FHWA/IN/JTRP-2010/17

Final Report

EVALUATION OF IN-SITU STIFFNESS OF SUBGRADE BY RESILIENT AND FWD MODULUS

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May 2010

INDOT Research

TECHNICAL *Summary*

Technology Transfer and Project Implementation Information

May 2010
Publication No.: FHWA/INDOT/SPR-3008 *Final Report*

EVALUATION OF IN-SITU STIFFNESS OF SUBGRADE BY RESILIENT AND FWD MODULUS

INTRODUCTION

Resilient modulus (Mr) has been used for characterizing the non-linear stress-strain behavior of subgrade soils subjected to traffic loadings in the design of pavements.

Over the past ten years, the Indiana Department of Transportation (INDOT) has advanced the characterization of subgrade materials by incorporating the resilient modulus testing, which is considered the most ideal triaxial test for the assessment of behavior of subgrade soils subjected to repeated traffic loadings.

The National Cooperative Highway Research Program (NCHRP) has recently released the New Mechanistic-Empirical Design Guide (Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, NCHRP 1-37A, Final Report, July 2004) for pavement structures. The M-E Pavement Design Guide (MEPDG) requires that the resilient modulus of unbound materials be inputted in characterizing layers for their structural design. It recommends that the resilient modulus for design inputs be obtained from either by tests (resilient modulus test or FWD test) for Level 1 input (the highest input level) or by available correlations for Level 2 input or Level 3.

As indicated above, a laboratory resilient modus test and a FWD test are usually used to obtain the resilient modulus of subgrade. However, the difference in the resilient modulus obtained from these two methods is considerably large due to the fact that these tests are conducted under different conditions. This difference gives engineers a significant confusion about how they input appropriately the resilient modulus in the MEPDG software.

In the present study, FWD tests were conducted on several Indiana highways in different seasons, and laboratory resilient modulus tests were performed on the subgrade soils that were collected from the FWD test sites. A comparison was made of the resilient moduli obtained from the laboratory resilient modulus tests with those from the FWD tests. Several correlations between the laboratory resilient modulus and the FWD modulus have been developed based on the FWD and resilient modulus tests.

FINDINGS

The primary objective of this study was to develop the relationship between the modulus from the FWD test and the resilient modulus from the lab resilient modulus test by comparing the results obtained from the FWD test on subgrade and the laboratory repeated triaxial load test on subgrade soil samples molded at OMC in Indiana varying over different climatic conditions.

Based on the results of FWD tests and laboratory tests on some Indiana subgrades, the following conclusions can be drawn:

- On average, the FWD modulus is about 2 times higher than the lab resilient modulus of the soil compacted at OMC.
- Winter FWD modulus is about 40% higher than early summer FWD modulus.

IMPLEMENTATION

With the release of the new M-E Pavement Design Guide, highway agencies are required to implement the MEPDG, and the characterization of the stiffness of subgrade is an important part of it. Based on the FWD tests on several existing pavements and resilient modulus tests on the subgrade soils, the following can be implemented from this study:

(1) When characterizing a subgrade layer with the MEPDG software, a factor of 0.48 is recommended for the laboratory resilient modulus as compared to the FWD modulus.

(2) Winter FWD modulus is about 40% higher than early summer FWD modulus. These relationships can be used for seasonal variation of subgrade modulus in Indiana in the Mechanical-Empirical Pavement Design Guide Software (MEPDG).

(3) Based on the review of the resilient modulus test data given by the INDOT Office of Geotechnical Engineering, the resilient modulus of Indiana cohesive soils for Level 3 Design is in the range of 4,000 to 9,000 psi.

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/IN/JTRP-2010/17	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle EVALUATION OF IN-SITU STIFFNESS OF SUBGRADE BY RESILIENT AND FWD MODULUS		**5. Report Date** May 2010
		6. Performing Organization Code
7. Author(s) Daehyeon Kim, Yigong Ji, and Nayyar Zia Siddiki		**8. Performing Organization Report No.** FHWA/IN/JTRP-2010/17
9. Performing Organization Name and Address Joint Transportation Research Program 1284 Civil Engineering Building Purdue University West Lafayette, IN 47907-1284		**10. Work Unit No.**
		11. Contract or Grant No. SPR-3008
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

Resilient modulus has been used for characterizing the stress-strain behavior of subgrade soils subjected to traffic loadings in the design of pavements. With the recent release of the M-E Pavement Design Guide, highway agencies are further encouraged to implement the resilient modulus test to improve subgrade design. A laboratory resilient modus test and a FWD test are usually used to obtain the resilient modulus of subgrade. However, the difference in the resilient modulus obtained from these two methods is considerably large due to the fact that these tests are conducted under different conditions. This difference gives engineers a significant confusion about how they input appropriately the resilient modulus in the MEPDG software. In the present study, FWD tests, resilient modulus (Mr) tests and physical property tests were conducted to develop the relationship between the modulus from the FWD test and the resilient modulus from the lab resilient modulus test by comparing the results obtained from the FWD test on subgrade and the laboratory repeated triaxial load test on subgrade soil samples molded at OMC in Indiana varying over different climatic conditions. Based on the results of FWD tests and laboratory tests on some Indiana subgrades, the following conclusions can be drawn:

- On average, the FWD modulus is about 75% lower than the lab resilient modulus of the soil compacted at OMC.
- Winter FWD modulus is about 40% higher than early summer FWD modulus.

When inputting the resilient modulus of subgrade in the MEPDG software, this relationship can be implemented.

17. Key Words *Resilient modulus, Subgrade, FWD modulus, MEPDG, seasonal variation*		**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 42	**22. Price**

Form DOT F 1700.7 (8-69)

INDOT Research Project Implementation Plan

Date: May 21, 2010

Research Project Number: SPR-3008

Project Title: EVALUATION OF IN-SITU STIFFNESS OF SUBGRADE BY RESILIENT AND FWD MODULUS

Principal Investigator (PI): Daehyeon Kim *Project Administrator (PA):* Tommy E. Nantung

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Name of Implementor: Nayyar Zia Siddiki

Items (Research Results) to be implemented:

With release of the new M-E Pavement Design Guide, highway agencies are required to implement the MEPDG, and the characterization of the stiffness of subgrade is an important part of it. Based on the FWD tests on several existing pavements and resilient modulus tests on the subgrade soils, the following can be implemented from this study:

- When characterizing a subgrade layer with the MEPDG software, a factor of 0.48 is recommended for the laboratory resilient modulus as compared to the FWD modulus.
- Winter FWD modulus is about 40% higher than early summer FWD modulus. These relationships can be used for seasonal variation of subgrade modulus in Indiana in the Mechanical-Empirical Pavement Design Guide Software (MEPDG).
- Based on the review of the resilient modulus test data given by the INDOT Office of the Geotechnical Engineering, the resilient modulus of cohesive subgrade for Level 3 design is in the range of 4,000 to 9,000 psi.

The M-E Design Guide assumes that the subgrade is compacted to optimum moisture content, leading to unconservative design. In order to ensure a conservative design for subgrades, the use of the average resilient values is recommended.

Help or resources needed for implementation (e.g., help from PI, funding, equipment, etc.):
None, INDOT Geotechnical Office has the equipment already.

Name of Implementor:

Items (Research Results) to be implemented:

Help or resources needed for implementation (e.g., help from PI, funding, equipment, etc.):

Name of Implementor:

Items (Research Results) to be implemented:

Help or resources needed for implementation (e.g., help from PI, funding, equipment, etc.):

Signatures of SAC members: ____

____

Please send a copy of this form to the INDOT Research Division and FHWA with the final report.

Final Report

FHWA/IN/JTRP-2010/17

EVALUATION OF IN-SITU STIFFNESS OF SUBGRADE BY RESILIENT AND FWD MODULUS

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Joint Transportation Research Program

SPR- 3008

Conducted in Cooperation with the
Indiana Department of Transportation
and the U.S. Department of Transportation
Federal Highway Administration

School of Civil Engineering
Purdue University
May 2010

ACKNOWLEDGEMENTS

The authors deeply appreciate the opportunity to conduct this research under the auspices of the Joint Transportation Research Program (JTRP) with support from the Indiana Department of Transportation and the Federal Highway Administration. They wish to recognize the active input from the Study Advisory Committee members: Dave Andrewski, Arnie Apple, Greg Ellis, and Jeff James (INDOT); Vincent Drnevich (PURDUE); and Lee Gallivan (FHWA).

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ABSTRACT

Kim, Daehyeon., Ji, Yigong., and Siddiki, Nayyar Zia. “Evaluation of In-Situ Stiffness of Subgrade by Resilient and FWD modulus,” Final Report FHWA/IN/JTRP-2009/XX, SPR 3008, Joint Transportation Research Program, Purdue University, May 2010

Keywords: Resilient modulus, Subgrade, FWD modulus, MEPDG, seasonal variation

Resilient modulus has been used for characterizing the stress-strain behavior of subgrade soils subjected to traffic loadings in the design of pavements. With the recent release of the M-E Pavement Design Guide, highway agencies are further encouraged to implement the resilient modulus test to improve subgrade design. A laboratory resilient modus test and a FWD test are usually used to obtain the resilient modulus of subgrade. However, the difference in the resilient modulus obtained from these two methods is considerably large due to the fact that these tests are conducted under different conditions. This difference gives engineers a significant confusion about how they input appropriately the resilient modulus in the MEPDG software. In the present study, FWD tests, resilient modulus (Mr) tests and physical property tests were conducted to develop the relationship between the modulus from the FWD test and the resilient modulus from the lab resilient modulus test by comparing the results obtained from the FWD test on subgrade and the laboratory repeated triaxial load test on subgrade soil samples molded at OMC in Indiana varying over different climatic conditions. Based on the results of FWD tests and laboratory tests on some Indiana subgrades, the following conclusions can be drawn:

1) On average, the FWD modulus is about 75% lower than the lab resilient modulus of the soil compacted at OMC.
2) Winter FWD modulus is about 40% higher than early summer FWD modulus.

When inputting the resilient modulus of subgrade in the MEPDG software, this relationship can be implemented.

CHAPTER1.INTRODUCTION

1.1. Research Motivation

Resilient modulus (Mr) has been used for characterizing the non-linear stress-strain behavior of subgrade soils subjected to traffic loadings in the design of pavements. Over the past ten years, the Indiana Department of Transportation (INDOT) has advanced the characterization of subgrade materials by incorporating the resilient modulus testing, which is considered the most ideal triaxial test for the assessment of behavior of subgrade soils subjected to repeated traffic loadings.

The National Cooperative Highway Research Program (NCHRP) has recently released the New Mechanistic-Empirical Design Guide (Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, NCHRP 1-37A, Final Report, July 2004) for pavement structures. The M-E Pavement Design Guide (MEPDG) requires that the resilient modulus of unbound materials be inputted in characterizing layers for their structural design. It recommends that the resilient modulus for design inputs be obtained from the resilient modulus test for Level 1 input (the highest input level) or by available correlations (FWD tests versus Resilient modulus tests) for Level 2 input or Level 3.

As indicated above, a laboratory resilient modus test and a FWD test are usually used to obtain the resilient modulus of subgrade. However, the difference in the resilient modulus obtained from these two methods is considerably large due to the fact that these tests are conducted under different conditions. This difference gives engineers a significant confusion about how they input appropriately the resilient modulus in the MEPDG software. The motivation of the study is to clarify relationships between the FWD modulus and the lab resilient modulus.

1.2. Problem Statement

The Resilient Modulus (Mr) is used as a design input in the draft M-E Pavement Design Guide. Pavement engineers usually use the value of CBR and a conversion factor of 1500 to calculate the Mr from the CBR. It is widely accepted that the CBR test is variable and stress conditions are not representative to that of the field conditions. In addition, the “1500” factor is just an “average” factor of factors ranging between 800 to 3000, depending on material type and conditions.

Generally, Mr is obtained from a repeated triaxial test on a laboratory compacted sample. Needless to say, the most important thing in performing a resilient modulus test is that the sample should be representative of the in-situ conditions of subgrade materials. Although the sample is prepared and tested as closely as possible to the in-situ condition, it is true that the sample may not represent completely the in situ subgrade because of various different conditions such as boundary conditions and temperature, etc. The evaluation of the resilient behavior without sampling or laboratory testing would be more efficient if a reliable methodology could be developed. Non-Destructive deflection (NDT) testing or FWD deflection testing presents a quick, easy way to evaluate the in-situ subgrade conditions. Deflection testing is characterized as “an extremely valuable and rapidly developing technology. When properly applied, FWD testing can provide a vast amount of information and analysis at a very reasonable expenditure of time, money, and effort (AASHTO, 1993)”.

In order to better characterize in-situ conditions (in-situ moduli or strength) of the subgrade materials, a study based on resilient modulus test and FWD test is needed. Additionally, in the M-E Pavement Design Guide, the monthly resilient moduli are to be inputted. INDOT has not established how to apply the monthly resilient moduli in the design. Seasonal or monthly variation of resilient modulus needs to also be studied.

1.3. Scope and Objectives

As previously discussed, there exists considerable difference between the resilient modulus obtained from the FWD test and the resilient modulus test. The main objective of the study is to develop relationships between laboratory resilient modulus and in-situ resilient modulus obtained from the FWD test for typical Indiana subgrade soils for use in the MEPDG software. These relationships are based on the FWD tests performed in several different months throughout the year and the resilient modulus tests molded at OMC. This will result in some useful relationships between the laboratory Mr and monthly or seasonal in-situ Mr obtained from the FWD test for typical subgrade materials.

1.4. Report Outline

This report consists of five chapters, including this introduction.

Chapter 2 presents the literature review on the relationship between the resilient modulus and FWD modulus of subgrade soils and reviews the Mechanical Empirical Pavement Design Guide.

Chapter 3 describes the testing program of the project. This chapter covers the soils used, resilient modulus tests, FWD tests and physical property tests.

Chapter 4 discusses the results of FWD tests and resilient modulus tests on compacted subgrade soils. Some relationships between the FWD modulus and resilient modulus are discussed.

Chapter 5 summarizes the conclusions and recommendations drawn from this study and proposes implementation initiatives.

CHAPTER 2. LITERATURE REVIEW

2.1. FWD Modulus Versus Laboratory Resilient Modulus

In previous studies (Ping et al. 2002, Rahim and George. 2003, Daleiden et al. 1994, Lee et al. 1988), FWD tests and laboratory tests were performed on subgrade soils (fine-grained and coarse-grained) in several different locations around the country. The difference between the FWD back-calculated modulus and the laboratory resilient modulus was not close to the value designated by AASHTO (ASSHTO design guide 1986, 1993 recommends the resilient modulus (Mr) from the FWD test to be 2-3 times higher than the Mr from laboratory resilient modulus test). There are several possible reasons for these results.

- The samples collected for the laboratory triaxial load test are all disturbed samples. These samples do not represent the actual conditions of the subgrade in the field, and need to be recompacted before the test. (Ping et al. 2002, Rahim and George. 2003, Daleiden et al. 1995, Lee et al. 1988, Hossain et al. 2000).
- The samples were tested immediately test after they were compacted. (Ping et al. 2002).
- The confining pressure on the sample is applied through compressed air, which is a weak imitation of the self induced passive earth pressure in the field (Ping et al. 2002, Rahim and George. 2003).
- Different volumes of samples are tested in the laboratory and in the field (Rahim and George. 2003).

- The FWD back-calculation program is not a unique method and is based on the linear elastic theory of multiple layer pavement structures while the pavement is not elastic (Ping et al. 2002)
- Greater variations are seen in test site with extensive cracking (Lee et al. 1988).

The variations in resilient modulus can also be caused by different types of soils (fine-grained or coarse-grained) and climatic conditions. In terms of the time of the year, resilient modulus of subgrade is typically 12 to 4 times higher in the coldest months (December, January and February) as compared to the rest of the year (Jong et al. 1998). This is mainly because of the stiffness increase caused by the freezing of the moisture in the subgrade (Jong et al. 1998). Resilient modulus also becomes substantially lower in the thawing period (March, April) because the melted ice fully saturates the soil and the soil reaches its weakest state (Watson 2000). Varying precipitation and water table can affect the subgrade moisture content, thus affecting the resilient moduli. Effect of precipitation on moisture content of subgrade is not as significant as the freezing; therefore not much change is observed in resilient modulus values (Hossain et al. 2000).

Soils at OMC have the highest resilient modulus values and decreases at lower or higher moisture content than OMC (Hossain et al. 2000). This is mainly because of the higher density of the soil at OMC (Hossain et al. 2000). Fine-grain soils and coarse-grained soils have higher FWD moduli results at higher confining stresses (Rahim and George. 2003). This effect is more evident in coarse-grained non-cohesive soils. This is also due to the different change in density of fine-grained soils and coarse-grained soils with varying confining stresses (Rahim and George. 2003).

Temperature of the asphalt concrete layer affects the stiffness of the layer, which in turn affects the deflection data of the FWD test because the asphalt layer acts a buffer between the subgrade and the FWD load (Hossain et al. 2000). Significant changes in FWD resilient moduli are also observed in subgrades with pavements and without pavements. Subgrades with pavements have higher moduli mainly because of the increase in the confinement pressure caused by the additional layer. This effect is seen more in coarse-grained soils than in fine-grained soils (Rahim and George. 2003).

2.2. Subgrade Characterization in MEPDG

2.2.1. Hierarchical Design Inputs – Level 1, Level 2, Level 3

The M-E Pavement Design Guide employs hierarchical design approach to the pavement design and analysis input parameters. It consists of Level 1, Level 2 and Level 3 inputs, in the order of importance and accuracy. The highest level of design accuracy, Level 1, requires an agency a capability of performing rigorous laboratory tests as indicated in the manual. Different level inputs can be chosen for each input parameter for a given design.

Level 1 inputs result in the highest level of design accuracy, leading to the lowest level of uncertainty error. For Level 1 inputs, laboratory testing or field testing, such as the resilient modulus testing of subgrade or non-destructive testing (NDT) such as the Falling Weight Deflectometer (FWD) is necessary. Consequently, Level 1 inputs demand much more time and resources than Level 2 and Level 3 inputs. Level 1 design is suitable to be implemented in major highways where heavy traffic is expected and roadway functional classification is very critical to the transportation system. Level 2 design provides an intermediate level of accuracy and can have similar results as in the existing AASHTO Guide. Level 2 design can be used in place of Level 1 design in the case of unavailability of testing equipment. Level 3 inputs offer the lowest level of accuracy.

2.2.2. Input Parameters for Unbound Materials and Sugrades

Three major categories for the material parameters required for unbound granular materials and subgrades in the M-E Design Guide are as follows (NCHRP 1994):

- Pavement response model material inputs: resilient modulus (Mr) and Poisson's ratio;
- ECIM material inputs: Plasticity Index (PI), Sieve Analysis (percent passing No. 200 sieve, percent passing No. 4 sieve, D 60 (mm)), degree of saturation;
- Other unbound material parameters: coefficient of lateral pressure (k_o).

2.2.2.1. Resilient Modulus-Level 1 design: Laboratory testing

Level 1 design is based on laboratory resilient modulus testing. The NCHRP report on the new M-E Design Guide (NCHRP 2004) recommends Mr to be obtained from the repeated triaxial testing or resilient modulus testing following NCHPR 1-28 A, “Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design” or AASHTO T307, “Determining the resilient modulus of soil and aggregate materials”.

Many researchers have proposed numerous predictive models to capture the resilient behavior of soils. The first model for granular materials is the K-θ model (Seed et al. 1967) as follows:

$$Mr = k_1\theta^{k_2} \tag{2. 1}$$

where $k_1$and $k_{2,}$ = regression coefficients; θ = sum of principal stresses. This model describes the resilient behavior of soils only as a function of confining stress, and the effect of deviator stress is not considered.

The another model for cohesive material is the K-σ_d model is given by:

$$Mr = k_1{\sigma_d}^{k_2} \tag{2.2}$$

where σ_d is deviator stress. The K-σ_d model is only associated with the deviator stress.

In order to account for both the confining and deviator stresses, Uzan (1985) suggested a universal model, which is a more advanced model than both the K-θ model and the K-σ_d model. The predicted Mr values can be obtained from the following equation:

$$Mr = k_1 p_a (\frac{\theta}{p_a})^{k_2} (\frac{\sigma_d}{p_a})^{k_3} \tag{2.3}$$

where, $k_{1,}$ $k_{2,}$ $k_{3,}$ = regression coefficients; θ = sum of principal stresses; p_a = reference pressure = 100 kpa ≈ 1 kgf/cm^2 ≈ 2000 psf ≈ 14.5 psi; and σ_d = deviator stress in the same unit as p_a.

In the M-E design Guide (NCHRP 2004), resilient modulus is predicted using a similar model to the equation (2.3), as shown below in equation (2.4):

$$Mr = k_1 p_a (\frac{\theta}{p_a})^{k_2} (\frac{\tau_{oct}}{p_a} + 1)^{k_3} \tag{2.4}$$

where τ_{oct} is the octahedral shear stress. The regression coefficients of the predictive model can be calculated by performing a regression analysis for the laboratory Mr test data following AASHTO T 307.

2.2.2.2. Resilient Modulus-Level 2 design: Correlations with other material properties

Level 2 design can be selected when laboratory Mr testing is not available. The value of resilient modulus can be obtained using typical correlations between resilient modulus and physical soil properties (dry unit weight, Atterberg limits, specific gravity) or between resilient modulus and strength properties (i.e., CBR, unconfined compressive strength). The following correlations are suggested in the M-E Design Guide:

$$CBR = 28.09\ (D_{60}) \tag{2.5}$$

$$CBR = 75/(1+0.728\ (wPI) \tag{2.6}$$

$$CBR=292/DCP^{1.12} \tag{2.7}$$

$$Mr = 2555(CBR)^{0.64} \tag{2.8}$$

Where D_{60} = diameter at 60% passing from the grain size distribution (mm); wPI is weighted plasticity index; CBR = California Bearing Ratio (%); Mr = resilient modulus (psi); DCP = DCP index (mm/blow). When estimating Mr, the material property is first related to CBR and then CBR is related to Mr.

For level 2 design, the M-E Design Guide software allows users the following two options.

- Input a representative value of Mr and use EICM to adjust it for the effect of seasonal climate (i.e., the effect of freezing, thawing, etc.);

- Input Mr for each month (season) of the year.

2.2.2.2. Resilient Modulus-Level 3 design: Typical Values

For design Level 3, only a typical representative Mr value at optimum moisture content is required. EICM is used to adjust the representative Mr for the seasonal effect of climate. Pavement designers may select the representative Mr value without the results being affected by EICM.

CHAPTER 3. FIELD AND LABORATORY TESTING PROGRAM

3.1. Testing Program

The testing program consisted of both field and laboratory tests. Four roads with existing asphalt pavements across Indiana were chosen for this study. Test sites were chosen to represent typical subgrade material throughout Indiana. A map of these sites is shown in Figure 1. Three sites of 100 meter sections were selected for US-27, SR-32, and SR-69, respectively, and Test Road in the INDOT Research office was included. Subgrades at these sites mostly consisted of A-4 and A-6 soils. Lime treated subgrades were found more commonly, except for Test Road and one section in SR-32 and SR-69. A more detailed description of the sites is shown in Table 1. Additional dates of the test road are 4th (12/27/05), 5th (1/25/06), 6th (2/22/06), 7th (4/19/06), 8th (5/4/06), 9th (6/19/06), 10th (7/27/06), 11th (8/9/06), 12th(9/11/06), 13th(10/12/06), 14th(11/11/06), 15th(12/10/06), 16th (1/4/07), 17th(3/13/07), 18th (4/4/07) and 19th(5/3/07).

As mentioned previously, the objective of this study is to construct relationships between the laboratory Mr and monthly or seasonal in-situ Mr obtained from the FWD test for typical subgrade materials.

For example ***Lab Mr (at Optimum Moisture Content) = FWD Mr × Factor.*** Where Factor is the function of moisture content, temperature and etc. ASSHTO design guide 1986, 1993 recommends Factor value to be 0.33 for all seasons and types of subgrades.

Disturbed soil samples were collected at two locations from each section. Laboratory tests were performed to evaluate soil index properties. These tests include:

- Specific gravity (G_s) and water content (w %) tests.
- Atterberg limit tests.
- Hydrometer tests for grain size distribution.
- Compaction tests

Results of these tests are shown in Table 2.

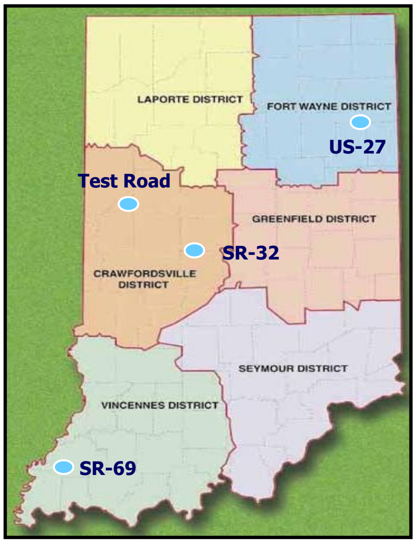

Figure 1. Existing Pavements

Table 1 Existing Pavements for FWD Tests

Existing Pavement										
Road Name	US27			SR-32			SR-69			Test Road
County / District	Adams Co./ Fort Wayne			Boone Co./ Crawfordsville			Posey Co./ Vincennes			Tippecanoe Co./ Fort Wayne
Contract No.	R-26449			R-26614			R-25808			
Pavement Type	HMA			Full depth HMA			Full depth HMA			HMA
FWD Tests Rp. No.	85 - 85.06 (100m)	85.36-85.42 (100m)	85.78 – 85.84 (100m)	58.60 -58.66 (100m)	59.14 -59.20 (100m)	59.68 – 59.20 (100m)	27-27.06 (100m)	28.01-28.07 (100m)	29.04-29.10 (100m)	
Pavement Thickness for each Layer	HMA(*) (15.7”) Subgrade Lime Treatment (16")	HMA(*) (15.7”) Subgrade Lime Treatment (16")	HMA(*) (15.7”) Subgrade Lime Treatment (16")	HMA 8" Base 9"	HMA(*) (15.8”) Subgrade Lime Treatment (16")	HMA(*) (15.8”) Subgrade Lime Treatment (16")	HMA(*) (16.25”) Subgrade Lime Treatment (16")	HMA(*) (16.25”) Subgrade Lime Treatment (16")	HMA(*) (16.25”) Compacted Subgrade (24")	HMA 8" Base: 9"
Pavement Construction	Oct, 05	Oct, 05	Oct, 05		Nov, 05	Nov, 05	Nov, 04	Nov, 04	Nov, 04	Oct, 02
FWD Tests	1st (5/24/06) 2nd(10/18/06) 3rd (5/24/07)	1st (5/24/06) 2nd(10/18/06) 3rd (5/24/07)	1st (5/24/06) 2nd(10/18/06) 3rd (5/24/07)	1st (5/31/06) 2nd(11/12/06) 3rd (4/16/07)	1st(5/31/06) 2nd(11/12/06) 3rd(4/16/07)	1st (5/31/06) 2nd(11/12/06) 3rd (4/16/07)	1st (8/14/06) 2nd(10/24/06) 3rd(5/24/07)	1st (8/14/06) 2nd(10/24/06) 3rd(5/24/07)	1st (8/14/06) 2nd(10/24/06) 3rd(5/24/07)	1st (9/7/04) 2nd (8/11/05) 3rd (11/23/05)
FWD Analysis	1st, 2nd , 3rd	1st, 2nd , 3rd	1st, 2nd , 3rd	1st, 2nd , 3rd	1st, 2nd , 3rd	1st, 2nd , 3rd	1st, 2nd , 3rd	1st, 2nd , 3rd	1st, 2nd , 3rd	1ST to 19th
Resilient Modulus Test	OMC, WET	OMC, WET	OMC, WET	OMC, WET	OMC, WET	OMC, WET	OMC, WET	OMC, WET	OMC, WET	OMC, WET

Table 2 Material Properties for Soils Used

Site	Sample	AASHTO	USCS	F200	Liquid Limit	Plastic Limit	Plasticity Index	Specific Gravity	Optimum Moisture Content	Maximum Dry Density (pcf)
U.S. 27	85.00	A-6	CL	77.1%	34.8%	20.8%	14.1%	2.55	14.8%	115.4
	85.06	A-6	CL	65.7%	27.2%	17.0%	10.2%	2.58	15.5%	117.3
	85.36	A-4	CL-ML	72.3%	22.6%	15.8%	6.9%	2.57	12.9%	118.6
	85.42	A-4	CL	64.0%	23.6%	15.9%	7.7%	2.71	13.0%	118.6
	85.78	A-4	CL-ML	72.9%	28.9%	22.1%	6.8%	2.55	16.8%	110.4
	85.84	A-4	ML	78.4%	36.4%	27.1%	9.3%	2.64	19.6%	107.0
SR 32	58.60	A-4	ML	55.2%	37.4%	26.8%	10.6%	2.96	17.5%	108.0
	58.66	A-4	ML	57.4%	27.5%	24.3%	3.2%	3.14	15.3%	109.8
	59.14	A-4	CL	57.5%	33.2%	24.1%	9.0%	2.75	15.0%	118.6
	59.20	A-6	CL	80.3%	40.3%	23.3%	17.0%	2.70	19.0%	108.6
	59.68	A-4	SC	47.5%	30.5%	21.2%	9.3%	2.75	13.2%	120.4
	59.74	A-4	ML	56.2%	29.1%	25.3%	3.8%	3.05	15.5%	122.3
SR 69	27.00	A-4	ML	90.9%	25.5%	24.8%	0.7%	2.81	17.3%	104.8
	27.06	A-4	CL	94.2%	30.7%	21.6%	9.1%	2.48	16.2%	111.7
	28.01	A-4	CL	52.3%	26.7%	19.4%	7.3%	2.67	14.9%	115.4
	28.07	A-4	ML	83.5%	25.1%	23.1%	1.9%	2.82	15.5%	111.7
	29.04	A-1-b	SM	24.2%	19.4%	18.5%	0.9%	2.73	7.5%	124.8
	29.10	A-4	ML	60.7%	19.4%	16.4%	3.0%	2.66	10.3%	123.6
Test Ro		A-4	CL	63.7%	30.6%	21.4%	9.1%	2.68	15.4%	109.6

3.2. FWD tests

Field Falling Weight Deflectometer tests were performed three times on each site using Dynatest 8000 FWD System. To examine seasonal variations, the same series of test were performed in April/May and October/November. FWD tests were done at about 20 m intervals.

3.3. Resilient Modulus Tests

Triaxial resilient modulus tests were performed on molded samples in OMC conditions. Molded samples were 2.8 inches in diameter and 6 inches in height. LoadTrac II testing unit was used for the resilient modulus test. The method adopted for this test was AASHTO T 307-99. Confining pressure of 6 psi, 4 psi and 2 psi were applied using air. The deviator stress varied from 2 psi to 10 psi for 100 repetitions and stress was applied using a hydraulic system. These loads were intended to represent the actual traffic load of 18 kip ESAL. One LVDT was attached outside the vacuum chamber to measure the deflection data. The slopes of the deviator stress and axial strain curve were maintained and used to calculate the resilient modulus.

CHAPTER 4. DISCUSSION OF THE TEST RESULTS

4.1. Test Results

The resilient modulus of subgrade is stress dependent. In order to compare the two moduli, it is very important to know the state of stress of soils in the FWD test (3). Stress calculations for the FWD back-calculated modulus were made assuming a multi-layered-elastic analysis. The program KENLAYER was used to calculate stresses in pavements under static loads. The vertical and horizontal stresses were obtained with 18 kips ESAL, imitating actual traffic conditions. The results of the resilient modulus test and the FWD test are shown in Table 3. MEPDG level 1 inputs for the resilient modulus test are listed in Table 4 through Table 6.

The results are plotted in Figure 2. AASHTO design guide 1986, 1993 suggests that the back-calculated moduli are approximately 2 to 3 times higher than the resilient modulus obtained from the triaxial resilient modulus test. The red line on the figure shows the relationship as recommended by AASHTO. The slope achieved from the tests is negative which is in disagreement with the positive slope of the red line. Even though the relationship does not follow AASHTO recommendations, the results obtained show that the average FWD back-calculated moduli are approximately 2 times higher than the laboratory resilient moduli.

$$\text{Lab Mr (at Optimum Moisture Content)} = \text{FWD Mr} \times \boldsymbol{\mathit{0.48}}$$

This result is close to the recommendations of ASSHTO, but the large scatter in these values suggests that there is no clear relationship between the two. There are several possible reasons for this result. Firstly, the FWD tests were performed on in-situ conditions whereas the resilient modulus tests were performed on soil samples at OMC conditions. Secondly, the FWD tests were performed in different times of the year, causing variations in moisture content on the soil which affects the FWD modulus. Thirdly, the confining pressure in the resilient modulus test were applied using air in a vacuum chamber which is a weak imitation of the confining pressure induced by the earth pressure on the subgrade (Ping et al. 2002, Rahim et al. 2003). Fourthly, the stress calculations for the FWD test were based on a multi-layer-elastic analysis while the pavements are not elastic (Ping et al. 2002). Fifthly, different volumes of samples were tested in both the test (Rahim et al. 2002).

Figure 3 and Figure 4 show the changes in Lab Mr and FWD Mr from the summer and winter months. Even though the FWD Mr values are higher in Figure 4, almost the same relationship can be observed in both the graphs. The increase in the FWD Mr during the winter season is mainly because of the freezing of the moisture in subgrade. Freezing of the moisture in the subgrade increases the stiffness and strength of the subgrade.

Figure 5, 6, 7 and 8 reinforce the same theory as above. As evidenced in these figures the FWD Mr at all test sites increases when early summer and winter months are compared. In terms of the time of the year, resilient modulus of subgrade is typically 12 to 4 times higher in the coldest months (December, January and February) as compared to the rest of the year (Jong et al. 1998). The results obtained from this study show that:

Average Dec. FWD Mr = 1.64 Average May FWD Mr (US-27)

Average Dec. FWD Mr = 1.16 Average May FWD Mr (SR-32)

Average Dec. FWD Mr = 1.57 Average May FWD Mr (SR-69)

Average Dec. FWD Mr = 1.38 Average May FWD Mr (Test Rd.)

Resilient modulus also becomes substantially lower in the thawing period of March and April. The melted ice fully saturates the soil and the soil reaches its weakest state (Watson et al. 2000). Resilient Modulus varies with variation in the moisture content. It is highest at OMC and decreases at higher or lower moisture contents. In April and May due to the melting of ice the moisture content of the subgrade increases and saturates the soil. This leads to a lower FWD Mr value. As the moisture begins to drain out in the months ahead, the subgrade moduli increases again and reaches its peak in the months of December and January. Varying precipitation can also affect the subgrade moisture content, thus affecting the resilient moduli but the effect of precipitation on moisture content of subgrade is not substantial (Hossain et al. 2000). This trend is properly shown in Figure 8, as you can see the gradual increase in the FWD Mr from April to December. Results show that on average the FWD Mr increases by approximately 40% from May to December.

Table 3 Results for laboratory resilient modulus test and FWD test

Site #	Test Date	Bulk (psi)	Vertical (psi)	Horizontal (psi)	MR (psi)	Avg. lab Mr (psi)	FWD back-calculated (psi)	LAB/FWD
Us27-sec1	10/18/200	13	5	4	8799	8799	4692	1.88
Us27-sec2	10/18/200	14	5	4	13074	13074	4370	2.99
Us27-sec3	10/18/200	13	5	4	6905	6905	13426	0.51
us27-sec1-85.06-OMC	5/24/2007	13	5	4	5632	8112	2601	3.12
us27-sec2-85.42-OMC	5/24/2007	14	5	5	11759	12949	3513	3.69
us27-sec3-85.42-OMC	5/24/2007	14	5	5	5360	6706	7152	0.31
SR32-sec1-58.66-OMC	11/1/2006	13	5	4	10648	8995	7483	0.40
SR32-sec2-59.20-OMC	11/1/2006	10	4	3	4445	4495	13983	0.32
SR32-sec3-59.74-OMC	11/2/2006	11	4	4	4647	4601	23501	0.20
SR32-sec1-58.66-OMC	4/16/2007	13	5	4	10590	8944	6004	1.49
SR32-sec2-59.20-OMC	4/16/2007	11	4	3	4440	4500	12409	0.36
SR32-sec3-59.74-OMC	4/16/2007	12	4	4	4648	4615	21389	0.22
SR69-sec1-27.06-OMC	10/24/200	13	5	4	4957	6164	16867	0.37
SR69-sec2-28.07-OMC	10/24/200	13	5	4	6380	7147	16637	0.43
SR69-sec3-29.10-OMC	10/24/200	12	4	4	6665	7723	17345	0.45
SR69-sec1-27.06-OMC	5/24/2007	17	6	5	4986	6261	12185	0.51
SR69-sec2-28.07-OMC	5/24/2007	16	6	5	6617	7207	12851	0.56
SR69-sec3-29.10-OMC	5/24/2007	13	5	4	6773	7898	8548	0.31
Test Rd-Apr-06		16	6	5	10994	10994	3339	3.29
Test Rd-Jul-06		19	7	6	10931	10931	3602	3.03
Test Rd-OCT-06		13	5	4	11055	11055	4270	2.59
Test Rd-Dec-06		12	4	4	11070	11070	4618	2.40
					AVG.	8143	10036	1.34

Table 4 MEPDG Level 1 Input from Laboratory resilient modulus test
(confine stress=7.5 psi, bulk stress=40 psi)

Location	**Moisture**	**K1**	**K2**	**K3**	**Resilient Modulus (psi)**
US 27 85.00	OMC	730.65	0.00181	0.00003	10778
	OMC + 2%	110.15	-0.197	-0.058	1366
US 27 85.06	OMC	265.83	-0.00341	-0.344	3549
	OMC + 2%	116.55	0.023	-0.588	1485
US 27 85.36	OMC	961.95	-0.09	-0.012	13152
	OMC + 2%	217.22	-0.497	-0.424	1919
US 27 85.42	OMC	739.23	-0.0473	-0.0888	10233
	OMC + 2%	971.36	0.101	0.0179	15576
US 27 85.78	OMC	490.53	-0.0227	-0.119	6866
	OMC + 2%	141.2	-0.139	-0.385	1674
US 27 85.84	OMC	268.74	0.331	-0.312	4717
	OMC + 2%	181.05	-0.12	-0.0219	2411

Table 5 MEPDG Level 1 Input from Laboratory resilient modulus test (confine stress=7.5 psi, bulk stress=40 psi)

Location	**Moisture**	**K1**	**K2**	**K3**	**Resilient Modulus (psi)**
SR 32 58.60	OMC	458.36	-0.0304	-0.0828	6441
	OMC + 2%	254.13	0.115	0.0719	4183
SR 32 58.66	OMC	597.71	0.0807	-0.188	8908
	OMC + 2%	295.64	0.0584	0.0794	4662
SR 32 59.14	OMC	298.37	0.188	-0.0834	4983
	OMC + 2%	300.68	0.188	0.165	5380
SR 32 59.20	OMC	184.78	0.412	-0.481	3300
	OMC + 2%	140.79	-0.429	-0.148	1417
SR 32 59.68	OMC	332.54	0.312	-0.0168	6241
	OMC + 2%	391.95	-0.0859	0.168	5652
SR 32 59.74	OMC	269.75	0.178	-0.172	4361
	OMC + 2%	278.83	-0.0537	0.241	4209

Table 6 MEPDG Level 1 Input from Laboratory resilient modulus test
(confine stress=7.5 psi, bulk stress=40 psi)

Location	**Moisture**	**K1**	**K2**	**K3**	**Resilient Modulus (psi)**
SR 69 27.00	OMC	466.01	0.173	-0.0942	7668
	OMC + 2%	316.93	0.109	-0.0223	5058
SR 69 27.06	OMC	286.28	0.189	-0.176	4664
	OMC + 2%	132.95	0.189	0.0343	2296
SR 69 28.01	OMC	528.59	-0.0436	-0.023	7474
	OMC + 2%	280.72	0.223	-0.27	4577
SR 69 28.07	OMC	327.86	0.452	-0.308	6340
	OMC + 2%	240.07	0.402	0.0843	4976
SR 69 29.04	OMC	632.37	0.287	-0.0126	11649
	OMC + 2%	-	-	-	
SR 69 29.10	OMC	375.01	0.379	-0.231	6993
	OMC + 2%	250.25	0.278	-0.139	4419

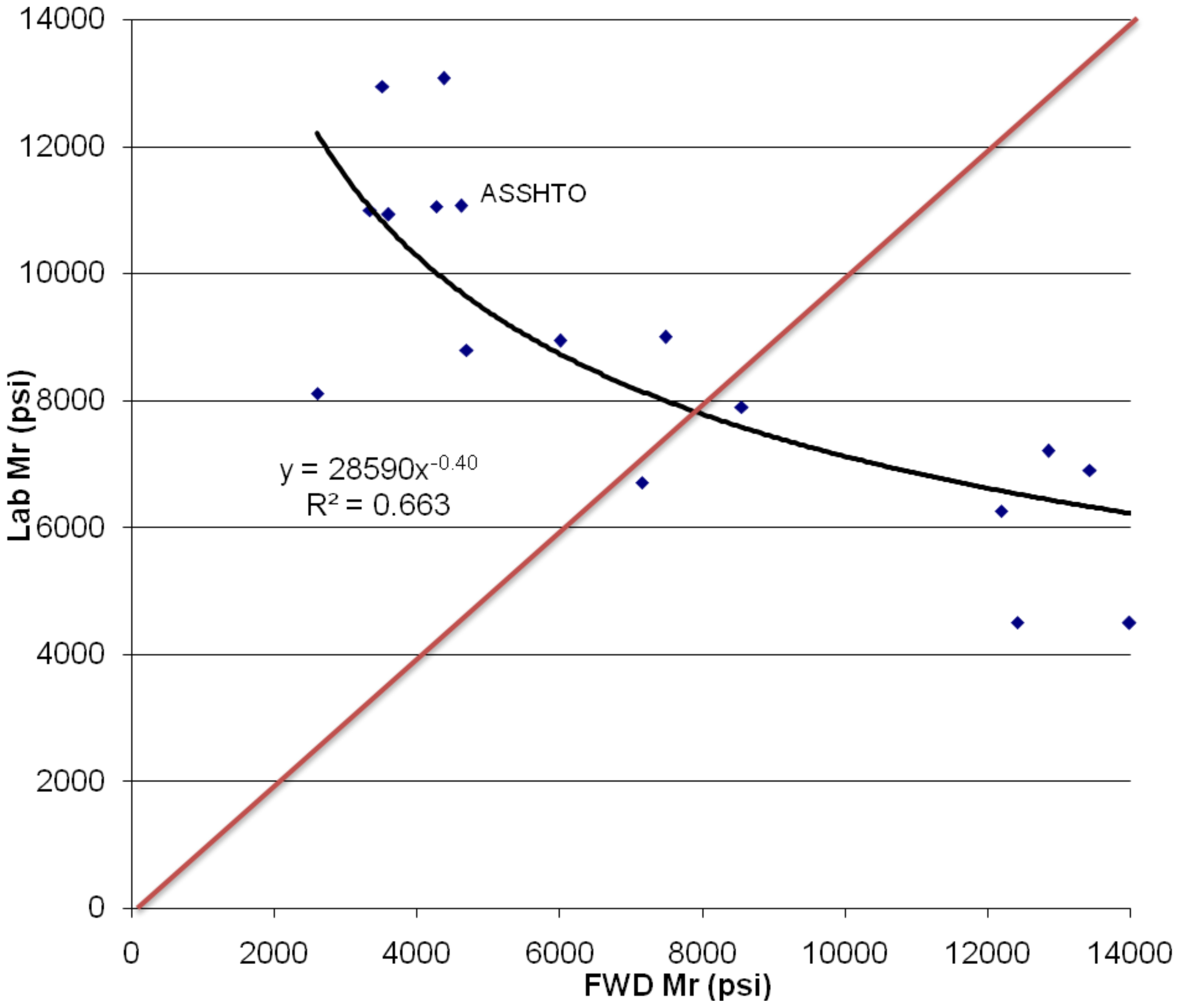

Figure 2. Lab Mr at OMC versus FWD back-calculated modulus

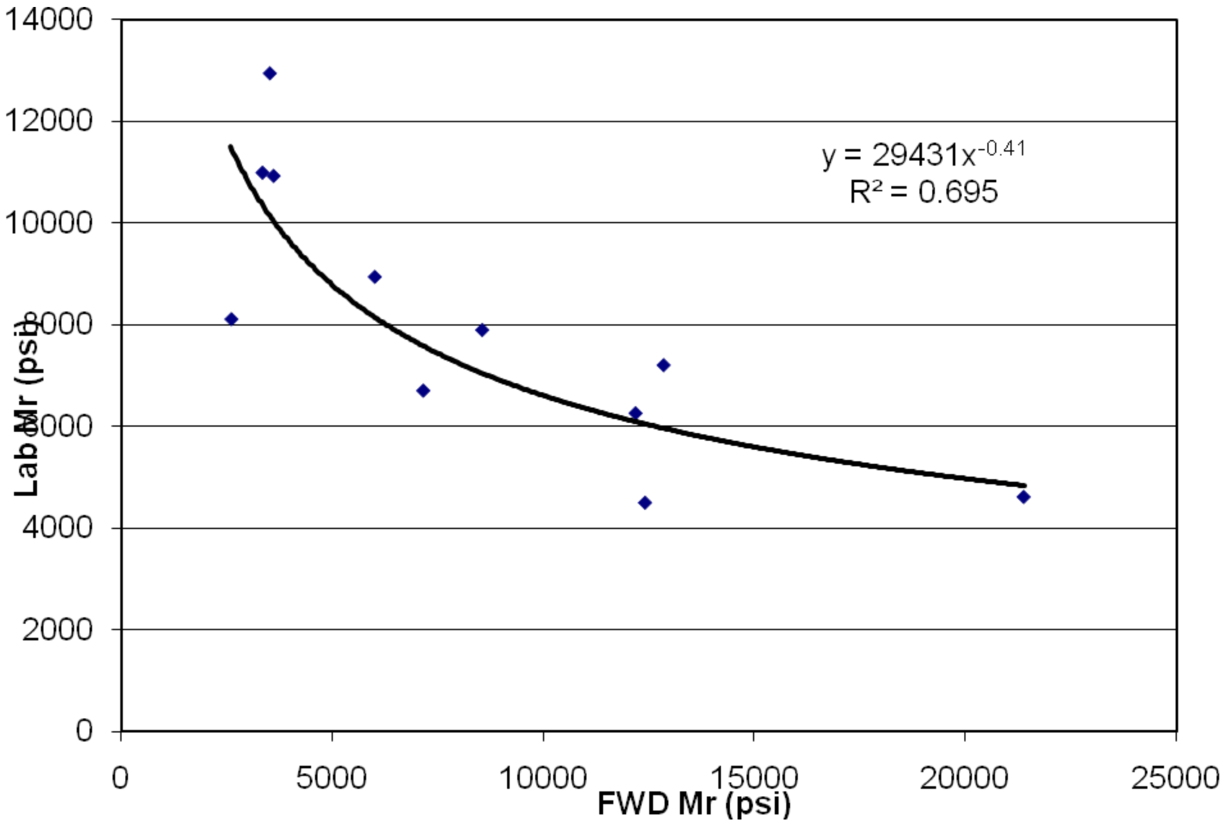

Figure 3. Lab Mr at OMC versus FWD modulus (early summer)

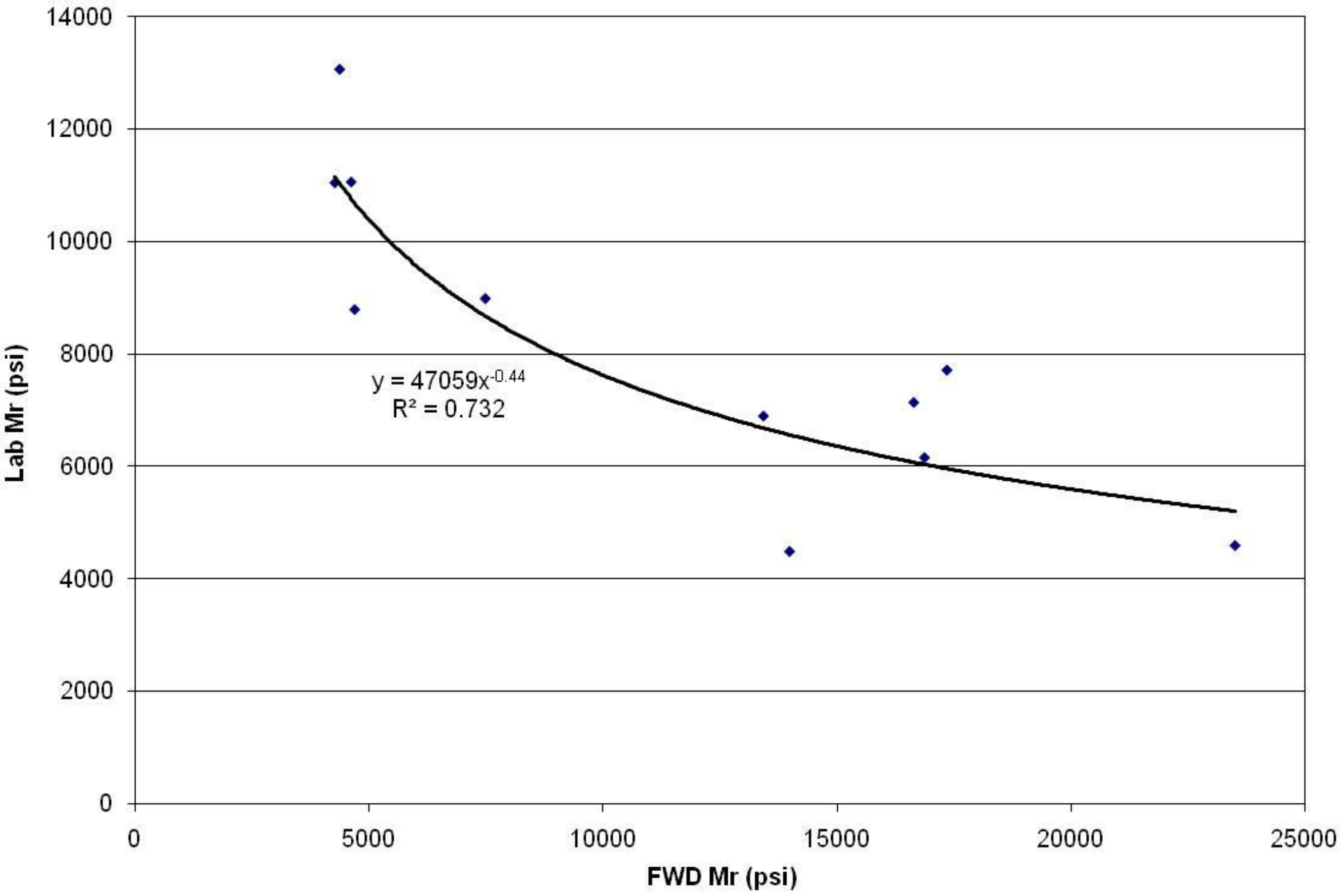

Figure 4. Lab Mr at OMC versus FWD modulus (winter)

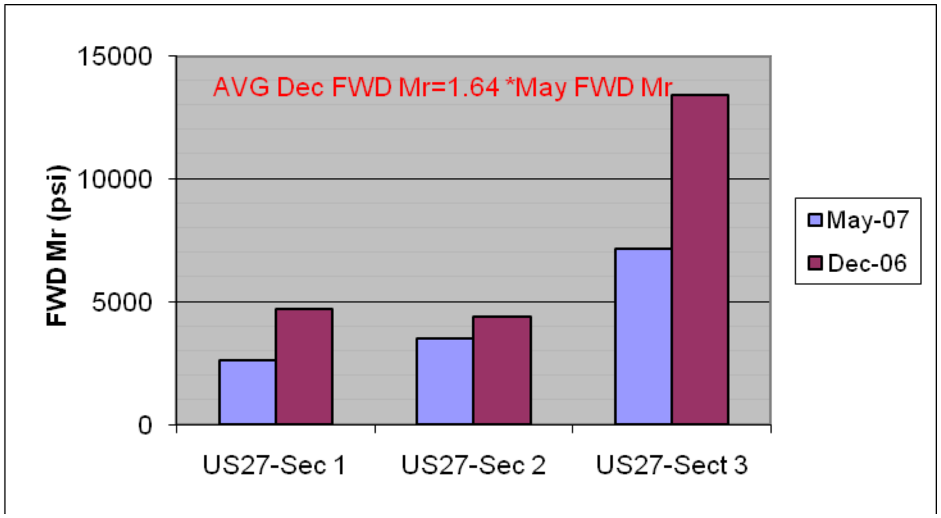

Figure 5. Monthly variation of FWD Mr in US-27

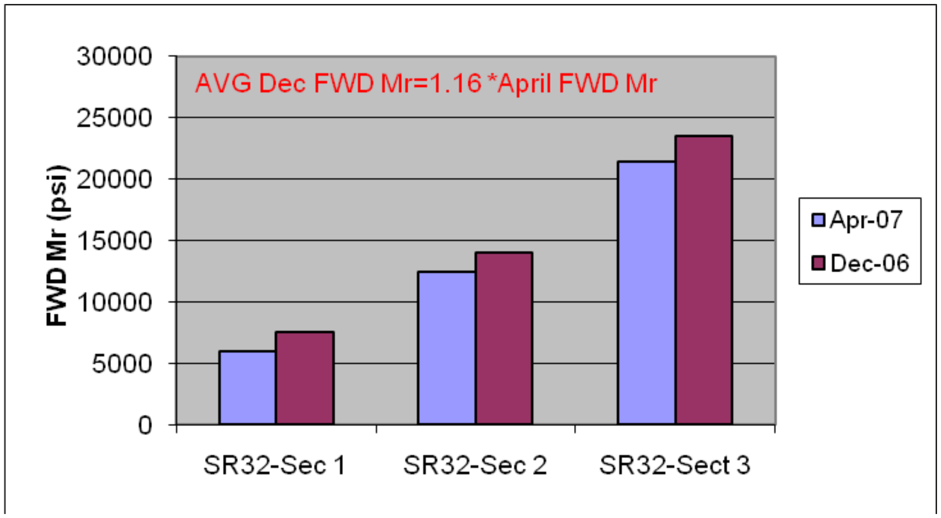

Figure 6. Monthly variation of FWD Mr in SR-32

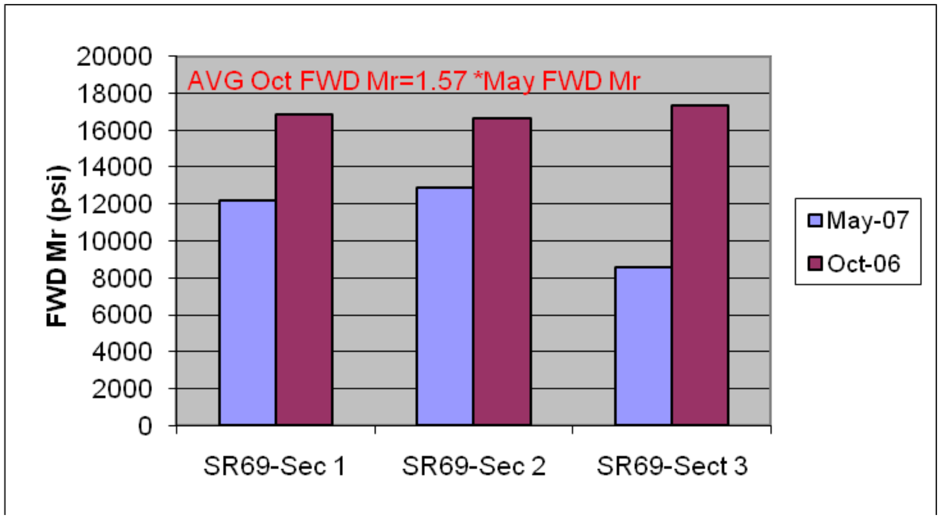

Figure 7. Monthly variation of FWD Mr in SR-69

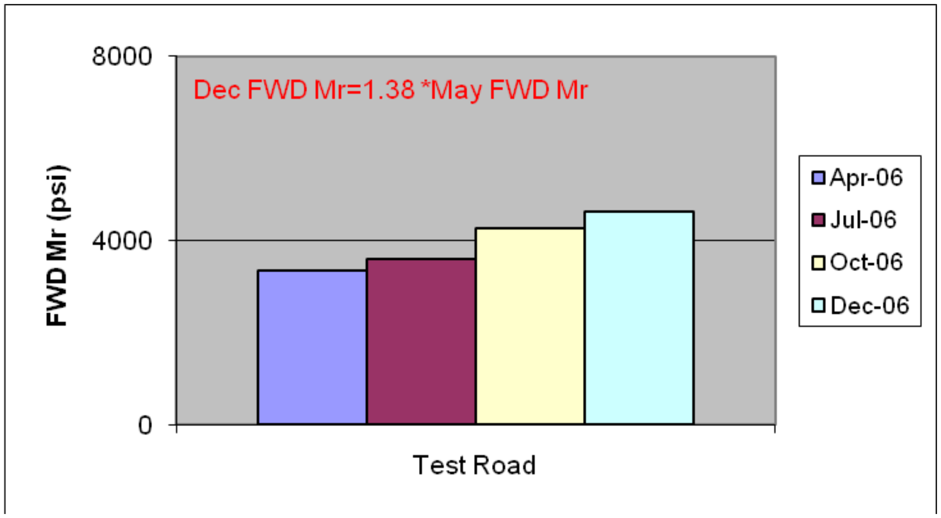

Figure 8. Monthly variation of FWD Mr in Test Road

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The main objective of the study was to develop relationships between laboratory resilient modulus and in-situ resilient modulus obtained from the FWD test for typical Indiana subgrade soils for use in the MEPDG software. These relationships are based on the FWD tests performed in several different months throughout the year and the resilient modulus tests molded at OMC. Even though average values for the factor are close to the recommendations of AASHTO, the large scatter of values show that there is little or no relationship between the two (Daleiden et al. 1994). More research needs to be conducted to determine the calibration between the laboratory resilient modulus and the FWD back calculated modulus. Based on the results of FWD and resilient modulus tests, the following conclusions can be drawn.

- On average, the FWD modulus is about 2 times higher the lab resilient modulus of the soil compacted at OMC.

$$\textbf{\textit{Lab Mr (at Optimum Moisture Content) = FWD Mr}} \times \textbf{\textit{0.48}}$$

- Winter FWD modulus is about 40% higher than early summer FWD modulus.

These relationships can be used for seasonal variation of subgrade modulus in Indiana in the Mechanical-Emprical Pavement Design Guide Software (MEPDG).

5.2. Implementation of Subgrade Design Inputs

5.2.1. Subgrade Design Input Level 3

In Level 3 design, a modulus value for unbound material is required. There are two options to determine the modulus: 1) ICM Calculated Modulus, and 2) User Input Modulus (i.e., Representative Modulus). The ICM Calculated Modulus allows seasonal variation in the moduli for different months while the User Input Modulus remains constant for the entire design period. Therefore, it is desirable to use the ICM input module. In addition, a general equation between the Mr and CBR values is provided. Typical CBR values for most of untreated fine-grained soils in Indiana are in the range of 3 to 5% corresponding to Mr values from about 4,000 to 9,000 psi (based on the range of the resilient modulus data given by the INDOT Office of Geotechncial Engineering) . This range of Mr appears to be reasonable in the design input Level 3.

5.2.2. Subgrade Design Input Level 2

In Level 2 design, the following properties: Mr, CBR, R-value, Dynamic Cone Penetration Test (DCPT), layer coefficient and Plasticity Index (PI) and gradation can be selected. As discussed earlier, there are two design input options: 1) EICM input and representative Mr input, and 2) seasonal input. Several analyses revealed that similar outputs are observed in both Level 3 and Level 2 when a resilient modulus is selected using the Integrated Climatic Model (ICM) module. For seasonal design input option, monthly resilient moduli are required.

Kim and Zia (2005) suggested an equation based on the results of unconfined compressive tests on Indiana subgrade soils. This type of equation can be used for Level 2 design.

$$Mr = 11267.7\times\ln(E_t)+3217.239\times\ln(q_u)-76.9/\varepsilon_y + -8725.31\times\ln(E_f)\ 2587.73\times\ln(q_y) +127.5/\varepsilon_y - 13513.9 \qquad (5.1)$$

Where E = tangent elastic modulus, q_u = unconfined compressive strength, E_f = Secant modulus at failure, ε_y = strain at yield stress, Mr = Resilient modulus at a confining stress of 2 psi and a deviator stress of 6 psi.

All the tested soils were prepared at dry of optimum (95% of the maximum dry density), optimum, and wet of optimum (95% of the maximum dry density). When State DOTs are not capable of performing a resilient modulus test, this type of equation based on the unconfined compressive test would be quite useful to predict the resilient modulus.

5.2.3. Subgrade Design Input Level 1

In Level 1 design, non-linear coefficients k_1, k_2, and k_3 are required. In order to generate a Mr predictive model, Kim and Zia (2005) developed the following non-linear regression coefficients based on the testing data for fourteen compacted cohesive subgrade soils.

$$\text{Log } k_1=6.660876 - 0.22136 \times \text{OMC} - 0.04437 \times \text{MC} - 0.92743 \times \text{MCR} - 0.06133 \times \text{DD} + 10.64862 \times \text{\%COMP} + 0.328465 \times \text{SATU} - 0.04434 \times \text{\%SAND} - 0.04349 \times \text{\%SILT} - 0.01832 \times \text{\%CLAY} + 0.027832 \times \text{LL} - 0.01665 \times \text{PI}$$

$$k_2=3.952635 - 0.33897 \times \text{OMC} + 0.076116 \times \text{MC} - 2.45921 \times \text{MCR} - 0.06462 \times \text{DD} + 6.012966 \times \text{\%COMP} + 1.559769 \times \text{SATU} + 0.020286 \times \text{\%SAND} + 0.002321 \times \text{\%SILT} + 0.011056 \times \text{\%CLAY} + 0.077436 \times \text{LL} - 0.05367 \times \text{PI}$$

k_3=2.634084 + 0.124471 x OMC - 0.09277 x MC + 0.366778 x MCR - 0.01168 x DD - 1.32637 x %COMP + 1.297904 x SATU - 0.01226 x %SAND - 0.00512 x %SILT - 0.00492 x %CLAY - 0.05083 x LL + 0.018864 x PI (5.2)

where; OMC (Optimum Moisture Content), MC (Moisture Content), MCR (Moisture Content Ratio = Moisture Content/ Optimum Moisture Content), DD (Dry Density), %COMP (Percent Compaction = Dry Density/ Maximum Dry Density), SATU (Degree of Saturation), %SAND (Percent Sand in Particle Size Distribution Curve), %SILT (Percent Silt in Particle Size Distribution Curve), %CLAY (Percent Clay in Particle Size Distribution Curve), LL (Liquid Limit) and PI (Plasticity Index).

The resilient modulus can be calculated by inserting the regression coefficient into the following equation (5.3) which is recommended by M-E Design Guide (NCHRP 2004):

$$Mr = k_1 p_a (\frac{\theta}{p_a})^{k_2} (\frac{\tau_{oct}}{p_a} + 1)^{k_3} \tag{5.3}$$

where, k_1, k_2, k_3 = regression coefficients; θ = sum of principal stresses; p_a = reference pressure = 100 kpa $\approx$ 1 kgf/cm^2 $\approx$ 2000 psf $\approx$ 14.5 psi; σ_d = deviator stress in the same unit as p_a, and τ_{oct} is the octahedral shear stress.

If a resilient modulus testing can be done, it is the best way to obtain the nonlinear regression coefficients through a laboratory Mr test data obtained from AASHTO T 307.

5.2.4. Design Example – Level 1, Level 2

Two design examples are presented in the following case studies. A pavement section consists of 4 inches of hot-mix asphalt surface and intermediate layers, 3 inches of hot-mix asphalt permeable base, 3 inches of hot-mix asphalt base layer on 24 inches of subgrade layer, and a semi-infinite layer, top to bottom. The pavement location is in Northwest Indiana and the climatic data available for South Bend station were selected.

In order to design the subgrade, the following physical and mechanical tests are needed: sieve analysis, Atterberg limit tests, compaction test, unconfined compressive tests on samples compacted at OMC and wet of optimum, resilient modulus tests on samples compacted at OMC and wet of optimum.

Table 7 Material properties for a design example

soil	% Gravel	% Sand	% Silt	% clay	LL	PI	AASHTO	USCS
#4soil	2.5	23.2	59.8	14.5	43	21	A-7-6	CL

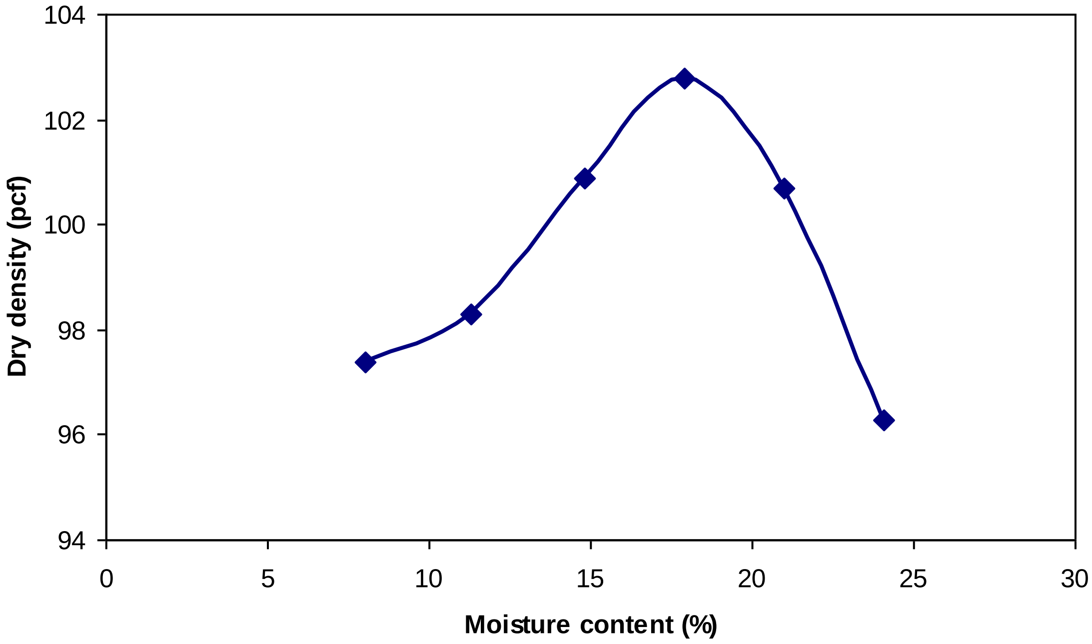

Figure 9. Compaction curve following AASHTO T 99

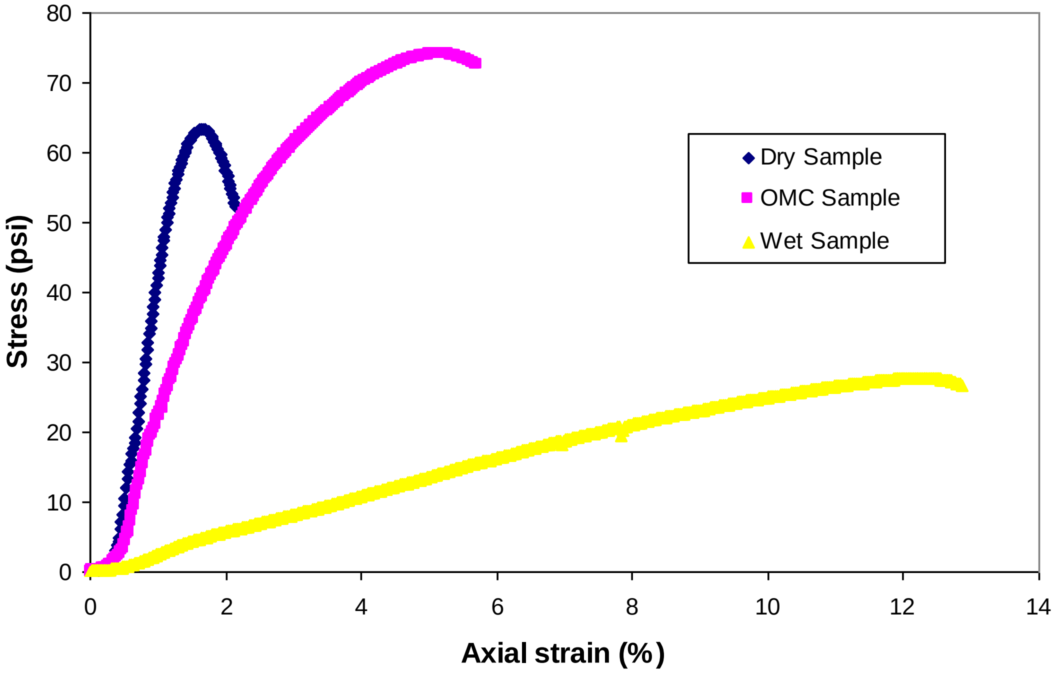

Figure 10. Unconfined compressive tests for Dry, OMC and Wet samples

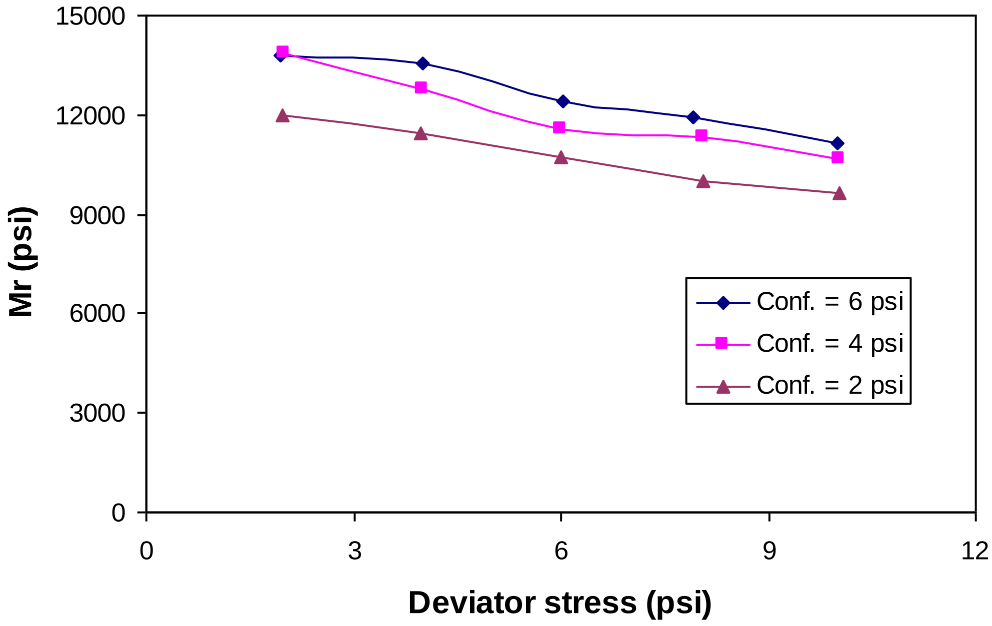

Figure 11. Resilient modulus test for OMC sample following AASHTO T-307

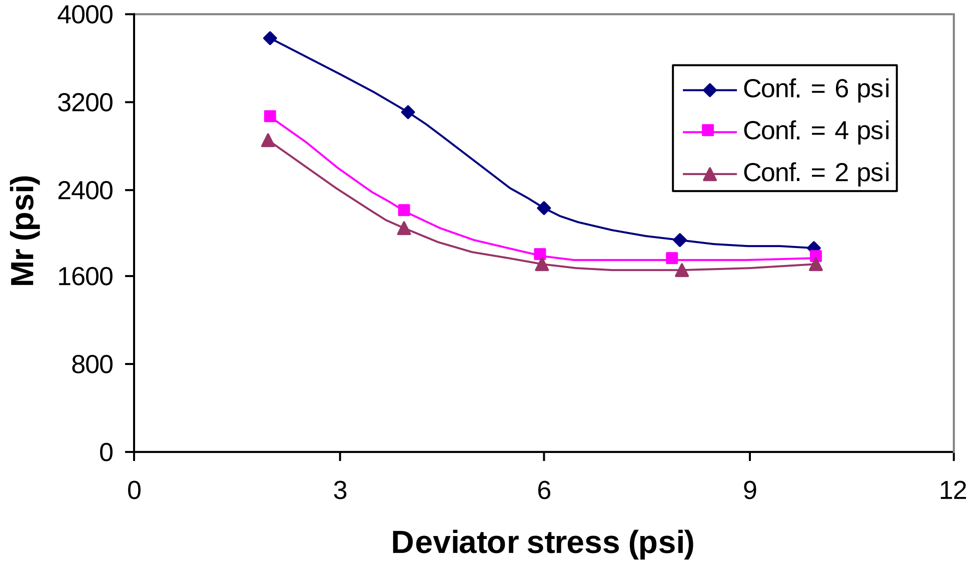

Figure 12. Resilient modulus test for wet sample following AASHTO T-307

Table 8 Parameters for use in equation (5.2)

Soil	**OMC sample**	**WET sample**
OMC	17.9	17.9
MC	17.493	22.234
MCR	0.977263	1.242123
MDD	102.8	102.8
DD	102.286	100.738
%comp	0.995	0.979942
SATU	0.797	0.971
%sand	23.2	23.2
%silt	59.8	59.8
%clay	14.5	14.5
LL	43	43
PI	21	21

The following procedure for Level 1 and Level 2 is recommended in the M-E Design Guide.

- Step 1: Assume initial compacted conditions are $\gamma_d = \gamma_{max}$, $w = w_{opt}$, use γ_{dmax} and w_{opt} for subbases and subgrades;
- Step 2: For each layer measure γ_{max} and w_{opt};
- Step 3: For each layer measure Mr_{opt} for a range of confining pressures and stress levels to obtain k_1, k_2, k_3;
- Step 4: Use output from the EICM to estimate the moisture change from the optimum condition to the equilibrium condition, $S_{equil} - S_{opt}$;
- Step 5: Use an equation suggested in NCHRP 1-37A to estimate Mr/Mr_{opt} for Mr for each layer, to account for moisture change;

- Step 6: Account for change in moduli due to freezing, thawing, and recovery using the recommendations by NCHRP report (2004).

As discussed previously, the M-E Design Guide may lead to unconservative design for subgrade, the following conservative design procedure is proposed:

- Step 1: To be conservative assume $\gamma_d = \gamma_{avg} = (\gamma_{dmax} + \gamma_{wet})/2$, $w = w_{avg} = (w_{opt}+w_{wet})/2$, use γ_{avg} and w_{avg} for subbases and subgrades. The maximum dry density and dry density corresponding to wet of optimum (95% of γ_{dmax}) and optimum moisture content and moisture content for wet of optimum can be obtained from compaction curve shown in Figure 9. These are γ_{dmax} = 102.8 pcf, γ_{wet} = 97.66 pcf, γ_{avg} = 100.23 pcf, w_{opt} = 17.9 %, w_{wet} = 24 % and w_{avg} = 20.95 %;
- Step 2: For each layer determine γ_{avg} and w_{avg}. Use the values obtained above;
- Step 3: For each layer measure $Mr_{avg} = (Mr_{opt}+Mr_{wet})/2$ for a range of confining pressures and stress levels to obtain k_1, k_2, k_3 or use equation (5.2) based on the soil properties. Mr_{opt} and Mr_{wet} are obtained from Figures 76 and 77. Mr_{avg} = 6, 207 psi, Mr_{opt} = 9, 855 psi, and Mr_{wet} = 2, 559 psi for a confining stress of 2 psi and a deviator stress of 6 psi are obtained using equation (5.2) based on the soil parameters shown in Table 5. When a resilient modulus test is not available, perform an unconfined compressive test as shown in Figure 10;
- Step 4: Use output from the EICM to estimate the moisture change from the optimum condition to the equilibrium condition, $S_{equil} - S_{avg}$, or use equation an equation suggested in NCHRP 1-37A to obtain S_{equil}, or use SWCC diagram shown in NCHRP report (2004). S_{equil} = 0.97, S_{avg} = 0.884, S_{wet} = 0.971, S_{opt} = 0.797 $S_{equil} - S_{avg}$ = 0.086 are obtained;

- Step 5: Use equation an equation suggested in NCHRP 1-37A to estimate Mr/Mr_{avg} for Mr for each layer, to account for moisture change. Figure 78 shows the variation in Mr/Mr_{avg} with respect to change degree of saturation;
- Step 6: Account for change in moduli due to freezing, thawing, and recovery using the recommendations following the M-E Design Guide. For the freezing moduli, use the values suggested by Lee et al. (1993) to be conservative. For thawing Mr, select the Mr for wet sample until the thawed Mr is accumulated.

Using the input parameters obtained with the proposed procedure, two analyses were performed: one with optimum values and the other with average values. A comparison of permanent deformations in the subgrade between the two analyses is shown in Figure 14. It is observed that when using the average values, the permanent strain in the subgrade is increased by approximately 23%. Changes in resilient modulus over the design period are plotted in Figures 15 and 16. As expected, the smaller resilient modulus values are observed throughout the design life. As evidenced in Figure 15 by the change in resilient modulus with respect to the month, the M-E Design Guide assumes the thawed resilient modulus to be about 1,000,000 psi.

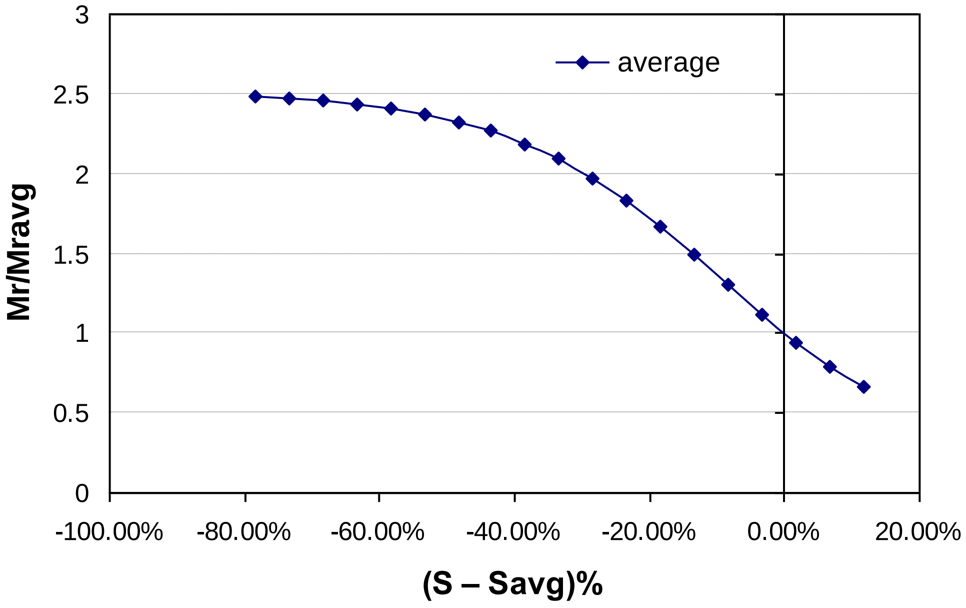

Figure 13. Modulus ratio due to change in moisture

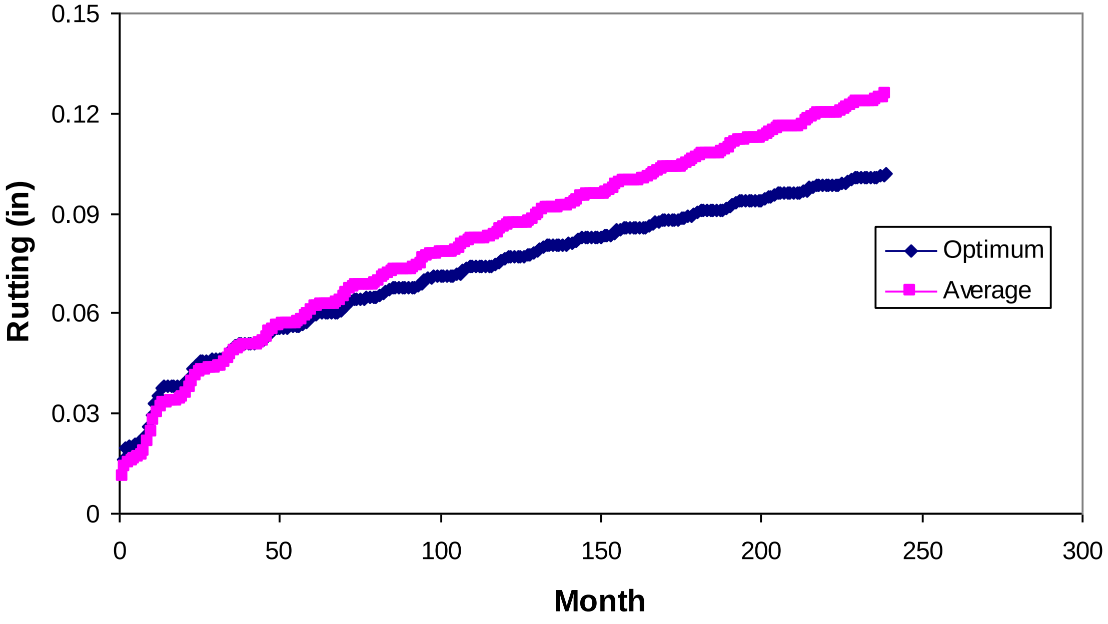

Figure 14. Comparison of permanent deformations (rutting) between optimum and average values

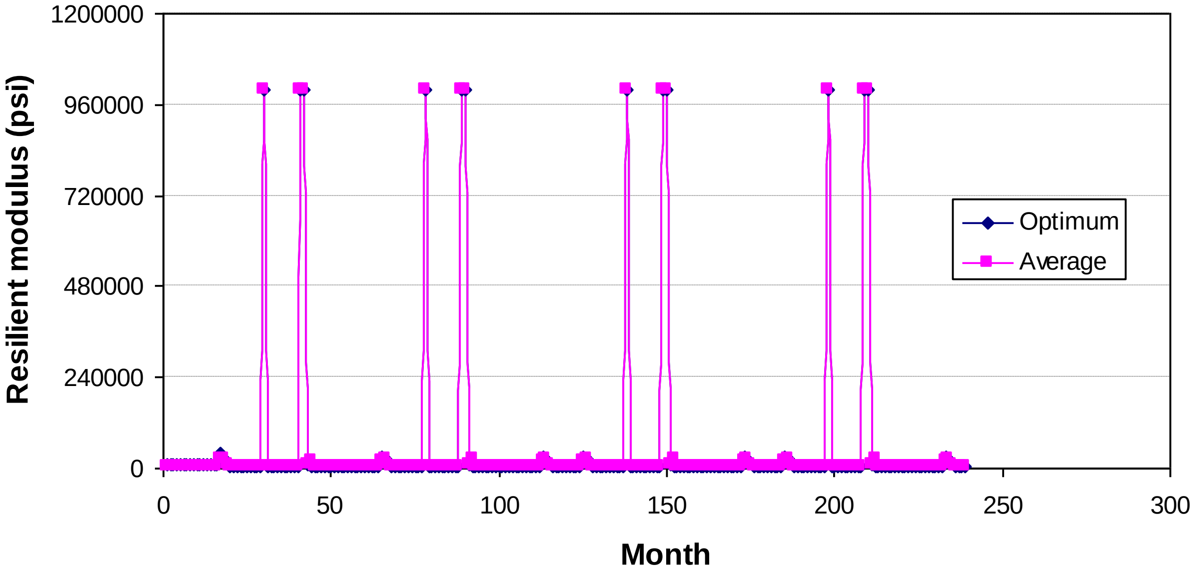

Figure 15. Modulus ratio due to change in moisture

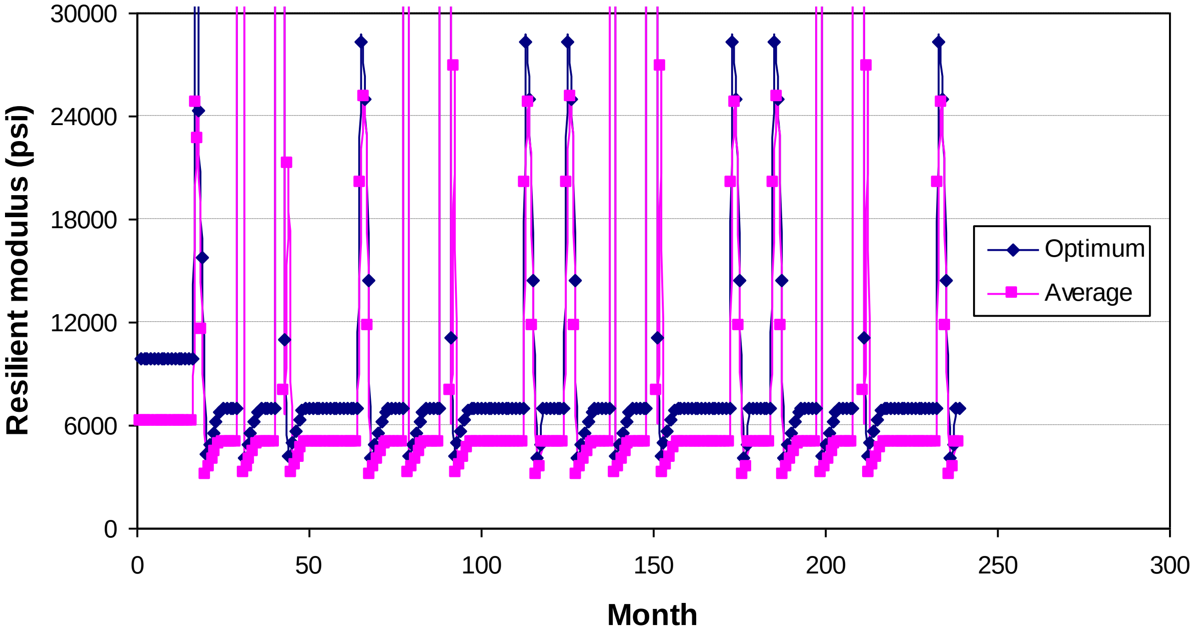

Figure 16. Modulus ratio due to change in moisture (expanded)

5.2.5. Implementation of the Study

With release of the new M-E Pavement Design Guide, highway agencies are required to implement the MEPDG, and the characterization of the stiffness of subgrade is an important part of it. Based on the FWD tests on several existing pavements and resilient modulus tests on the subgrade soils, the following can be implemented from this study:

1) When characterizing a subgrade layer with the MEPDG software, a factor of 0.48 is recommended for the laboratory resilient modulus as compared to the FWD modulus.
2) Winter FWD modulus is about 40% higher than early summer FWD modulus. These relationships can be used for seasonal variation of subgrade modulus in Indiana in the Mechanical-Empirical Pavement Design Guide Software (MEPDG).
3) Based on the review of the resilient modulus test data given by the INDOT Office of the Geotechnical Engineering, the resilient modulus of cohesive subgrade for Level 3 design is in the range of 4,000 to 9,000 psi.
4) The M-E Design Guide assumes that the subgrade is compacted to optimum moisture content, leading to unconservative design. In order to ensure a conservative design for subgrades, the use of the average resilient values is recommended.

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