28A protocol. Figure 2 summarizes the survey results, and Appendix A includes the detailed results.

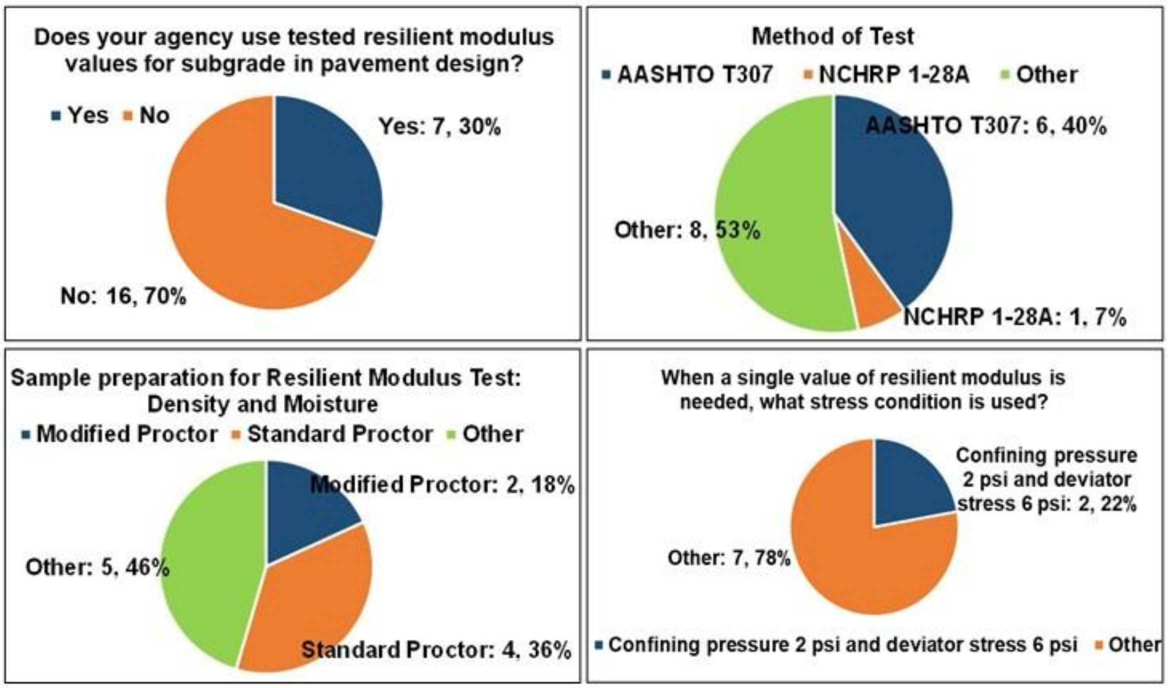

Figure 2. State Departments of Transportation Responses to Survey Questionnaire. AASHTO = American Association of State Highway and Transportation Officials; NCHRP = National Cooperative Highway Research Program.

Laboratory Test Results

Soil Index Properties

All six sources of soil were tested for gradation, liquid limit, plastic limit, specific gravity, and standard Proctor. Table 3 summarizes the results along with respective AASHTO soil class. Standard Proctor test was conducted on the fraction passing a No. 4 sieve and corrected for oversize particles according to VDOT standard VTM-1, which is comparable with AASHTO T99 Method A.

Table 3. Coarse-Grained Soil Properties

Source	AASHTO Class	Specific Gravity	% Passing on Sieve			D_{60} mm	Atterberg Limits			Standard Proctor[a]	
			No. 4	No. 40	No. 200		LL	PL	PI	OMC, %	MDD, pcf
NOVA 1	A-2-6	2.656	73.1	43.2	22.4	1.852	27	14	13	8.1	128.3
NOVA 2	A-2-4	2.737	79.8	36.9	23.5	1.306	27	20	7	8.1	133.7
NOVA 2a	A-2-4	2.726	78.7	32.7	18.9	1.454	26	19	7	8.0	132.5
Salem Piney	A-2-4	2.825	78.4	48.5	29.9	1.230	24	19	5	9.4	130.6
Bay Sand	A-2-4	2.676	100	85.8	14.6	0.350	15	NP	NP	11.5	116.7
Paxton	A-3	2.658	100	71.9	5.4	0.390	17	NP	NP	15.0	107.3

[a] Standard Proctor according to Virginia Test Method-1. AASHTO = American Association of State Highway and Transportation Officials; D_{60} = diameter corresponding to 60% finer; LL = liquid limit; MDD = maximum dry density; OMC = optimum moisture content; NOVA = Northern Virginia; NP = non-plastic; PI = plasticity index; PL = plastic limit.

Resilient Modulus Test

As mentioned previously, all sources were tested for M_r according to AASHTO T307 and NCHRP 1-28A loading sequence. All samples were compacted to standard Proctor MDD but at different moisture contents. Table 4 presents the results. Some of the M_r testing was conducted using AASHTO loading sequence, with others following NCHRP loading sequence. The NCHRP 1-28A loading sequences were developed to prevent any premature failure during the testing, and it covers a wider range of loading conditions with higher confinement. Because of the limited supply (availability) of materials, some of the sources were tested for only two moisture contents. Degrees of saturation were calculated from compaction moisture and density, along with specific gravity of the soil solids. All samples were tested at OMC, which is the design value input requirement. The variations of moisture were dry of optimum, wet of optimum, or both. The high R^2 values (> 0.9) for regression coefficients indicate a very good fit for the stress dependency model.

The effect of moisture and density on M_r is investigated in Figure 3 in terms of degrees of saturation of each sample. In general, higher degrees of saturation equate to lower M_r values, but some were less sensitive than others. Both sandy soils were less sensitive to moisture, and they were difficult to compact at wet-of-optimum moisture—moisture did not hold and drained out from the sample.

Lightweight Deflectometer

Tests were conducted on all six sources at three different moisture contents and three drop heights. Samples were compacted to standard Proctor MDD. Table 5 presents the results. The values of each load, deflection and corresponding modulus represent the average of last six drops, and the coefficients of variation for the last six measurements were mostly below 5%, except for a few at 5 to 10%. Only two coefficients of variation for NOVA 2a measurements at high moisture were very high (>10%). Although three fixed drop heights were used, applied loads varied a little. The following shows the applied pressure ranges:

- 5-inch drop height: 26.5 to 33.0 psi.
- 16-inch drop height: 43.3 to 49.1 psi.
- 27-inch drop height: 60.6 to 68.4 psi.

Table 4. Resilient Modulus Test Results[a]

Sources and Class	Proctor Results		Loading Sequence	Sample Properties			Universal Constitutive Model Parameters				M_r (psi)
	OMC (%)	MDD (pcf)		w (%)	ρ_d (pcf)	S%	k_1	k_2	k_3	R^2	
NOVA 1 A-2-6	8.1	128.3	NCHRP	6.3	128.3	57	1616.9	0.7429	– 1.2553	0.98	17,500
				8.0	128.3	73	1626.1	0.7716	– 0.8823	0.98	16,390
NOVA 2 A-2-4	8.1	133.7	AASHTO	6.5	133.8	64	1356.3	1.0947	– 0.8783	0.95	13,680
				8.4	133.8	83	1193.2	1.0246	– 2.1299	0.98	9,794
NOVA 2a A-2-4	8.0	132.5	AASHTO	7.8	132.6	75	1324.4	0.9164	– 1.8560	0.98	11,660
			NCHRP	6.4	132.6	62	1171.1	1.0071	– 1.0642	0.99	11,636
				7.8	132.6	75	1156.3	0.7380	– 0.7334	0.97	12,862
				8.8	132.6	85	586.8	0.6785	– 0.0350	0.97	7,470
Salem Piney A-2-4	9.4	130.6	NCHRP	9.2	130.1	73	1,235.5	0.6556	– 1.1334	0.98	13,025
				10.8	130	86	714.5	0.8003	– 1.1812	0.87	7,252
Bay Sand A-2-4	11.5	116.7	AASHTO	9.4	115.1	56	599.3	0.5683	– 0.7409	0.95	6,891
				11.4	128.2	101	487.3	0.5667	– 0.4540	0.97	5,895
				11.3	113.3	64	555.0	0.6091	– 0.4199	0.98	6,697
			NCHRP	9.5	114.4	55	577.5	0.5349	– 0.1139	0.96	7,465
				11.3	114.9	67	567.1	0.5879	– 0.2247	0.96	7,112
				12.7	114.8	75	584.8	0.5951	– 0.3075	0.97	7,217
Paxton Sand A-3	15.0	107.3	AASHTO	12.9	107	62	574.6	0.6152	– 0.4177	0.99	6,927
				14.1	106.2	67	524.6	0.5597	– 0.3239	0.98	6,502
				12.8	118.4	85	684.4	0.6430	– 0.6728	0.99	7,844
			NCHRP	12.9	106.3	61	591.6	0.6165	– 0.2650	0.99	7,324
				14.0	105.7	65	595.9	0.6123	– 0.3645	0.99	7,256
				12.9	117.9	84	470.7	0.5552	1.3704	0.75	7,869

[a] No materials were scalped for the M_r test; the first four sources were tested using a 6-inch x 12-inch sample, whereas both sands were tested using a 3-inch x 6-inch sample. M_r values are calculated at 2 pounds per square inch confining pressure and 6 pounds per square inch deviator stress. AASHTO = American Association of State Highway and Transportation Officials; NCHRP = National Cooperative Highway Research Program; NOVA = Northern Virginia; OMC = optimum moisture content; MDD = maximum dry density; w = moisture content; ρ_d = dry density; S = degree of saturation; M_r = resilient modulus.

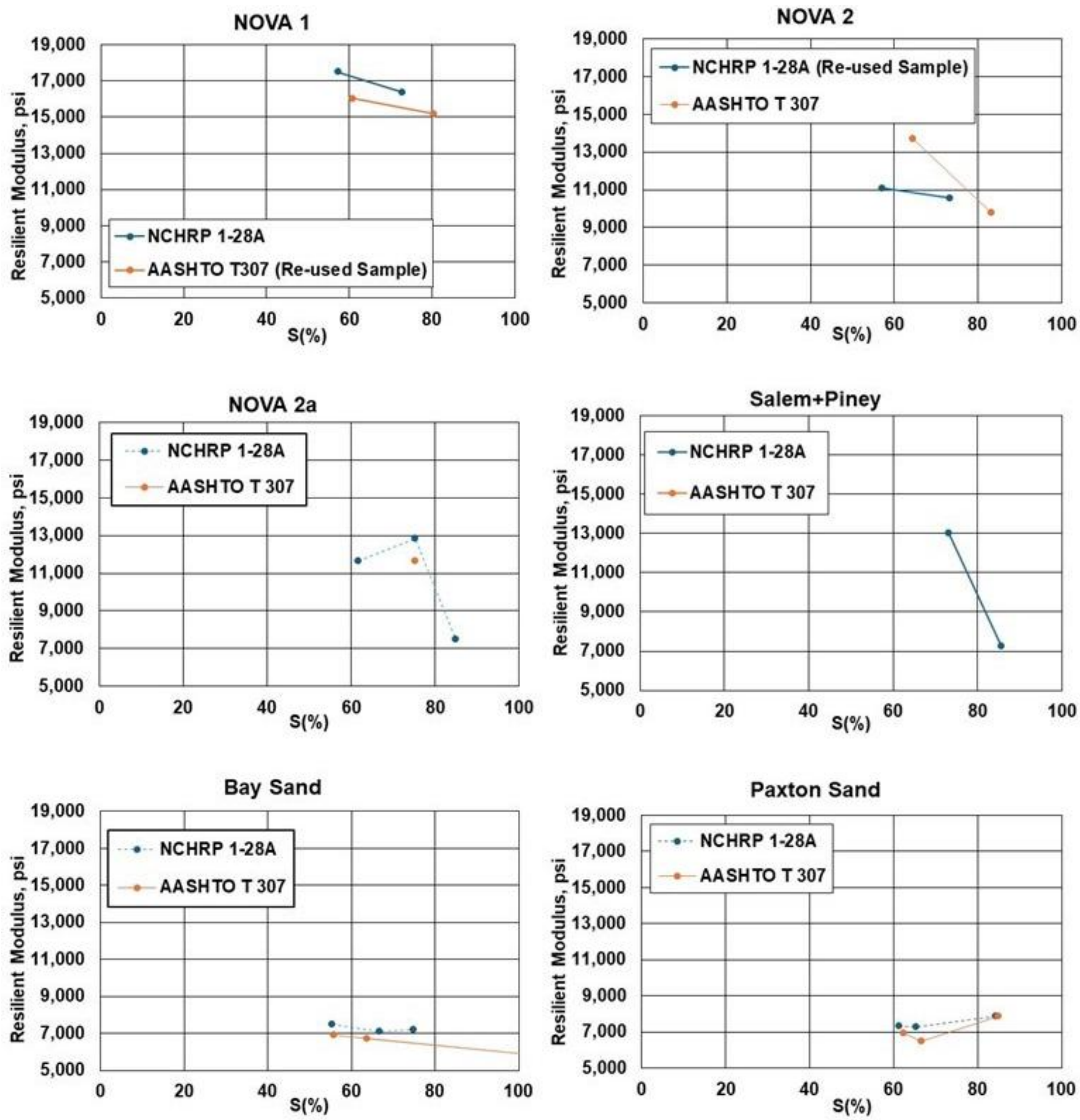

Figure 3. Effect of Moisture and Density on Resilient Modulus of Coarse-Grained Soil. AASHTO = American Association of State Highway and Transportation Officials; NCHRP = National Cooperative Highway Research Program; NOVA = Northern Virginia.

Table 5. LWD Test Results for Coarse-Grained Soils with Particles Retained on No. 4 Sieve

Source and Soil Class	Sample Properties			Drop Height, in.	LWD Measurements		
	w (%)	ρ_d (pcf)	S%		Load, lbf	Deflection, mil	Modulus, psi
NOVA 1 A-2-6 (OMC: 8.1% and MDD: 128.3 pcf)	6.0	128.6	55.5	5	747.9	10.4	7,204.7
				16	1,197.5	13.0	9,218.8
				27	1,676.3	18.2	9,244.0
	7.7	130.0	74.9	5	738.1	9.1	7,925.0
				16	1,219.6	14.2	8,389.7
				27	1,683.8	18.4	8,910.1
	8.8	130.4	86.0	5	742.2	21.9	3,370.5
				16	1,195.6	30.6	3,885.7
				27	1,670.7	34.6	4,800.6
NOVA 2 A-2-4 (OMC: 8.1% and MDD: 133.7 pcf)	6.6	133.4	64.2	5	741.9	7.0	10,677.0
				16	1,205.7	10.7	11,372.8
				27	1,688.7	14.9	11,330.2
	7.9	134.6	80.1	5	724.6	29.7	2,448.1
				16	1,185.5	32.2	3,689.3
				27	1,673.7	34.6	4,868.4
NOVA 2a A-2-4 (OMC: 8.0% and MDD: 132.5 pcf)	7.1	131.6	65.9	5	737.0	10.3	7,232.8
				16	1,200.1	12.2	9,919.6
				27	1,666.2	15.8	10,648.3
	9.3	129.8	81.8	5	824.7	45.4	1,830.1
				16	1,237.2	45.2	2,757.9
				27	1,843.8	45.5	4,118.7
	9.4	132.0	89.1	5	904.9	66.9	1,362.0
				16	1,345.1	34.6	4,003.5
				27	1,873.8	18.2	11,140.9
Salem Piney A-2-4 (OMC: 9.4% and MDD: 130.6 pcf)	9.8	127.6	72.5	5	731.8	14.5	5,104.4
				16	1,205.7	17.4	6,998.8
				27	1,658.7	22.3	7,500.3
	11.0	131.0	90.1	5	816.1	54.8	1,529.5
				16	1,276.2	63.8	2,043.5
				27	1,756.5	67.2	2,673.0
Bay Sand A-2-4 (OMC: 11.5% and MDD: 116.7 pcf)	8.9	116.8	55.1	5	739.6	5.8	12,780.4
				16	1,196.0	9.2	12,959.5
				27	1,688.3	12.1	13,937.2
	10.8	117.1	68.0	5	740.0	9.7	7,644.3
				16	1,205.4	12.6	9,586.3
				27	1,698.4	15.1	11,247.7
	12.0	116.6	74.5	5	818.3	39.9	2,053.4
				16	1,341.7	42.0	3,184.8
				27	1,767.7	40.0	4,418.0
Paxton Sand A-2-4 (OMC: 15.0% and MDD: 107.3 pcf)	12.1	108.6	60.8	5	743.4	9.7	7,688.6
				16	1,224.1	12.9	9,495.0
				27	1,717.5	16.3	10,582.2
	14.3	107.7	70.4	5	747.5	10.9	6,834.1
				16	1,205.4	14.4	8,372.7
				27	1,714.2	15.9	10,767.9
	15.6	108.6	78.5	5	750.9	7.5	10,102.1
				16	1,223.3	9.9	12,418.8
				27	1,729.2	14.2	7,204.7

LWD = lightweight deflectometer; MDD = maximum dry density; NOVA = Northern Virginia; OMC = optimum moisture content; w = moisture content; ρ_d = dry density; S = degree of saturation.

The stress dependency of material response and moisture effect were investigated by plotting the results in Figure 4. LWD modulus is showing an increasing trend with increasing drop height, which is the typical stress dependency of coarse-grained soil—higher modulus with higher confining stress. Higher drop height imparts higher load, and the rigid boundary confinement of the test mold generates higher confining stress. The effect of moisture on LWD modulus is similar to M_r. In most cases, LWD modulus decreases with increasing degrees of saturation. A few exceptions to this trend were noted at higher moisture levels, most likely because of pore pressure development with the drop load.

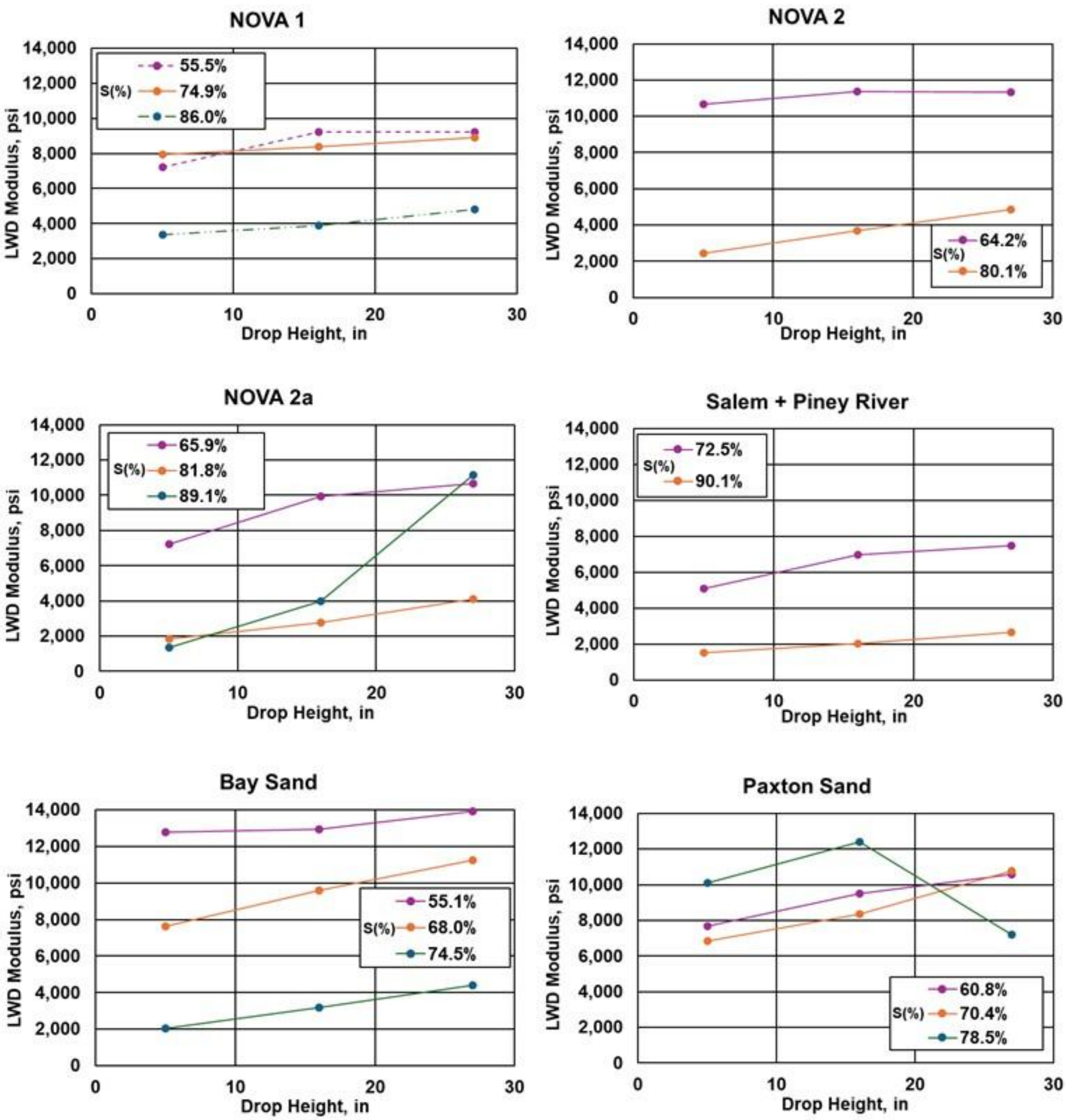

Figure 4. Effect of Drop Load and Moisture Level on LWD Modulus. LWD = lightweight deflectometer; NOVA = Northern Virginia.

California Bearing Ratio Test Results

Like other tests, CBR test was performed on all six sources at two or three different degrees of saturation. Most tests were performed in unsoaked conditions, with only a few soaked tests. Table 6 presents the results. As expected, unsoaked CBR values decrease with increasing degrees of saturation or increase in moisture content (Figure 5).

Table 6. CBR Test Results

Source and Soil Class	Standard Proctor Results		Sample Properties			CBR (%)—0.1 in	
	OMC (%)	MDD (pcf)	w (%)	ρ_d (pcf)	S%	Unsoaked	Soaked
NOVA 1 A-2-6	8.1	128.3	6.0	128.9	56	100	N/A
			7.7	124.8	63	48	44
			8.8	129.7	84	28	N/A
NOVA 2 A-2-4	8.1	133.7	6.6	133.4	64	31	N/A
			7.9	134.6	80	7	N/A
			9.2	131.6	85	N/A	4
NOVA 2a A-2-4	8.0	132.5	6.3	128.4	53	39	N/A
			7.9	136.4	87	53	25
			9.0	132.4	86	28	9
Salem Piney A-2-4	9.4	130.6	9.8	130.8	80	32	N/A
			11.0	131.3	91	8	N/A
Bay Sand A-2-4	11.5	116.7	8.9	118.2	57	13	N/A
			10.8	117.7	69	12	N/A
			12.0	117.2	76	6	N/A
Paxton Sand A-3	15.0	107.3	12.1	108.2	60	23	N/A
			14.3	107.5	70	21	N/A
			15.6	108.5	78	8	N/A

CBR = California Bearing Ratio; MDD = maximum dry density; N/A = data not available; NOVA = Northern Virginia; OMC = optimum moisture content; w = moisture content; ρ_d = dry density; S = degree of saturation.

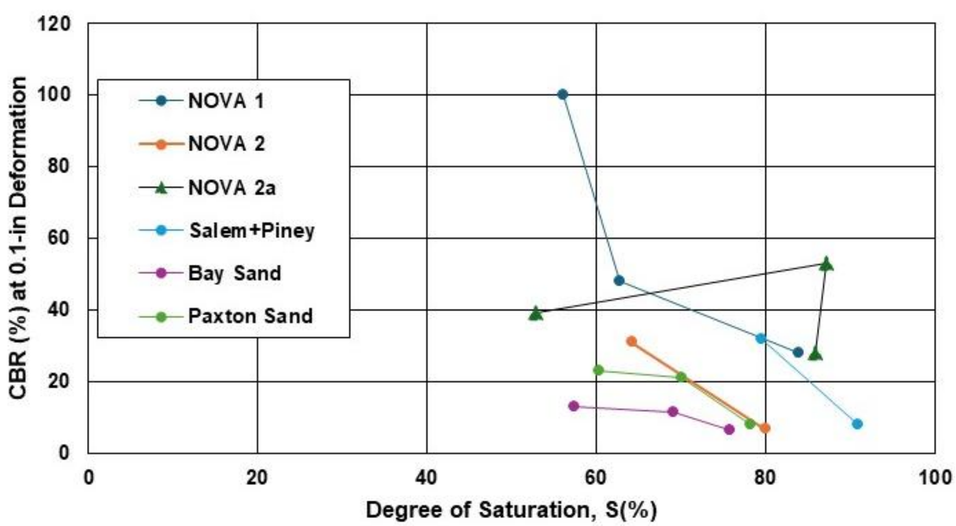

Figure 5. Variation of CBR with Moisture Content. CBR = California Bearing Ratio; NOVA = Northern Virginia.

Typical Resilient Modulus Value for Coarse-Grained Soil

This study focuses on pavement design using AASHTOWare Pavement ME, and Table 7 lists the typical values recommended in the MEPDG manual of practice (AASHTO, 2020). Subgrade M_r values are stress dependent, values listed in Table 7 have lower values for rigid pavement because the stress under rigid pavement is expected to be less than that of flexible pavement. Although different values are listed for rigid and flexible pavement, AASHTOWare Pavement ME software version 2.2.6 picks up the lowest default values as a conservative estimate during the actual design, even in flexible pavement. Table 8 lists the default soil properties and M_r values. The usual VDOT practice for subgrade compaction is at standard Proctor values, which could result in lower modulus values than default values in Table 8.

Table 7. AASHTOWare Pavement Mechanistic-Empirical Default Values for Subgrade Resilient Modulus[a]

AASHTO Soil Classification	Recommended Resilient Modulus for Subgrade Soil, psi	
	Flexible Pavements	Rigid Pavements
A-1-a	29,500	18,000
A-1-b	26,500	18,000
A-2-4	24,500	16,500
A-2-5	21,500	16,000
A-2-6	21,000	16,000
A-2-7	20,500	16,000
A-3	16,500	16,000

[a] Subgrades are supposed to be compacted at optimum moisture content and maximum dry density according to modified Proctor values following AASHTO T180. AASHTO = American Association of State Highway and Transportation Officials.

Table 8. AASHTOWare Pavement Mechanistic-Empirical Software Default Values in Version 2.2.6

AASHTO Soil Class	Gradation (% Passing)			Atterberg Limits		Sample Properties				Resilient Modulus, psi[a]
	No. 4	No. 40	No. 200	LL	PI	OMC	MDD	Sp. Gr.	S (%)	
A-1-b	74.2	37.6	13.4	11	1	9.1	123.7	2.7	68	18,000
A-2-4	87.2	67.2	22.4	14	2	9.0	124.0	2.7	68	16,500
A-2-5	81.0	61.0	30.0	50	6	10.1	121.9	2.7	71	16,000
A-2-6	67.2	43.5	24.8	32	15	10.0	121.9	2.7	71	16,000
A-2-7	55.4	37.1	27.4	50	29	10.6	120.8	2.7	73	16,000
A-3	95.3	76.8	5.2	11	NP	7.3	120.0	2.7	49	16,000

[a] Resilient modulus values are calculated at confining pressure 2 psi and deviator stress 6 psi. AASHTO = American Association of State Highway and Transportation Officials; LL = liquid limit; MDD = maximum dry density; OMC = optimum moisture content; NP = non-plastic; PI = plasticity index; S = degree of saturation; Sp. Gr. = specific gravity.

For a relative comparison, a few tested values were gathered from published study reports (Table 9). The samples were from Alabama (Von Quintus et al., 2015), Georgia (Von Quintus et al., 2015), New Mexico (Hassan et al., 2019), South Carolina (Rahman et al., 2023), and Mississippi (James et al., 2010). Most of the soil in these studies are A-2-4. Resilient values and were calculated at a confining pressure of 2 psi and deviator stress of 6 psi, although the actual stress conditions at the field would depend on pavement structure and loading.

Table 9. Measured Resilient Modulus Values from Literature and this Study

AASHTO Soil Class	Gradation (% Passing)			Atterberg Limits		Sample Properties				Resilient Modulus, psi[a]
	#4	#40	#200	LL	PI	w (%)	ρ_d (pcf)	Sp. Gr.	S (%)	
Alabama										
A-2-4	81.2	43.7	29.4	26	4	10.6	120.2	2.7	71	4,000–7,000
Georgia										
A-2-4	81.8	55.0	23.7	N/A	NP	14.6	110.1	2.7	74	3,200–5,300
South Carolina										
A-1-b	N/A	N/A	1.5	N/A	NP	9.5	122.6	2.7	69	12,586
A-2-4	N/A	N/A	24.7	26	9	10.2	124.6	2.7	78	9,719
A-2-4	N/A	N/A	20.6	18	1	8.9	121.2	2.7	62	11,897
A-2-4	N/A	N/A	22.8	20	4	9.3	124.5	2.7	71	10,845
A-3	N/A	N/A	0.8	N/A	NP	11.9	109.0	2.7	59	13,605
New Mexico										
A-2-4	74.1	45.6	14.8	N/A	NP	13.8	114.5	2.7	79	11,646
A-2-4	99.3	93.1	34.1	N/A	NP	9.8	117.5	2.7	61	18,109
A-2-4	96.4	87.2	18.0	N/A	NP	10.1	119.3	2.7	66	14,972
A-2-4	86.9	56.2	11.0	N/A	NP	11.0	118.4	2.7	70	11,088
A-2-4	43.6	15.5	7.2	N/A	NP	7.2	125.3	2.7	56	14,438
Virginia										
A-2-4	79.8	36.9	23.5	27	7	8.4	133.8	2.737	83	9,794
A-2-4	78.7	32.7	18.9	26	7	7.8	132.6	2.726	75	12,862
A-2-4	78.4	48.5	29.9	24	5	9.2	130.1	2.825	73	13,025
A-2-6	73.1	43.2	22.4	27	13	8.0	128.3	2.656	73	16,390
A-3 (A-2-4)	100	85.8	14.6	15	NP	11.3	114.9	2.676	67	7,112
A-3	100	71.9	5.4	17	NP	14.0	105.7	2.658	65	7,256
Mississippi										
A-2-4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10,500–23,000
A-2-6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	8,800–13,600
A-3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	9,300–13,700

[a] Resilient Modulus values are calculated at confining pressure 2 psi and deviator stress 6 psi. AASHTO = American Association of State Highway and Transportation Officials; LL = liquid limit; PI = plasticity index; N/A = data not available; NP = non-plastic; ρ_d = dry density; S = degree of saturation; Sp. Gr. = specific gravity; w = moisture content.

As Table 9 shows, a wide variation is observed in modulus values of different soils of the same AASHTO class, such as A-2-4. Although the values measured for Virginia A-2-4 soils during this study are somewhat less than MEPDG default values, they are comparable with other studies. The values of Virginia A-2-4 range from 9,700 to 13,000 psi, comparable with South Carolina soils, and both studies used standard Proctor values. In an email communication with Florida DOT, staff confirmed the range of modulus values being 10,000 to 13,500 psi for coarse-grained soil (Sasidhar Ayithi, State Geotechnical Materials Engineer, Florida DOT "personal communication"). On the other hand, New Mexico values for A-2-4 soil range from 11,000 to 18,000 psi. These values are slightly higher than Virginia values, but they used modified Proctor. Because density and moisture affect the M_r value, the use of standard Proctor parameters in Virginia compared with modified Proctor values in the MEPDG defaults could be one of the contributing factors, which would need further study. The placement of LVDTs to measure deformation during M_r test, internal versus external, could also influence the values. The M_r value for Viriginia A-2-6 soil is slightly higher than the MEPDG default. Both moisture and density of the tested sample contributed to this outcome, that is, moisture is slightly less than the default, and density is slightly higher. The M_r values for the two A-3 soils from

Virginia are around 7,000 psi, which is significantly less than the default value of 16,000 psi. Density and moisture of the tested sample might be attributed to the low values. In this case, density is low, and moisture is high—both usually contribute to lower M_r. Use of modified Proctor compaction effort could narrow the difference. Further investigation of sand soil is needed.

VDOT's Materials Division conducted a series of M_r tests on soils samples collected from construction projects, and those values were significantly lower compared with MEPDG default values. Those tests were conducted on small-size samples of 3 inches x 6 inches and could not accommodate particles larger than a 3/8-inchsieve. In some cases, scalping of those larger particles was necessary, and others did not have any larger particles. The Federal Highway Administration Round Robin study soil values in Table 9 are also low (Von Quintus et al., 2015); large-size particles were scalped before testing in 3-inch x 6-inch-size samples. In a previous VTRC study (Hossain, 2010), one A-2-4 soil sample with 25% particles larger than No. 4 sieve was tested using both 6-inch x 12-inch- and 3-inch x 6-inch-size samples and the M_r values were different. The M_r values at confining pressure of 2 psi and deviator stress of 6 psi were 12,629 psi and 8,040 psi for large- and small-size samples, respectively. All particles, including larger than No. 4 sieve size, were included in the large-size sample.

M_r values are stress dependent, as depicted by the universal constitutive model. Nearly all tests during this study have perfect fit to the model with $R^2 > 0.9$. Figure 6 shows one of the test results, in which M_r is increasing with increasing confining pressure. Therefore, the use of actual stress conditions to calculate M_r values should be explored further. Appendix A includes other plots.

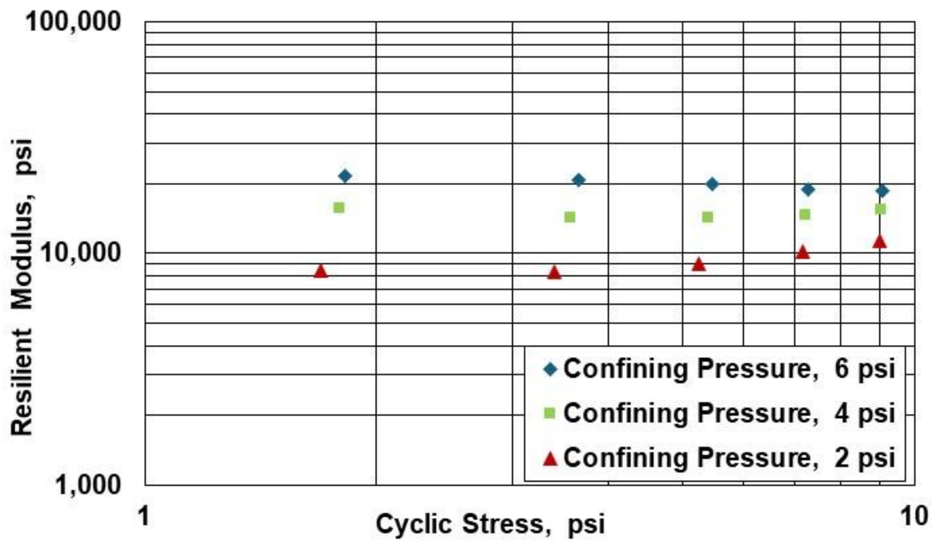

Figure 6. Resilient Modulus Values for 15 Load Cycles for NOVA 2 (A-2-4) at Optimum Moisture Content and Maximum Dry Density

Correlation Analysis

The correlation analysis was conducted to find any meaningful model that can reasonably estimate or predict M_r from other measured properties of subgrade soil. The direct estimation of a single value of M_r was tried first. Only six subgrade soils were available for this study, providing six data points. This limited amount of data is usually not enough to develop a robust model. Moreover, soil types were limited to three. M_r values calculated at confining pressure of 2 psi and deviator stress of 6 psi were used for the model development; samples compacted at OMC and MDD were used. To correlate these modulus values with unsoaked CBR and LWD modulus, corresponding values were picked from Figure 4 and 5 at matching degrees of saturation as M_r values. Table 10 presents the values used for correlation analysis. No correlation or trend with CBR or LWD was present when all data points were used. The unsoaked CBR value for NOVA 2 soil tested very low and was considered suspect or an outlier. The remaining five data points show fair correlation between unsoaked CBR and M_r (Figure 7). Similarly, LWD modulus followed strong correlation for four soils, but two of the sands were completely off the trend (Figure 8); two sands were considered outliers in the trend analysis. LWD modulus from all three drop heights have similar trends to M_r.

Table 10. Values Used in Correlation Analysis

Soil	Resilient Modulus, psi[a]	Degree of Saturation	Unsoaked CBR	LWD Modulus, psi		
				5-in. Drop	16-in. Drop	27-in. Drop
NOVA 1: A-2-6	16,390	73	40	7,900	8,500	8,900
NOVA 2: A-2-4	9,794	83	5	2,300	3,500	4,800
NOVA 2a: A-2-4	12,862	75	50	3,600	5,500	6,300
Salem Piney: A-2-4	13,025	73	45	5,100	7,000	7,500
Bay Sand: A-3 (A-2-4)	7,112	67	12	7,700	9,600	11,250
Paxton Sand: A-3	7,256	65	22	7,200	8,900	10,500

[a] Resilient Modulus values are calculated at confining pressure 2 psi and deviator stress 6 psi. CBR = California Bearing Ratio; LWD = lightweight deflectometer; NOVA = Northern Virginia.

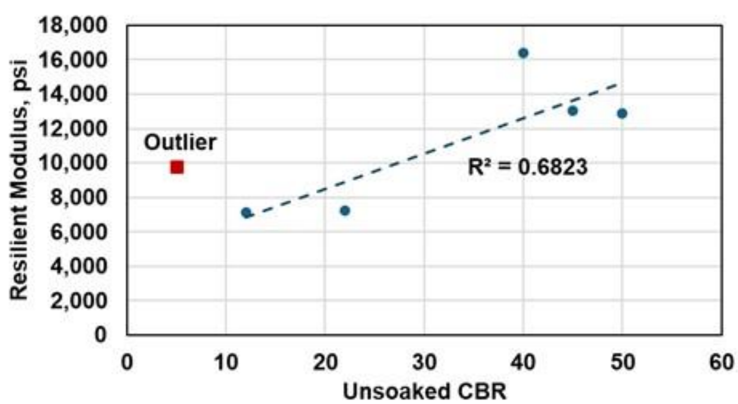

Figure 7. Correlation between CBR and Resilient Modulus. CBR = California Bearing Ratio.

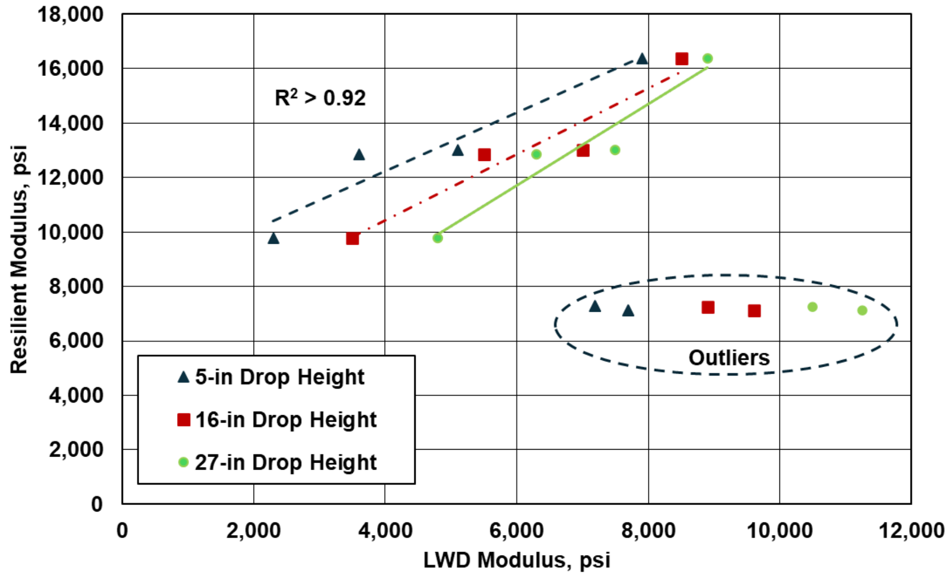

Figure 8. Correlation between LWD Modulus and Resilient Modulus. LWD = lightweight deflectometer.

Both sand sources behaved differently under LWD modulus testing than under M_r testing of these sands. They are outliers in the correlation analysis presented in Figure 8. Further investigation is needed to determine the causes of such discrepancies.

The soil index properties were also analyzed to develop models for predicting M_r. Table 11 lists the soil properties and correlation R^2 (regression coefficient of determination) for each property when regressed to M_r values, presented at the last row of the table. The correlations with soil properties are very strong, such as the R^2 for D_{60} or percent passing a No. 4 sieve or PI is greater than 0.8. Based on these correlation analyses (Table 11), it is possible to develop a strong multi-variable model using soil index properties to predict M_r, but the limited number of samples hampered a meaningful model development in this study.

Table 11. Correlation between Soil Index Properties and Resilient Modulus

M_r, psi[a]	OMC (%)	MDD, pcf	S (%)	D_{60}, mm	% Passing on sieve size			Atterberg Limits		
					No. 4	No. 40	No. 200	LL	PL	PI
16,390	8.1	128.3	72.8	1.852	73.1	43.2	22.4	27	14	13
9,794	8.5	133.7	83.2	1.306	79.8	36.9	23.5	27	20	7
12,862	8.0	132.5	75.2	1.454	78.7	32.7	18.9	26	19	7
13,025	9.4	130	73.2	1.230	78.4	48.5	29.9	24	19	5
7,112	11.5	116.7	66.7	0.350	100	85.8	14.6	15	0	0
7,256	15.0	107.3	65.4	0.390	100	71.9	5.4	17	0	0
R^2	*0.57*	*0.46*	*0.14*	*0.87*	*0.83*	*0.52*	*0.44*	*0.64*	*0.47*	*0.83*

[a] Resilient Modulus values are calculated at confining pressure 2 psi and deviator stress 6 psi. D_{60} = diameter corresponding to 60% finer; LL = liquid limit; MDD = maximum dry density; M_r = resilient modulus; OMC = optimum moisture content; PI = plasticity index; PL = plastic limit; S = degree of saturation.

The M_r values in Table 11 are calculated at a specified stress condition. Thus, using any such models to directly predict M_r would ignore the stress dependency. Therefore, the model constants (k-values, determined through regression) for the universal constitutive model were also investigated for correlation analysis. If k-values could be estimated from soil index properties, M_r could be calculated for actual expected field stress conditions. Table 12 presents the correlation analysis for the k-values. A few correlations are very strong, so it would be possible to develop predictive models for k-values for Virginia-specific soils, but more data points are needed, and thus, more coarse-grained soils need to be tested.

Table 12. Correlation between Soil Index Properties and K-Values of Universal Constitutive Model

Soil Index Properties		Correlation R^2 (Coefficient of Determination)		
		K_1	K_2	K_3
OMC		0.69	0.35	0.32
MDD		0.62	0.45	0.51
S (%)		0.39	0.87	0.88
D_{60} (mm)		0.96	0.33	0.28
% Passing on Sieve	No. 4	0.94	0.33	0.38
	No. 40	0.67	0.49	0.47
	No. 200	0.56	0.18	0.40
Atterberg Limits	LL	0.84	0.54	0.53
	PL	0.64	0.45	0.58
	PI	0.94	0.32	0.23

D_{60} = diameter corresponding to 60% finer; LL = liquid limit; MDD = maximum dry density; OMC = optimum moisture content; PI = plasticity index; PL = plastic limit; S = degree of saturation.

Although the data were limited to only six points, multiple regression was attempted to develop a predictive model for M_r at stress condition of 2 psi confining and 6 psi deviator. A strong predictive model using D_{60} (particle diameter corresponding to 60% finer) and degree of saturation (S) was observed with a coefficient of determination, $R^2 = 0.96$ and standard error of 715. Table 13 presents the model statistics. Although the model and all the coefficients are significant at the 5% level, the number of data points are very limited.

Table 13. Statistics for Multiple Regression Model

Statistic	Resilient Modulus Model
Model Parameters: M_r = resilient modulus (psi) D_{60} = Particle size at 60% passing (mm) S = degree of saturation (%)	$M_r = 21197.6 + 7455.6 \times (D_{60}) - 251.6 \times S$
Coefficient of determination, R^2	0.98
Adjusted R^2	0.96
Number of observations	6
Intercept	Non-zero
Standard error	714.8
Significance of model and coefficients (at 5% level)	Yes

Inputs to Pavement Mechanistic-Empirical and Sensitivity Analysis

The impact of using different M_r values of a subgrade soil in MEPDG was assessed with some example scenarios. One subgrade soil, A-2-4 with a fixed set of pavement structure, was analyzed using AASHTOWare Pavement ME software version 2.2.6. Only two major distresses, 15-years rutting and 30-years fatigue cracking, were considered for relative comparison (Figure 9). The level of truck traffic and pavement structure is more sensitive than subgrade M_r values. When the M_r values for A-2-4 subgrade vary from 8,000 psi to 21,000 psi, both rutting and bottom-up asphalt concrete fatigue cracking showed minor variation . Rutting varied less than 0.025 inch, and fatigue cracking less than 1% of lane area.

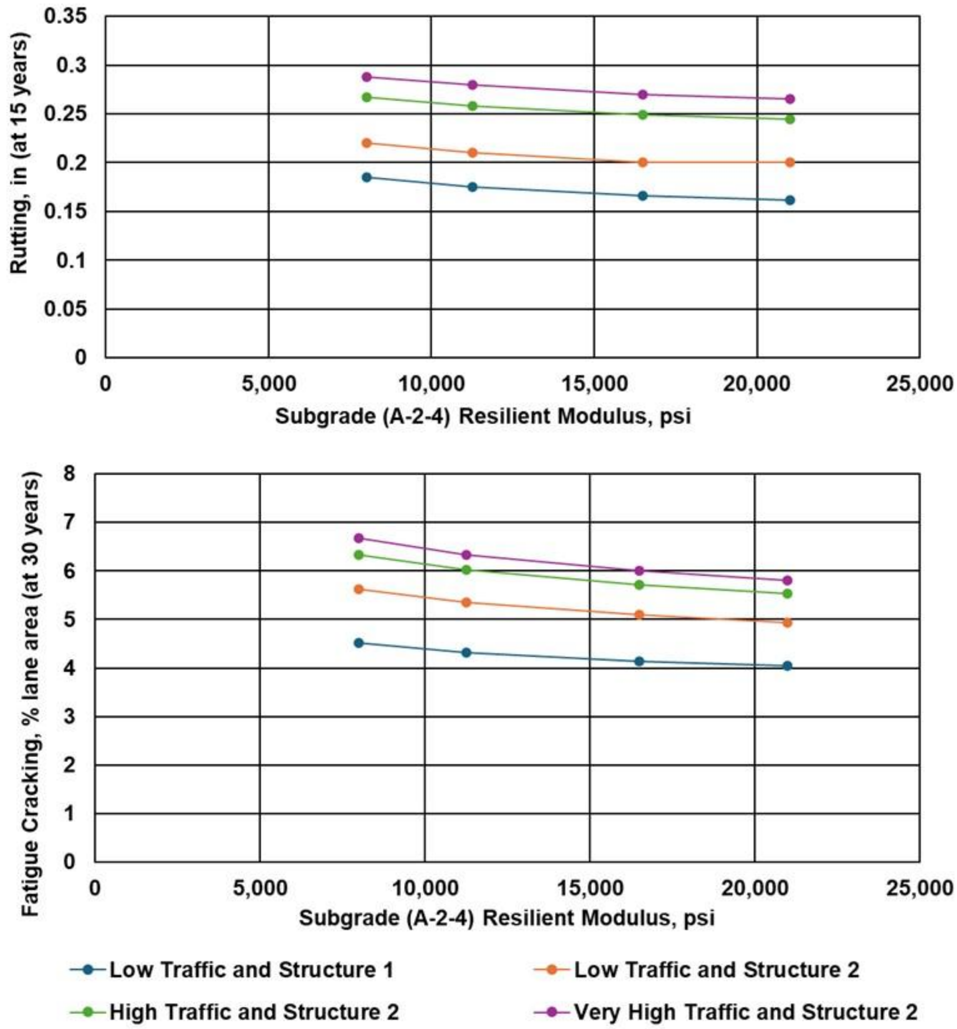

Figure 9. Sensitivity of Subgrade Resilient Modulus Values to Pavement Distress. Structure 2 is thinner than structure 1.

CONCLUSIONS

- *The M_r values were less than the MEPDG default for Virginia coarse-grained soils considered in this study when measured at specified stress and compaction conditions.* During this study, samples were compacted at standard Proctor values, whereas defaults were referred to modified Proctor values. The stress condition for the default values is not specified, but this study used confining pressure of 2 psi and deviator stress of 6 psi for the calculation of M_r.

- *M_r values obtained during this study were comparable with the measured values reported in the published literature, except for sands, which are classified as AASHTO A-3 soil.* Although A-3 soil could have particles bigger than a No. 4 sieve size, the sands considered in this study did not have any.

- *Compaction density and moisture content influenced measured M_r values for coarse-grained soil, as expected and supported in the literature. M_r values decreased with an increase in degree of saturation, which is a combined measure of moisture and density.*

- *M_r values measured at different stress conditions followed the universal constitutive model very closely (coefficient of determination, $R^2 > 0.9$), indicating stress dependency. The data plots in Figure 6 and in Appendix B also show stress dependency.*

- *When coarse-grained soils were tested at OMC and MDD, the M_r values calculated at a specific stress condition, 2 psi confining pressure and 6 psi deviator stress, showed fair to good correlation with both unsoaked CBR and LWD modulus with limited data.* Out of only six data points, one and two data points were omitted from the correlation analysis as outliers for CBR and LWD, respectively.

- *Although data points were limited, many soil index properties, such as D_{60} (particle size at 60% passing), showed good correlation with M_r values for coarse-grained soil.*

- *More coarse-grained soils need to be tested to develop a catalog of values and a useful predictive model for VDOT use.*

- *Based on limited sensitivity analysis, MEPDG distress prediction was not very sensitive to the M_r input values for a range of 8,000 to 21,000 psi for the two pavement structures considered during this study. The amount of truck traffic and the thickness of pavement structure showed some sensitivity. Additional analysis is needed to confirm these observations.*

RECOMMENDATIONS

1. *VDOT's Materials Division and VTRC should continue to test coarse-grained soils to populate the catalog of values for all different types of soil and explore the following:*

    - correlation with CBR, LWD, and soils index properties to predict M_r values. The recommendations should be adjusted accordingly when more data points are available.
    - investigate the reason for low M_r values for sandy soil.

2. *VDOT's Materials Division and VTRC should investigate M_r values determined using Standard and Modified Proctor compaction, given that the MEPDG default values are based on Modified Proctor.* Currently VDOT uses VTM-1 (equivalent to AASHTO T99 Method A) that precludes particles larger than passing a No. 4 sieve from testing. Other options in AASHTO T99 such as Methods C and D, which allow larger particles, should also be explored.

3. *VDOT's Materials Division and VTRC should conduct sensitivity analysis for subgrade modulus values specific to Virginia coarse-grained soils, as obtained from Recommendation*

1, with respect to default values for possible implication in pavement design. The use of a stress condition to determine a design M_r value should also be explored.

IMPLEMENTATION AND BENEFITS

The researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

With regard to Recommendations 1 and 2, VDOT's Materials Division and VTRC will continue to test coarse-grained soils as samples become available in the next 5-year period. This testing will help to explore correlations with soil index properties, CBR, and LWD as more data points become available. This testing will be initiated through a technical assistance study, through which VTRC will also evaluate the effect of using different Proctor methods and options in M_r tests.

With regard to Recommendation 3, VDOT's Materials Division and VTRC will conduct sensitivity analysis for input subgrade M_r values to pavement design when VDOT implements the web-based version of the AASHTOWare-ME software. This sensitivity analysis will be conducted within 2 years of implementing web-based software.

Benefits

This study provided a few measured M_r values for coarse-grained soils and are not enough to use those in mechanistic pavement design at this time. Although enough soil samples were not available during this project for testing, many valuable observations were made to move forward with some definitive directions to develop a catalog of values and a predictive model for VDOT to use as more coarse-grained soils become available.

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APPENDIX A: STATE DEPARTMENTS OF TRANSPORTATION SURVEY

Subgrade Modulus Input for pavement Design (MEPDG) - VDOT Survey

1. Does your agency use tested resilient modulus values for subgrade in pavement design?
   - ◯ Yes
   - ◯ No
2. Method of Test
   - ◯ AASHTO T307
   - ◯ NCHRP 1-28A
   - ◯ Other
3. Sample preparation for Resilient Modulus Test: Density and Moisture
   - ◯ Modified Proctor
   - ◯ Standard Proctor
   - ◯ Other
4. When a single value of resilient modulus is needed, what stress condition is used?
   - ◯ Confining pressure 2 psi and deviator stress 6 psi
   - ◯ Other

Figure A1. State Departments of Transportation Survey Questionnaire

Table A2. State DOT Survey Results

State DOT	Question 1		Question 2			Question 3			Question 4	
	Yes	No	AASHTO T307	NCHRP 1-28A	Other	Standard Proctor	Modified Proctor	Other	Confining 2 psi Deviator 6 psi	Other
Vermont		×								
Delaware		×								
North Carolina		×			×					
South Dakota		×			×			×		×
Wyoming		×			×					
Florida	×		×			×			×	
Minnesota		×								
New York		×								
Michigan	×				×	×		×	×	×
Maryland	×		×				×			
Connecticut		×			×					
California	×		×				×			
Missouri		×			×					
South Carolina		×								
Louisiana		×			×					
Ohio		×								
North Dakota	×				×			×		
Georgia		×			×	×				
Alabama	×		×				×			
Maine		×								
Indiana	×		×			×				
Mississippi		×		×		×				
Iowa		×								
Total	***7***	***16***	***5***	***1***	***9***	***5***	***3***	***3***	***2***	***2***

AASHTO = American Association of State Highway and Transportation Officials; DOT = departments of transportation; NCHRP = National Cooperative Highway Research Program.

Table A3. State DOT Survey Respondents and Contact Information

State DOT	Name	Email Address
Vermont	Ian Anderson	Ian.Anderson@vermont.com
Delaware	Robin Davis	RobinM.Davis@delaware.gov
North Carolina	Shihai Zhang	szhang2@ncdot.gov
South Dakota	Travor Diegel	travor.diegel@state.sd.us
Wyoming	Wes Bybee	wesley.bybee@wyo.gov
Florida	Sasidhar Ayithi	sasidhar.ayithi@dot.state.fl.us
Minnesota	Tim Andersen	Timothy.lee.andersen@state.mn.us
New York	Christian Olmoz	Christian.olmoz@dot.ny.gov
Michigan	Justin Schenkel	schenkelj@michigan.gov
Maryland	Paulo DeSousa	pdesousa@mdot.maryland.gov
Connecticut	Steve Norton	steve.norton@ct.gov
California	Raghubar Shrestha	raghubar.shrestha@dot.ca.gov
Missouri	Jason Blomberg	jason.blomberg@modot.mo.gov
South Carolina	Eric carroll	carrolle@scdot.org
Louisiana	Mark Ordogne	mark.ordogne@la.gov
Ohio	Patrick Bierl	patrick.bierl@dot.ohio.gov
North Dakota	Aaron Perez	asperez@nd.gov
Georgia	Ian Rish	irish@dot.ga.gov
Alabama	John Jennings	jenningsj@dot.state.al.us
Maine	Karen Gross	karen.gross@maine.gov
Indiana	Nayyar Siddiki	nsiddiki@indot.in.gov
Mississippi	William (Bill) Barstis	wbarstis@mdot.ms.gov
Iowa	Chris Brakke	chris.brakke@iowadot.us

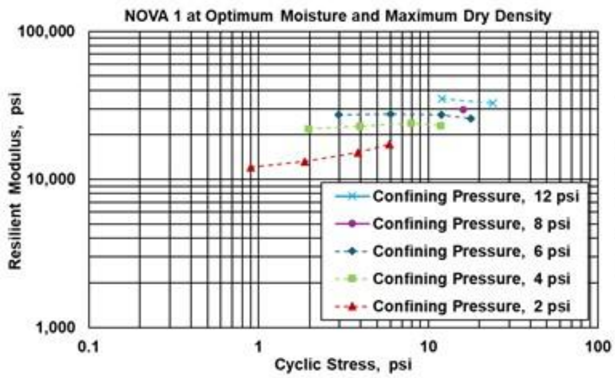
DOT = departments of transportation.

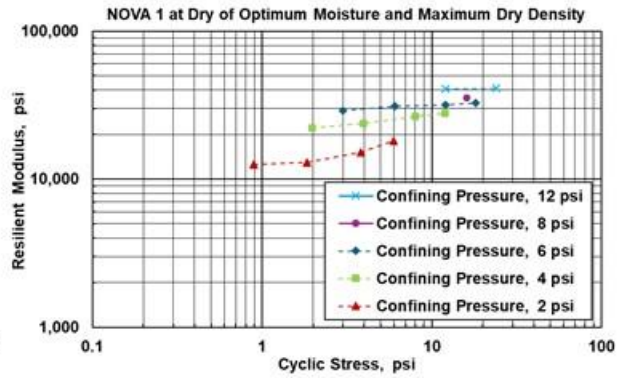
Table A4. State DOT Survey Comments

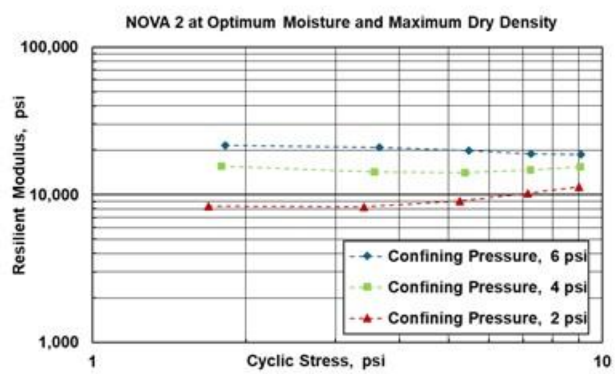
State DOT	Comments
Vermont	None
Delaware	None
North Carolina	Use Lab CBR correlation
South Dakota	We use resilient modulus values from the USDA website to input into AASHTO 1993. We use assumed values from the USDA website. We use the lowest relative resilient modulus to input into AASHTO 1993.
Wyoming	WYDOT performed a research study with our local university to develop equations to convert R-Values to M_r.... The research study tested a wide variety of samples across Wyoming to develop this relationship.
Florida	FDOT uses ME Design only for rigid pavement designs. We still use AASHTO 93 for designing flexible pavements. For our rigid designs, using ME Design (specifically PMED), we use a standard input value for stabilization (12" Type B Stabilization, LBR 40) of M_r of 16,000 psi for an A-2-4 soil. Our standard input value for embankment subgrade is a M_r of 12,000 psi for an A-2-4 soil. These standard values are based on past research projects completed by FDOT for local calibration of PMED.
Minnesota	None
New York	None
Michigan	This type of subgrade testing is not conducted in-house or for all projects. However, when we do, we use both—AASHTO T307 is the test procedure and NCHRP 1-28A recommendations of that procedure's results for data value used in PMED.
Maryland	We base the test density from a modified proctor but use a Tinius Olsen press to mold the sample at optimum moisture
Connecticut	None
California	not practiced yet
Missouri	DCP data that correlates to modulus
South Carolina	None
Louisiana	DCP
Ohio	None
North Dakota	We just started doing resilient modulus on subgrade. The testing firms we have hired out use AASHTO T307. For most of our in house testing, we are doing R value testing with T 190-22 and then correlating to an M_r value.
Georgia	None
Alabama	Average of the 5 results based on AASHTO Soil Classification; Do not use them yet.
Maine	None
Indiana	None
Mississippi	Developed a catalog of values but do not use them yet (James et al., 2010)
Iowa	None

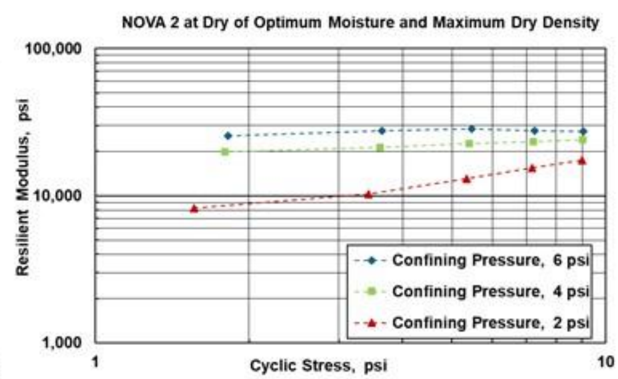
AASHTO = American Association of State Highway and Transportation Officials; CBR = California Bearing Ratio; DOT = departments of transportation; ME = mechanistic-empirical; M_r = resilient modulus; NCHRP = National Cooperative Highway Research Program.

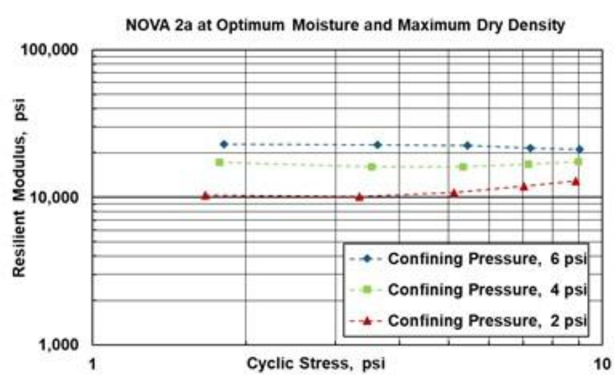
APPENDIX B: RESILIENT MODULUS TEST RESULTS

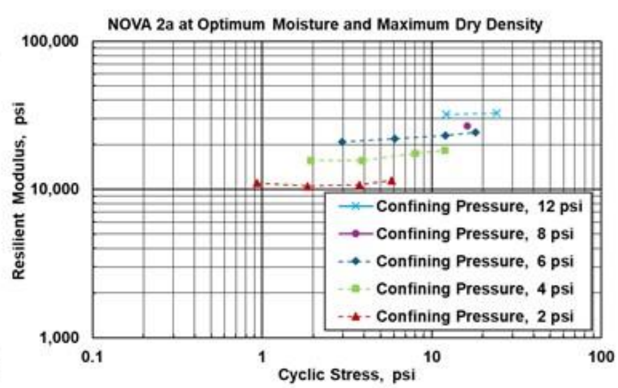


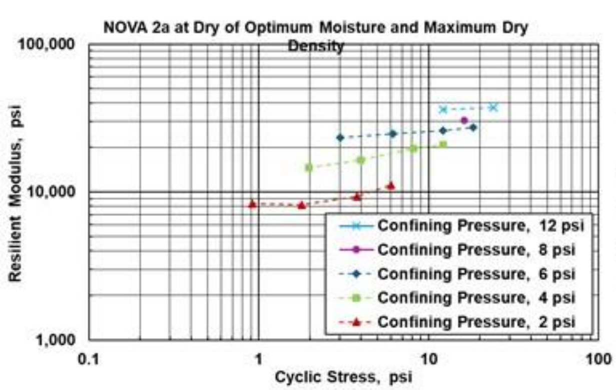


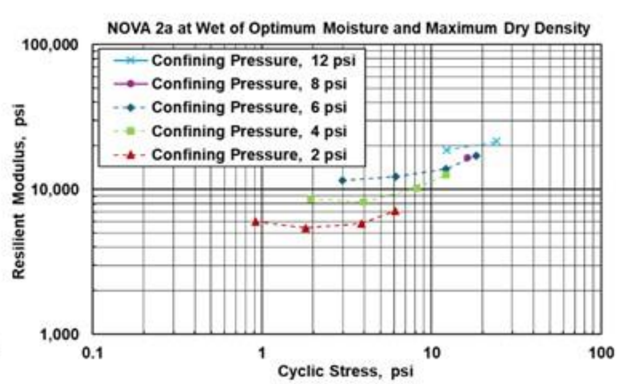


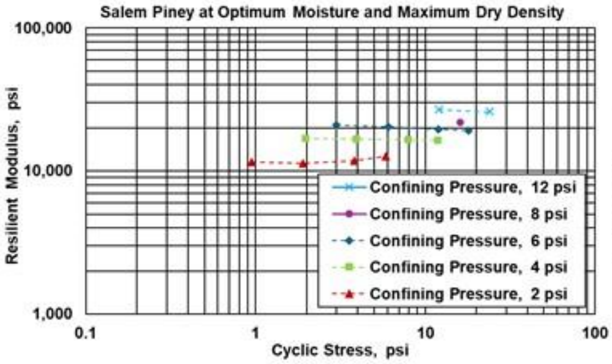


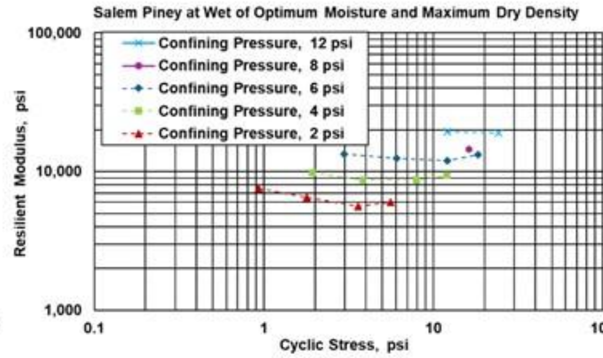


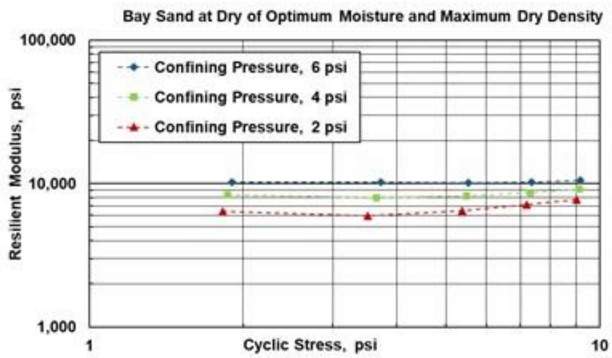


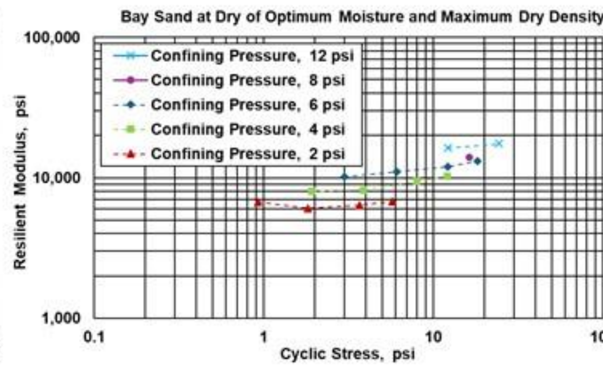


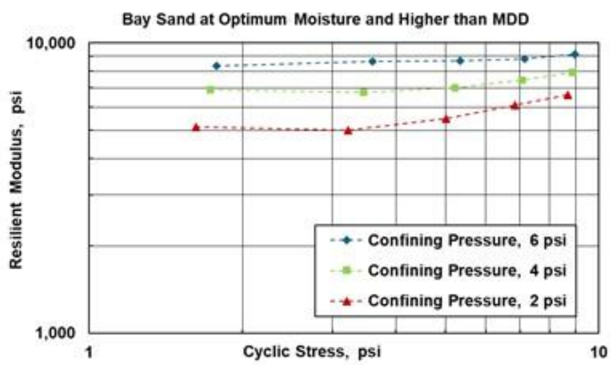


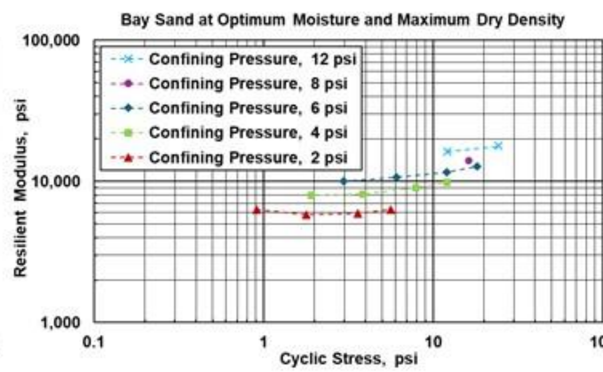

Salem Piney at Optimum Moisture and Maximum Dry Density
Resilient Modulus, psi
Cyclic Stress, psi
100,000
10,000
1,000
0.1
1
10
100
Confining Pressure, 12 psi
Confining Pressure, 8 psi
Confining Pressure, 6 psi
Confining Pressure, 4 psi
Confining Pressure, 2 psi

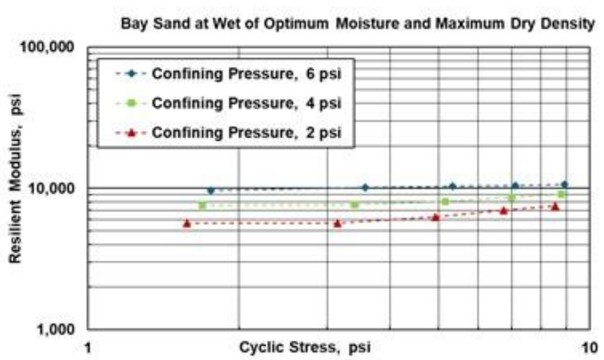

Salem Piney at Wet of Optimum Moisture and Maximum Dry Density
Resilient Modulus, psi
Cyclic Stress, psi
100,000
10,000
1,000
0.1
1
10
100
Confining Pressure, 12 psi
Confining Pressure, 8 psi
Confining Pressure, 6 psi
Confining Pressure, 4 psi
Confining Pressure, 2 psi

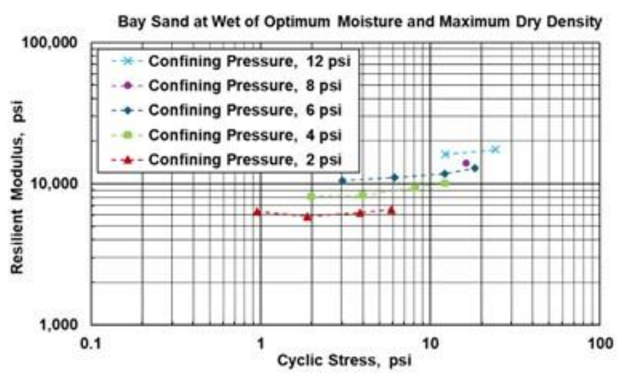

Bay Sand at Dry of Optimum Moisture and Maximum Dry Density
Resilient Modulus, psi
Cyclic Stress, psi
100,000
10,000
1,000
1
10
Confining Pressure, 6 psi
Confining Pressure, 4 psi
Confining Pressure, 2 psi

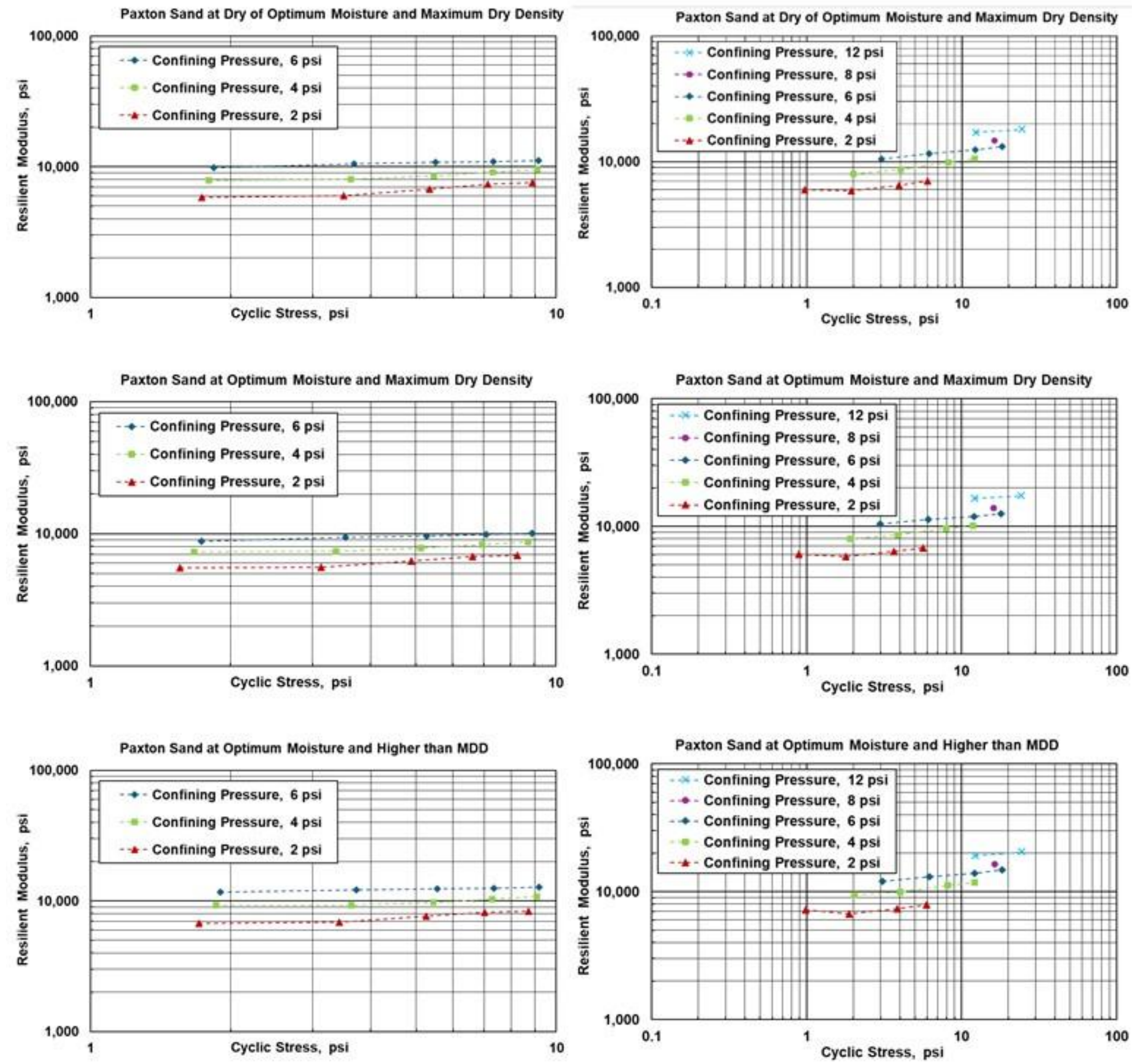

Bay Sand at Dry of Optimum Moisture and Maximum Dry Density
Resilient Modulus, psi
Cyclic Stress, psi
100,000
10,000
1,000
0.1
1
10
100
Confining Pressure, 12 psi
Confining Pressure, 8 psi
Confining Pressure, 6 psi
Confining Pressure, 4 psi
Confining Pressure, 2 psi


Bay Sand at Optimum Moisture and Higher than MDD
Resilient Modulus, psi
Cyclic Stress, psi
10,000
1,000
1
10
Confining Pressure, 6 psi
Confining Pressure, 4 psi
Confining Pressure, 2 psi


Bay Sand at Optimum Moisture and Maximum Dry Density
Resilient Modulus, psi
Cyclic Stress, psi
100,000
10,000
1,000
0.1
1
10
100
Confining Pressure, 12 psi
Confining Pressure, 8 psi
Confining Pressure, 6 psi
Confining Pressure, 4 psi
Confining Pressure, 2 psi


Bay Sand at Wet of Optimum Moisture and Maximum Dry Density
Resilient Modulus, psi
Cyclic Stress, psi
100,000
10,000
1,000
1
10
Confining Pressure, 6 psi
Confining Pressure, 4 psi
Confining Pressure, 2 psi


Bay Sand at Wet of Optimum Moisture and Maximum Dry Density
Resilient Modulus, psi
Cyclic Stress, psi
100,000
10,000
1,000
0.1
1
10
100
Confining Pressure, 12 psi
Confining Pressure, 8 psi
Confining Pressure, 6 psi
Confining Pressure, 4 psi
Confining Pressure, 2 psi



MDD = maximum dry density; NOVA = Northern Virginia.

APPENDIX C: LIGHTWEIGHT DEFLECTOMETER DEVICE SETUP