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Verification of the Enhanced Integrated Climatic Module Soil Subgrade Input Parameters in the MEPDG

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16. Abstract

At the beginning of 2009, INDOT adopted the Mechanistic-Empirical Pavement Design Guide (MEPDG) method to study the tong-term pavement performance. The implementation of this new design approach led to difficulties for the pavement to pass the INDOT performance criteria; in particular pavement roughness (IRI) when A-6 or A-7-6 soils were considered as subgrade. This study focuses on investigating the influence of the soil input parameters in the Enhanced Integrated Climatic Model (EICM) on the prediction of the soil resilient modulus (MR) in the MEPDG. A total of four sites located around the state of Indiana are used to propose/validate the observations and conclusions made in the research.

The study shows that (1) for the climatic conditions existing in Indiana, the location of the water table does not affect the value that the MEPDG uses for the subgrade MR; (2) the gravimetric water content is the most influential parameter on the EICM since it is directly related to the optimum degree of saturation of the subgrade; and (3) For A-7-6 soils, the overall deformation of the pavement structure is controlled by the subgrade (~80% of total deformation).

In order to properly model the pavement structure, the MR input into the MEPDG for the subgrade should represent the optimum condition. This value will then be reduced within the EICM to reflect actual site conditions; and the MR input into the MEPDG for the treated layer should be a constant (i.e. not affected by EICM) and with PI and P200 values that are representative of the soil after treatment, given that the fines content and plasticity of a chemically-treated soil tend to decrease with treatment.

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EXECUTIVE SUMMARY

VERIFICATION OF THE ENHANCED INTEGRATED CLIMATIC MODULE SOIL SUBGRADE INPUT PARAMETERS IN THE MEPDG

Introduction

At the beginning of 2009, the Indiana Department of Transportation (INDOT) adopted the Mechanistic-Empirical Pavement Design Guide (MEPDG) method to study long-term pavement performance. The implementation of this new design approach led to difficulties for the pavement to pass the INDOT performance criteria: in particular, pavement roughness (International Roughness Index (IRI)) for hot-mixed asphalt (HMA) and faulting for jointed plain concrete pavement (JPCP) when A-6 or A-7-6 soils were considered as foundation soils.

This study focuses on investigating the influence of the soil input parameters in the Enhanced Integrated Climatic Model (EICM) on the prediction of the soil resilient modulus (M_R) in the MEPDG. A total of four sites located around the state of Indiana are used to propose/validate the observations and conclusions made in the research.

Findings

An investigation of the influence of EICM input parameters and other factors controlling the pavement performance led to the following conclusions:

- For the climatic conditions existing in Indiana, the location of the water table does not affect the value that the MEPDG uses for the subgrade resilient modulus. For A-7-6 soils, the degree of saturation throughout the pavement design life will always be above the optimal condition. Therefore, there will always be a reduction of the resilient modulus. For a water table located between 2 ft and 100 ft below the surface, the M_R reduction ranges between 36% and 45%, with the maximum reduction (45%) observed when the water table is located at 2 ft (saturated condition).
- The gravimetric water content is the most influential parameter on the EICM since it is directly related to the optimum degree of saturation of the subgrade soil.
- For A-7-6 soils, the overall deformation of the pavement structure is controlled by the subgrade (~80% of total deformation). This is due to its relatively low stiffness compared to that of a lime or cement treated layer and of the asphalt layer.
- The treated layer plays an important role in the overall performance of the pavement. It controls the amount of stress and deformation in the foundation soil.

As part of this study, an assessment of the current subgrade modeling approaches was also conducted. The following observations were drawn:

- Current practice appears to produce a double reduction of the subgrade modulus used for pavement design, since the M_R values provided as input to MEPDG are not those obtained at optimum moisture content, but are reduced by the INDOT Geotechnical Office to account for the site conditions. A further reduction in M_R is performed within the EICM to account for the moisture conditions at the site.
- Laboratory measurements of the M_R for A-7-6 soils obtained at optimum moisture content provide average values ranging between 10,000 psi and 16,000 psi (e.g., see project SPR-3710 (Park, 2015) (SR-37, Mitchell, Lawrence County, Vincennes)). These values are higher than the reference value of 3,250 psi provided by the INDOT Geotechnical Office. Hence, it is necessary to define which condition (i.e., at optimum or reduced) is represented by the value of the resilient modulus given by the Geotechnical Office and/or used as input in the software.
- Current approaches for modeling treated soils neglect the changes in the nature of the soils that arise with treatment (i.e., an A-7-6 soil continues to be modeled as an A-7-6 soil, albeit with a higher modulus, and thus is susceptible to the same reduction in stiffness). Moreover, the values of M_R typically employed for treated A-6 and A-7-6 soils (~9,000 psi, provided by the INDOT Geotechnical Office) fall on the low end of the range reported in the literature (e.g., AASHTO, 2008).

Implementation

Three approaches for modeling the subgrade can be adopted:

1. Enable the EICM module and use as input a value of M_R that represents the optimum condition. This value will then be reduced within the EICM to reflect actual site conditions.
2. Disable the EICM module and introduce an input M_R that already accounts for moisture changes and reflects the in situ conditions.
3. Disable the EICM module and introduce an input M_R with seasonal reduction that reflects the in situ conditions.

Changes of the subgrade resilient modulus caused by the seasonal variations of the water table, modeled by placing it at 2, 4, 6, and 9 ft below the pavement surface, resulted in an average reduction of ~43%, which is nearly constant throughout the four seasons (winter, spring, summer, and fall). Thus, it appears that the third approach (i.e., using seasonal reduction) is less meaningful in Indiana and the first two approaches seem more practical.

Given that the fines content and plasticity of a chemically treated soil tend to decrease with treatment, the treated layer should be modeled with PI and P200 values that are representative of the soil after treatment. Moreover, the M_R input into the MEPDG for the treated layer should be a constant (i.e., not affected by EICM).

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1. INTRODUCTION: BACKGROUND AND PROBLEM STATEMENT

At the beginning of 2009, INDOT adopted the Mechanistic-Empirical Pavement Design Guide (MEPDG) method, which is a new design guide based on the FHWA Long Term Pavement Performance (LTTP). The new pavement design procedures and pavement design input parameters included in the guide differ from those in the AASHTO 1993 Pavement Design Guide, which was based on the AASTHO Road Test conducted in the 1950s. The implemented method requires the input of design parameters that can reflect the actual conditions in the field to better predict pavement performance over time, based on different criteria including roughness, rutting, faulting and fatigue cracks.

With the implementation of this new design approach, difficulties have been encountered to pass the INDOT performance criteria: in particular, pavement roughness (International Roughness Index (IRI)) for hot-mixed asphalt (HMA) and faulting for jointed plain concrete pavement (JPCP) when A-6 or A-7-6 soils were considered as subgrade. Given that the pavement performance is sensitive to soil stiffness (resilient modulus), it is necessary to re-verify the predictions of resilient modulus in relation to the soil input parameters in the Enhanced Integrated Climatic Model (EICM).

2. RESEARCH OBJECTIVES

The objectives of this research project are geared toward finding a practical solution in INDOT pavement design procedures to effectively determine the influence of the EICM input parameters and make necessary adjustments that can accurately predict the soil resilient modulus in MEPDG. The ultimate goal of the research is to create guidelines for selecting values of soil subgrade input parameters in the EICM module in MEPDG. Within this broad scope, the specific objectives of the work conducted as part of this research project are to:

a. Determine the influence of EICM soil input parameters on the "predicted" month-to-month soil resilient modulus in MEPDG over the pavement design life, for A-6 and A-7-6 soils (fine-grained soils) in high truck traffic cases.
b. Propose necessary adjustments to soil input parameters if needed.
c. Provide guidelines for the selection of subgrade values to be introduced in the model.

3. ACTIVITIES

The research objectives outlined above are pursued through the following activities:

- Study of the soil-water characteristic curves (SWCC) in MEPDG and assessment of the influence of the water table depth on the "predicted" month-to-month soil resilient modulus over the pavement design life (see Section 4.4.1);
- Parametric study to determine and rank the influence of the soil input parameters in the EICM module (see Section 4.4.2);
- Investigation of the influence of the subgrade input resilient modulus (see Section 4.4.3);
- Investigation of the influence of the treated layer input resilient modulus and material type (the PI and P_{200} generally decrease due to soil treatment) (see Section 4.4.4);
- Validation of the observations and conclusions drawn from the research through analysis of case studies of different sites in Indiana (see Section 5).

4. RESULTS AND DISCUSSION

This section presents the results of the long-term pavement performance analysis conducted using MEPDG and the influence of each input parameter on the pavement design life. Section 4.1 describes the pavement model that was used for this study. Section 4.2 presents the deformation of pavement structure and the contribution of each layer on the total deformation. The MEPDG pavement layers discretization is shown in Section 4.3. Section 4.4 discusses the different factors affecting the pavement performance in MEPDG.

4.1 Pavement Model

The pavement structure used for this study was based on real data obtained from the Fort Wayne I-469 project, which has the following characteristics:

- Design life: 19 years
- Pavement: Flexible-HMA
- Reliability level: 90%
- Climate station data: Fort Wayne, IN
- Water table depth: 2-ft
- Pavement structure: see Table 4.1

The subgrade resilient modulus was provided by the INDOT geotechnical office.

4.2 Deformation of Pavement Structure

The distribution of the average rutting per pavement layer obtained using the MEPDG method is presented in Figure 4.1. As it can be seen, the subgrade layer or foundation soil controls the overall deformation of the pavement structure (80% of total deformation).

4.3 MEPDG Pavement Layers Discretization

In order to analyze the pavement structure and predict the pavement performance over its design life, MEPDG discretizes the pavement layers into several sub-layers (referred to as "nodes") based on each layer type and thickness. This is summarized in Figure 4.2 and Table 4.2, where the three top asphalt layers are divided into 3, 2, and 2 nodes respectively. The treated layer is modeled with one node, whereas the subgrade is divided in 4 nodes.

TABLE 4.1
Pavement structure used in MEPDG.

Layer #	Layer Type	Material Type	Thickness (in)	Resilient Modulus (psi)
1	Flexible	Asphalt concrete	1.5	–
2	Flexible	Asphalt concrete	2.5	–
3	Flexible	Asphalt concrete	10.0	–
4	Subgrade	A-7-6 (treated)	14.0	9,000
5	Subgrade	A-7-6	Semi-infinite	3,250

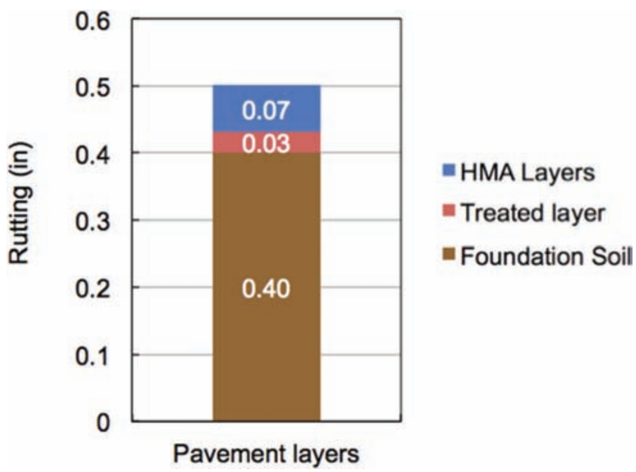

Figure 4.1 Average deformation per pavement layer.

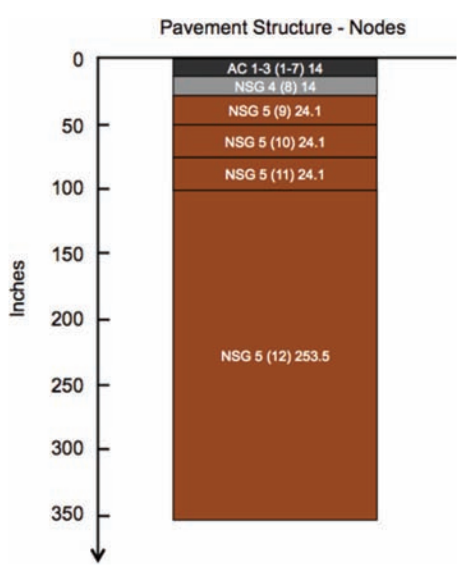

Figure 4.2 MEPDG pavement layers discretization.

4.4 Factors Affecting the Pavement Performance in MEPDG

There are several factors that influence the overall performance of the pavement structure in MEPDG, such as the location of the water table, the input parameters for the subgrade, and the input parameters for the treated layer. This section addresses these factors and presents a parametric study to assess the influence of soil input parameters in the EICM Module.

TABLE 4.2
MEPDG pavement layers discretization.

Label	Layer #	Node #	Layer Type	Thickness (in)
AC 1 (1-3)	1	1-3	Asphalt concrete	1.5
AC 2 (4-5)	2	4-5	Asphalt concrete	2.5
AC 3 (6-7)	3	6-7	Asphalt concrete	10
NSG 4 (8)	4	8	Treated soil	14
NSG 5 (9)	5	9	Foundation soil	24.1
NSG 5 (10)	5	10	Foundation soil	24.1
NSG 5 (11)	5	11	Foundation soil	24.1
NSG 5 (12)	5	12	Foundation soil	253.5

4.4.1 Water Table Depth

The soil-water characteristic curve (SWCC) describes the relationship between the degree of saturation and the soil matric suction. The latter is determined based on two possible conditions according to the NCHRP 9-23 project. If the water table is above 9-ft, the matric suction is determined by the position of the phreatic level. When the water table is below 9-ft, the matric suction is defined by the Thornthwaite Moisture Index (TMI). The TMI relates the amount of precipitation and the potential evapotranspiration of the soil as follows:

$$\mathrm{TMI}=75\left(\frac{P}{\mathrm{PE}}-1\right)+10 \tag{4.1}$$

where P = precipitation and PE = potential evapotranspiration of water.

For a given P_{200} (i.e., the percentage of material passing the U.S. No. 200 sieve) and plasticity index (PI), the matric suction, h, can be found using the following equation:

$$h=\alpha\left[e\left[\frac{\beta}{TM1+\gamma}\right]+\delta\right] \tag{4.2}$$

where the regression constants α, β, γ, and δ are summarized in Table 4.3.

The subgrade used in this study is A-7-6 soil with wPI (the product of P_{200} as a decimal and PI as a percentage) = 23.7. Using the corresponding regression constants from Table 4.3, the relationship between the matric suction and the TMI is obtained and plotted in Figure 4.3.

Given that the soil matric suction depends on the location of the water table, a total of six scenarios with different water table locations were evaluated. The scenarios included the following locations of the water table determined from the surface of the pavement: 2-ft, 4-ft, 6-ft, 12-ft, 48-ft and 100-ft. The month-to-month resilient modulus values predicted in MEPDG over the pavement design life for each scenario are presented in Figures 4.4 (a-f). Figure 4.4a shows that the resilient modulus of all the subgrade sub-layers (described in Table 4.2) is constant when the water table is located 2-ft below the surface since the degree of saturation is 100%. For this scenario the modulus drops from the initial 3250 psi to 1804 psi, representing a reduction of 45%. For the scenarios where the water table is at 4-ft and 6-ft, small fluctuations in resilient modulus are observed, as shown in Figures 4.4b and 4.4c. However, in both cases there is a significant reduction of the resilient modulus, similar in magnitude to the previous case.

TABLE 4.3
Regression constants for TMI-P200/wPI model, subgrade materials.

P_{200} or wPI*	α	β	γ	δ	R2
P200 = 10	0.300	419.07	133.45	15.00	>0.99
P200 = 50 / wPI ≤ 0.5	0.300	521.50	137.30	16.00	>0.99
wPI = 5	0.300	663.50	142.50	17.50	>0.99
wPI = 10	0.300	801.00	147.60	25.00	>0.99
wPI = 20	0.300	975.00	152.50	32.00	>0.99
wPI = 50	0.300	1171.20	157.50	27.80	>0.99

*wPI = the product of P_{200} as a decimal and PI as a percentage.

For the water table below 9-ft (i.e., 12-ft, 48-ft and 100-ft), the variation in the resilient modulus of the subgrade sublayers is similar. The modulus oscillates between 1,800 and 2,670 psi. The three cases show a similar trend because the matric suction is determined by the TMI or the temperature profile of the soil.

The results in Figure 4.4 demonstrate that the location of the water table has a small influence on the resilient modulus over time. The observed behavior is due to the degree of saturation that is determined by the SWCC. As illustrated in Figure 4.5, for matric suction values between 0.1 kPa and approximately 1,160 kPa, the degree of saturation for A-7-6 soils is greater than that corresponding to the optimum condition. The matric suction values derived for the depths of the water table examined in this analysis all fall in this range.

Figure 4.6 presents a summary of the values of the degree of saturation for each of the subgrade sublayers (described in Table 4.2) and for the different locations of the water table. As shown in the figure, regardless of the location of the water table, the degree of saturation (>95%) is above the optimum condition and thus there is a reduction in the resilient modulus.

The resilient modulus-moisture model used in MEPDG is defined by the following equation:

$$\log \frac{M_R}{M_{Ropt}} = a + \frac{b-a}{1+EXP\left(\ln\frac{-b}{a} + k_m\left(S - S_{opt}\right)\right)} \tag{4.3}$$

where a = -0.5934, b = 0.4, and k_m = 6.1324 for fine-grained material (e.g., A-7-6).

This relationship is shown in Figure 4.7. An increase in the stiffness (M_R), relative to the optimum condition (M_{Ropt}), occurs when $S < S_{opt}$ and a reduction occurs

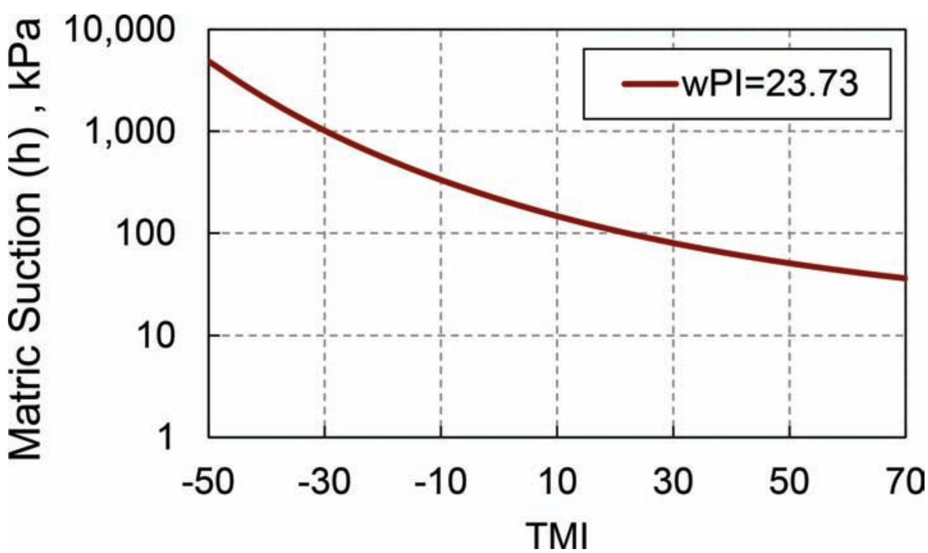

Figure 4.3 TMI-P200/wPI model for A-7-6 subgrade soil (wPI=23.73).

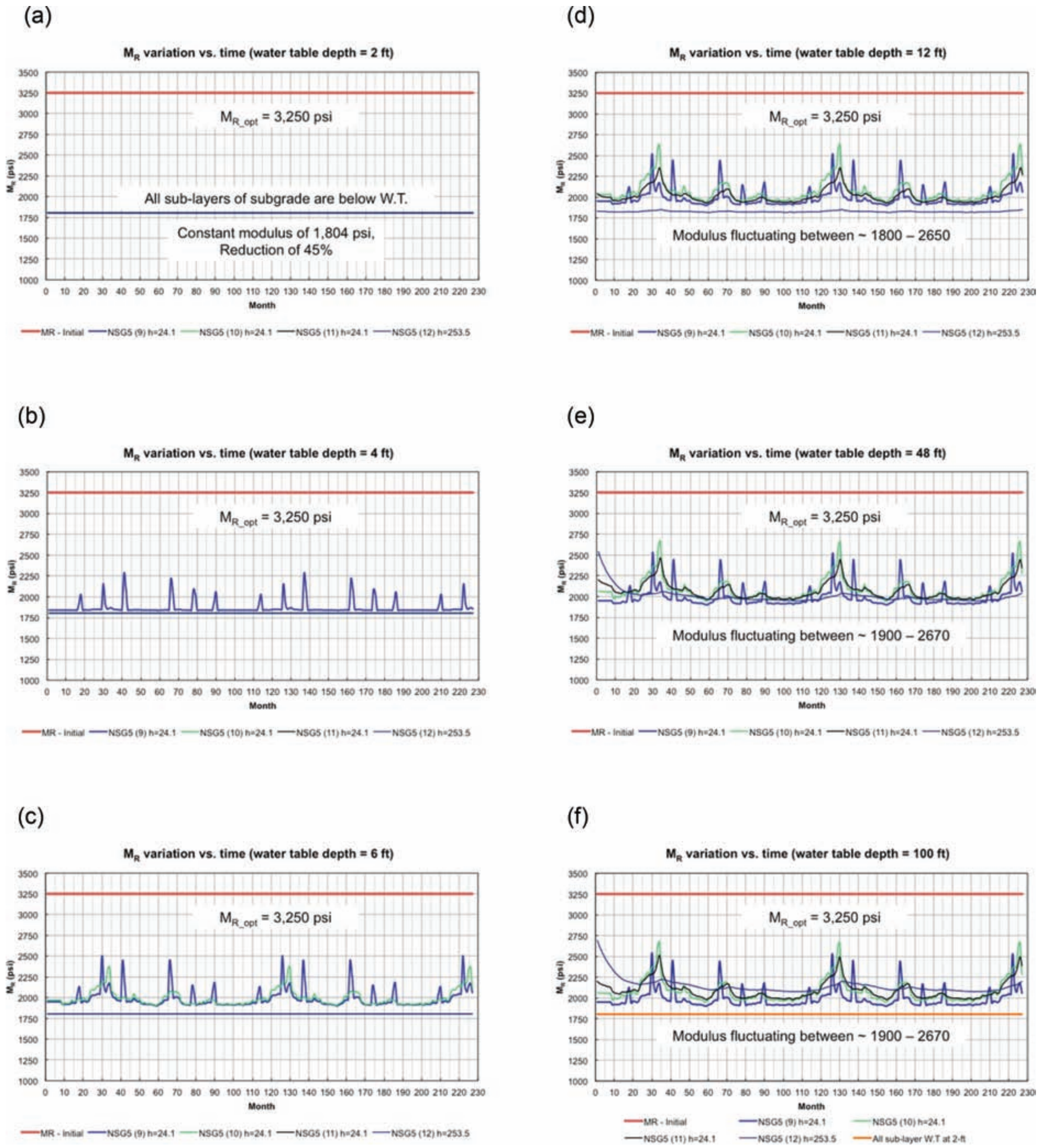

Figure 4.4 Variation of the subgrade resilient modulus with time for a water table located at (a) 2 ft, (b) 4 ft, (c) 6 ft, (d) 12 ft, (e) 48 ft, and (f) 100 ft.

when $S > S_{opt}$. For A-7-6 subgrade soils, there will always be reduction in the resilient modulus since the degree of saturation (>95%) will always be above the optimal condition (82.7%) regardless of the location of the water table.

4.4.2 Soil Input Parameters in the EICM Module: Parametric Study

A parametric study is conducted to assess the influence of soil input parameters in the EICM module. The study includes eight scenarios, all with a constant water table located 2-ft below the pavement surface. Table 4.4 lists the input parameters used for each case analyzed. The cells highlighted in gray indicate the values that change for each scenario while the rest remain constant.

As a point of reference, the default values for A-7-6 soils provided by the EICM are:

$$\gamma_{d_{max}} = 97.7\text{pcf}$$

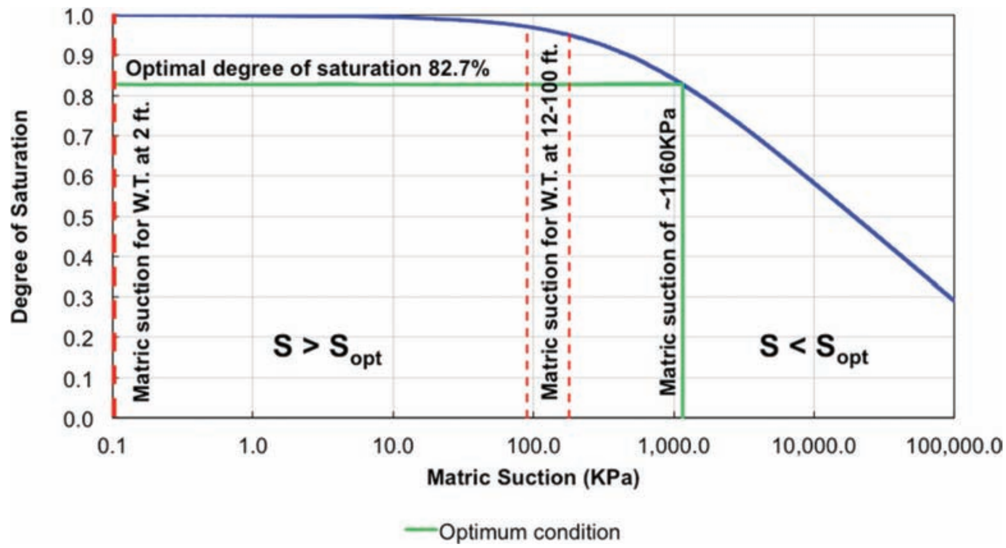

Figure 4.5 SWCC for A-7-6 subgrade soil.

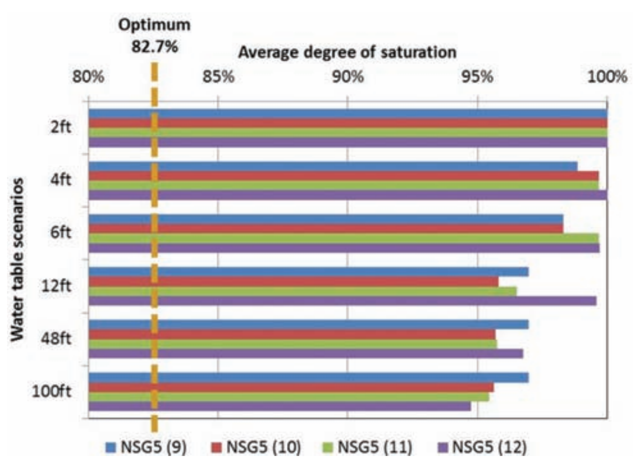

Figure 4.6 Average degree of saturation for subgrade's sublayers.

$$Gs = 2.70$$

$$k_{sat} = 8.9 \times 10^{-6} \text{ft}/\text{hr}$$

$$w_{opt} = 22.2\%$$

$$S_{opt} = 82.7\%$$

As one can see from Table 4.4, the parametric analysis explores the effects of changes of the key input parameters over a wide range of possible values.

The results of the parametric study are summarized in Table 4.5. It can be concluded that the soil input parameter that exerts the largest influence on the resilient modulus, IRI reliability, and average rutting is the optimum gravimetric water content. This is due to the fact that the optimum gravimetric water content is directly related to the optimum degree of saturation (as shown in Equations 4.4 and 4.5), which has a large influence on the resilient modulus-moisture model (Equation 4.3).

$$\theta_{opt} = \frac{w_{opt}\gamma_{dmax}}{\gamma_{water}} \tag{4.4}$$

$$S_{opt} = \frac{\theta_{opt}}{1 - \frac{\gamma_{dmax}}{\gamma_{water}G_s}} \tag{4.5}$$

4.4.3 Subgrade: Input Resilient Modulus

The input subgrade resilient modulus has a large influence on the pavement performance. Current practice appears to produce a double reduction of the subgrade modulus since the input M_R used in the program is not the value obtained at optimum moisture, but reduced by the INDOT Geotechnical office to account for actual soil conditions (in general field compaction is performed ~2% above optimum water content). However, the reduction in M_R to account for the moisture conditions at the site is automatically performed by the model when using the climatic model (EICM).

In order to address this issue, three approaches for modeling the subgrade can be adopted: (1) enabling the EICM module and using as input a value of M_R that represents the optimum condition (e.g., 5,855 psi). This value will then be reduced within the EICM to reflect the actual site conditions (to ~3,250 psi); (2) disabling the EICM module and introducing an input M_R that already accounts for moisture changes and reflects the in situ conditions (e.g., 3,250 psi); or (3) disabling the EICM module and introducing an input M_R with seasonal reduction that reflects the in situ conditions (note that for water table located at 2 ft, the subgrade is

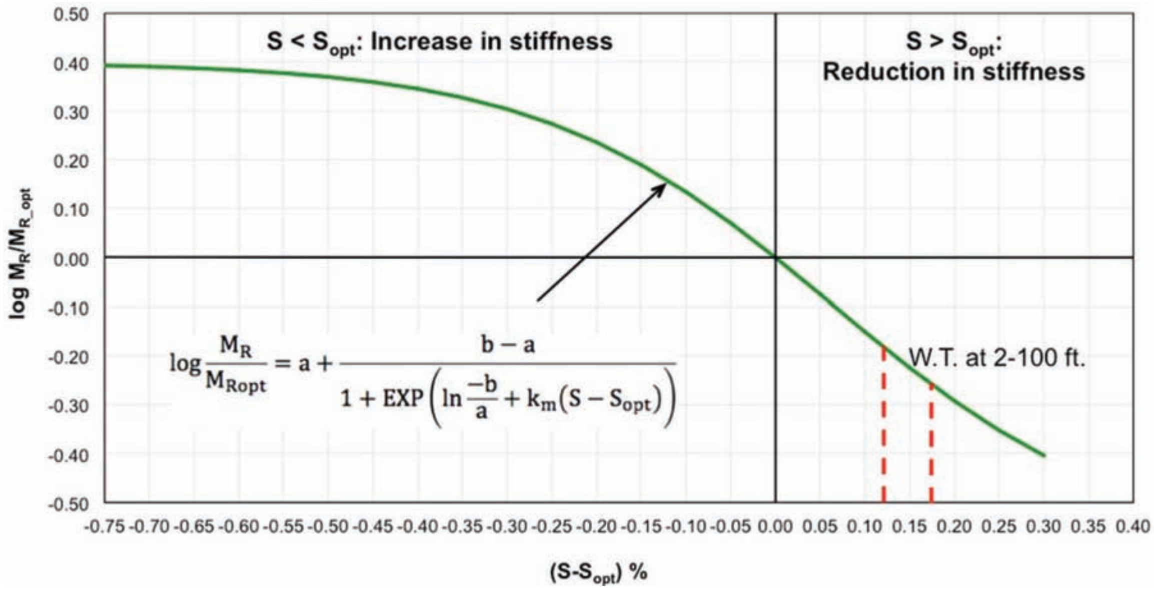

Figure 4.7 Resilient modulus-moisture model used in MEPDG.

TABLE 4.4
Parametric study scenarios.

Scenario	γ_{dmax} (pcf)	G_s	k_{sat} (ft/hr)	w_{opt}(%)	S_{opt} (%)
1	96.7	2.70	8.9E-6	22.2	80.7
2	98.7	2.70	8.9E-6	22.2	84.8
3	97.7	2.65	8.9E-6	22.2	84.9
4	97.7	2.75	8.9E-6	22.2	80.7
5	97.7	2.70	8.9E-5	22.2	82.7
6	97.7	2.70	8.9E-7	22.2	82.7
7	97.7	2.70	8.9E-6	20.2	75.3
8	97.7	2.70	8.9E-6	24.2	90.2

TABLE 4.5
Results from the parametric study.

Scenario	S_{opt}	M_{R_opt} (psi)	M_R (psi)	M_R / M_{R_opt}	IRI Reliability (%)	Average Rutting (in)
1	80.7	3250	1697	0.522	82.49	0.44
2	84.8	3250	1924	0.592	83.40	0.42
3	84.9	3250	1937	0.596	83.46	0.42
4	80.7	3250	1693	0.521	82.47	0.44
5	82.7	3250	1804	0.555	82.94	0.43
6	82.7	3250	1804	0.555	82.94	0.43
7	75.3	3250	1453	0.447	80.18	0.49
8	90.2	3250	2311	0.711	85.48	0.37

TABLE 4.6
Influence of subgrade resilient modulus.

Scenario	Analysis Type	M_{R_opt} (psi)	M_R (psi)	M_R/M_{R_opt}	IRI at Reliability (in/mi)	Failure year	Final Total Rutting (in)
1	ICM inputs	3250	1804	0.555	170.57	16.1	0.596
2	ICM inputs	5855	3250	0.555	162.77	18.3	0.444
3	Fixed value	3250	3250	1.000	162.52	18.3	0.439

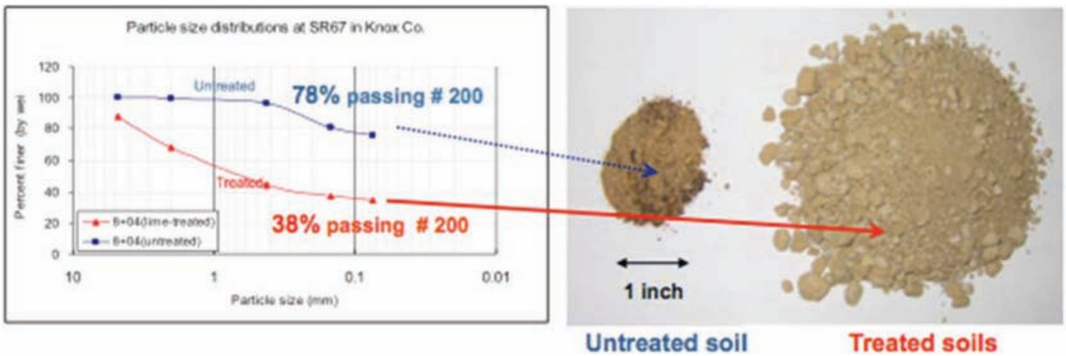

Figure 4.8 Natural versus lime-treated soil (Jung & Bobet, 2008).

TABLE 4.7
Soil classification for natural and treated soils (Jung & Bobet, 2008).

		Site (1)	Site (2)	Site (3)	Site (4)	Site (5)	Site (6)
Soil Type	Natural	A-7-5	A-4	A-7-6	A-6	A-6	A-6
	Treated	A-1-b	A-2-4	A-2-4	A-1-b	A-4	A-4

always fully saturated resulting in a constant 45% reduction in M_R throughout the year). Note that a reduction in the subgrade M_R due to seasonal variation of the water table located at 2, 4, 6, and 9 ft results in an average reduction of ~43% that is almost constant during the four seasons (winter, spring, summer, and fall). Hence, it appears that the third approach, i.e., using seasonal reduction, is less meaningful in Indiana and only the first two approaches should be adopted.

Table 4.6 shows the results of three different scenarios: Scenario 1 corresponds to the "double reduction" of the subgrade M_R, whereas Scenarios 2 and 3 correspond to approaches 1 and 2 proposed above, which are intended to reflect actual in situ conditions. Both approaches result in an ~8 in/mi decrease in the IRI or ~2 additional years before failure.

4.4.4 Treated Layer: Input Resilient Modulus and Material Type

An additional issue is the handling within the model of a treated subgrade. All the runs conducted in this research show that the limiting criterion controlling the pavement design is the roughness (IRI); hence it is essential to consider all the parameters affecting IRI (= f{…, PI, M_R, …}).

Many researchers (e.g., Jung & Bobet, 2008) showed that the PI and P_{200} generally decrease due to soil treatment. This is illustrated in Figure 4.8 and Table 4.7, where lime-treated soils from different sites were reported and the soil type changed due to the decrease of PI and P_{200} after treatment. Thus, it is not sufficient to model the treated layer by only increasing the M_R but representative values of PI and P_{200} should be also assigned.

In order to illustrate the influence of the treated layer and the importance of the input parameters mentioned above, five different scenarios were investigated using the same pavement structure described in section 4.1. The M_R used for the A-7-6 subgrade is 5,855 psi (which is reduced by the EICM to 3,250 psi). The results are summarized in Table 4.8.

Scenario 0 corresponds to a 14″ treated layer with the same properties as the subgrade, except for the input M_R of 9,000 psi, which is reduced by EICM to ~5,100 psi. Scenarios 1–4 correspond to a 14″ treated layer with

TABLE 4.8
Influence of treated layer resilient modulus and material type.

Scenario	Material Type	P_{200} (%)	PI (%)	LL (%)	S_{opt} (%)	IRI at Reliability (in/mi)	Failure Year	Final Total Rutting (in)
0	A-7-6	79.1	30	51	84.6	163.07	18.2	0.449
1	A-7-6	79.1	30	51	84.6	162.77	18.3	0.444
2	A-7-5	70.5	24	57	84.8	162.62	18.4	0.445
3	A-6	63.2	16	33	83.8	161.63	18.6	0.448
4	A-5	54.3	5	45	75.7	160	–	0.455

fixed M_R of 9,000 psi and varying the material type, i.e., A-7-6, A-7-5, A-6, and A-5 (reflecting the reduction in PI and P_{200} associated with the treatment).

Fixing the M_R of the treated layer to 9,000 psi (cases 0–1) leads to a slight improvement in pavement performance. However, varying the material type of the 14″ treated layer from A-7-6 to A-5 results in a ~3 in/mi decrease in the IRI and the pavement passing the performance criteria.

5. CASE STUDIES

Figure 5.1 shows the location of four different sites in Indiana that are used to propose/validate the observations and conclusions made in this research: (1) I-469, Fort Wayne; (2) CRN50E, Kokomo; (3) SR46, Terre Haute; and (4) I-65, Southport. The first site is used as a source of the input data for all the analysis reported in this research and summarized in the previous sections. The latter three sites are used to validate those conclusions, and will be described in this section. Table 5.1 summarizes the locations of the sites as well as the road names, and Table 5.2 presents the analysis parameters and the traffic data used for each site.

All three sites show a reduction of ~45-55% of the subgrade M_R due to the EICM to account for the moisture conditions at the site, which is consistent with the observation described in 4.4.1 and 4.4.3. Therefore, it is crucial to use input parameters that are representative of the material type and the site conditions.

Figure 5.1 Case studies in Indiana.

TABLE 5.1
Case studies in Indiana.

Site #	Road Name	Location	District
1	I-469	Fort Wayne, IN	Fort Wayne
2	CRN50E	Kokomo, Howard County, IN	Greenfield
3	SR46	Terre Haute, Vigo County, IN	Crawfordsville
4	I-65	Southport, Marion County, IN	Greenfield

5.1 Site 2: CRN50E, Kokomo

Table 5.3 summarizes the pavement structure used for this case, which is based on actual data obtained from the Kokomo CRN50E project. The subgrade resilient modulus was obtained from laboratory measurements obtained at optimum conditions from Project SPR-3710 (Park, 2015). The values ranged between 3,400 psi and 13,600 psi; the 5^{th} percentile, average, and 95^{th} percentile are used for analysis.

As described in section 4.4.3, the input subgrade resilient modulus has a large influence on the pavement performance. This is investigated by analyzing six different scenarios. The results are summarized in Table 5.4. Scenarios 1, 3, and 5 correspond to a fixed value of M_R obtained from Project SPR-3710 (Park, 2015) as the 5^{th} percentile, average, and 95^{th} percentile, respectively. Scenarios 2, 4, and 6 correspond to the same values of M_R, which are then reduced by the EICM module

TABLE 5.2
Analysis parameters and traffic data.

	Site 2	Site 3	Site 4
Design life (yrs)	20	20	20
Type of road	Local	Collector urban	Freeway
Terminal IRI (in/mile) [Reliability, %]	200 [70%]	190 [80%]	160 [90%]
AC Bottom-Up Cracking, Alligator Cracking (% lane area) [Reliability, %]	35 [70%]	30 [80%]	10 [90%]
AC Thermal Fracture (ft/mi/lane) [Reliability, %]	500 [70%]	500 [80%]	500 [90%]
Permanent Deformation – AC only (in) [Reliability, %]	0.4 [70%]	0.4 [80%]	0.4 [90%]
Initial two-way AADTT	50	1,145	27,800
# of lanes in design direction	1	1	3
Operational speed (mph)	45	55	55
Linear growth (%)	2.0	1.3	1.3
Water table depth (ft)	5.0	5.0	4.5

TABLE 5.3
Pavement structure used in MEPDG for site 2.

Layer #	Layer Type	Material Type	Thickness (in)	Resilient Modulus (psi)
1	Flexible	Asphalt concrete	1.5	–
2	Flexible	Asphalt concrete	2.5	–
3	Granular base	Crushed stones	6.0	25,000
4	Subgrade	A-4	Semi-infinite	3,400 – 13,600

TABLE 5.4
Influence of subgrade resilient modulus for site 2.

#	Analysis Type	M_{R_opt} (psi)	M_R (psi)	M_R/M_{R_opt}	IRI Reliability (%)	IRI at Reliability (in/mi)	Failure Year	Final Total Rutting (in)
1	Fixed value	3400	3400	1.000	96.9	152.3	–	0.700
2	ICM inputs	3400	1602	0.471	88.3	174.1	–	1.167
3	Fixed value	7600	7600	1.000	99.1	138.6	–	0.419
4	ICM inputs	7600	3581	0.471	97.2	150.7	–	0.672
5	Fixed value	13600	13600	1.000	99.6	132.7	–	0.303
6	ICM inputs	13600	6407	0.471	98.9	140.6	–	0.462

(the module reduces the M_R by about 53%). Scenarios 2, 4, and 6 result in an increase of the IRI of at least 12 in/mi. Note that for all six scenarios, the pavement did not fail. The reason is that the road is a county road with very low traffic and low reliability (70%).

5.2 Site 3: SR46, Terre Haute

Table 5.5 summarizes the pavement structure used for this case, which is based on data obtained from the Terre Haute SR46 project. The subgrade resilient modulus was obtained from laboratory measurements obtained at optimum water content, from Project SPR-3710 (Park, 2015). The values range between 8,600 psi and 16,300 psi; the 5th percentile, average, and 95th percentile are used for the analysis.

The influence of the EICM module on the input subgrade resilient modulus is investigated by analyzing six different scenarios. The results are summarized in Table 5.6. Scenarios 1, 3, and 5 correspond to a fixed

TABLE 5.5
Pavement structure used in MEPDG for site 3.

Layer #	Layer Type	Material Type	Thickness (in)	Resilient Modulus (psi)
1	Flexible	Asphalt concrete	1.5	–
2	Flexible	Asphalt concrete	2.5	–
3	Flexible	Asphalt concrete	8.6	–
4	Subgrade	A-6 (treated)	12.0	9,000
5	Subgrade	A-6	Semi-infinite	8,600 – 16,300

TABLE 5.6
Influence of subgrade resilient modulus for site 3.

#	Analysis Type	M_{R_opt} (psi)	M_R (psi)	M_R/M_{R_opt}	IRI Reliability (%)	IRI at Reliability (in/mi)	Failure Year	Final Total Rutting (in)
1	Fixed value	1400	1400	1.000	92.5	168.5	–	0.841
2	ICM inputs	1400	778	0.556	83.6	184.9	–	1.192
3	Fixed value	8600	8600	1.000	98.8	144.2	–	0.324
4	ICM inputs	8600	4780	0.556	98.2	148.8	–	0.423
5	Fixed value	16300	16300	1.000	99.0	142.4	–	0.288
6	ICM inputs	16300	9060	0.556	98.9	143.8	–	0.316

TABLE 5.7
Pavement structure used in MEPDG for site 4.

Layer #	Layer Type	Material Type	Thickness (in)	Resilient Modulus (psi)
1	Flexible	Asphalt concrete	1.5	–
2	Flexible	Asphalt concrete	3.0	–
3	Flexible	Asphalt concrete	12.5	–
4	Subgrade	A-6 (treated)	14.0	8,750
5	Subgrade	A-6	Semi-infinite	3,000

value of M_R obtained from Project SPR-3710 (Park, 2015) as the 5th percentile, average, and 95th percentile, respectively. Scenarios 2, 4, and 6 correspond to the same values of M_R but allowing the EICM module to decrease them. This results in a reduction of M_R of about 45% (e.g., compare cases 3 and 4) and in an increase of the IRI of about 4 in/mi. Note that for all six scenarios, the pavement did not fail. As with the previous case, the result is due to the fact that the road is a State road with very low traffic and low reliability (80%).

5.3 Site 4: I-65, Southport

Table 5.7 summarizes the pavement structure used for this case, which is based on data obtained from the Southport I-65 project. The subgrade resilient modulus was provided by the INDOT geotechnical office.

For this case, the influence of the EICM module on the input subgrade resilient modulus is investigated by analyzing six different scenarios. The results are summarized in Table 5.8. Scenario 1 corresponds to the "double reduction" of the subgrade M_R (described in section 4.4.3). The subgrade M_R = 3,000 psi, provided by the INDOT geotechnical office, represents the value that corresponds to the moisture conditions at the site. Hence, activating the EICM module will result into a double reduction (Scenario 1). Scenarios 2 and 3 correspond to approaches 1 and 2 proposed in section 4.4.3, which avoid the double reduction of M_R and reflect the in situ conditions. Both approaches resulted in a ~11 in/mi decrease in the IRI or ~3.3 additional years before failure. Scenarios 4 – 6 show the input subgrade M_R needed to sustain a longer lifespan: 5,500 psi for 18 years, 8,500 psi for 19 years, and 10,000 psi for 19.4 years.

TABLE 5.8
Influence of subgrade resilient modulus for site 4.

#	Analysis Type	M_{R_opt} (psi)	M_R (psi)	M_R/M_{R_opt}	IRI Reliability (%)	IRI at Reliability (in/mi)	Failure Year	Final Total Rutting (in)
1	ICM inputs	3000	1654	0.551	71.06	186.53	12.5	0.867
2	ICM inputs	5442	3000	0.551	80.2	174.98	15.8	0.65
3	Fixed value	3000	3000	1.000	80.16	175.09	15.8	0.649
4	Fixed value	5500	5500	1.000	85.71	167.19	18.0	0.497
5	Fixed value	8500	8500	1.000	88.17	163.24	19.0	0.421
6	Fixed value	10000	10000	1.000	88.74	162.26	19.4	0.402

TABLE 5.9
Influence of treated layer material type for site 4.

#	Material Type	P_{200} (%)	PI (%)	LL (%)	S_{opt} (%)	IRI Reliability (%)	IRI at Reliability (in/mi)	Failure Year	Final Total Rutting (in)
1	A-6	63.2	16	33	82.1	80.16	175.09	15.8	0.649
2	A-5	54.3	5	45	75.7	81.43	173.38	16.0	0.657
3	A-4	60.6	5	21	76.6	81.23	173.65	16.0	0.656
4	A-3	5.2	0	11	49.1	86.32	166.22	17.9	0.651

As described in section 4.4.4, the influence of the treated layer plays an important role in the overall performance of the pavement. This is investigated by analyzing four different scenarios. The results are summarized in Table 5.9. Scenarios 1–4 correspond to a 14″ treated layer with fixed M_R of 8,750 psi and varying the material type, i.e., A-6, A-5, A-4, and A-3 (reducing PI and P_{200}). The M_R used for the A-6 subgrade is 3,000 psi (fixed value). Varying the material type of the 14″ treated layer from A-6 to A-3 results in a ~9 in/mi decrease in the IRI and additional 2.1 years lifespan before failure.

6. CONCLUSIONS

At the beginning of 2009, INDOT adopted the MEPDG method to study the long-term pavement performance. The implementation of this new design approach led to difficulties for the pavement to pass the INDOT performance criteria; in particular pavement roughness (IRI) for hot-mixed asphalt (HMA) and faulting for jointed plain concrete pavement (JPCP) when A-6 or A-7-6 soils were considered as subgrade. This study is intended to find a practical solution in INDOT pavement design procedures to effectively determine the influence of the EICM input parameters to predict the soil resilient modulus in MEPDG. The ultimate goal of the research is to create guidelines for selecting values of soil subgrade input parameters in the EICM module in MEPDG. A total of four sites located around the state of Indiana were used to propose/validate the observations and conclusions made in the research. The study yielded the following conclusions, which are grouped into three concepts.

6.1 Influence of EICM Input Parameters and Factors Controlling Pavement Performance

- For the climatic conditions existing in Indiana, the variation of the subgrade resilient modulus is independent of the location of the water table. For A-7-6 soils, the degree of saturation (>95%) will always be above the optimal condition. Therefore, there will always be a reduction of the resilient modulus. This reduction ranges between 36% and 45% for a water table located between 2 ft to 100 ft below the surface, with the maximum reduction (45%) observed when the water table is located at 2 ft (saturated condition).
- A parametric study conducted to assess the influence of the soil input parameters (γ_{dmax}, G_s, k_{sat}, w_{opt}, and S_{opt}) on the SWCC shows that the gravimetric water content is the most influential parameter on the EICM since it is directly related to the optimum degree of saturation of the subgrade soil.
- For A-7-6 soils, the foundation soil controls the overall deformation of the pavement structure (~80% of total deformation) as a result of its relatively low stiffness compared to that of a lime or cement treated layer and of the asphalt layer.
- The treated layer plays an important role in the overall performance of the pavement. It controls the amount of stress and deformation in the subgrade.

6.2 Assessment of Current Subgrade Modeling Approaches

- Current practice appears to produce a double reduction of the subgrade modulus used for pavement design, since the M_R values provided as input to the software are not those obtained at optimum moisture content, but are reduced by the INDOT Geotechnical office to account for the site conditions. A further reduction in M_R is performed within the EICM to account for the moisture conditions at the site.
- Laboratory measurements of the M_R for A-7-6 soils obtained at optimum moisture content give average values ranging between 10,000 psi and 16,000 psi (e.g., see Project SPR-3710 (Park, 2015) (SR-37, Mitchell, Lawrence County, Vincennes)). These values are higher than the reference value of 3,250 psi provided by the INDOT Geotechnical office. Hence, it is necessary to define which condition (i.e., at optimum or reduced) is represented by the value of the resilient modulus given by the Geotechnical Office and/or used as input in the software.
- Current approaches for modeling treated soils neglect the changes in the nature of the soils that arise with treatment (i.e., an A-7-6 soil continues to be modeled as an A-7-6 soil, albeit with a higher modulus, and thus is susceptible to the same reduction in stiffness). Moreover, the values of M_R typically employed for treated A-6 and A-7-6 soils (~9,000 psi, given by the INDOT geotechnical office) fall on the low end of the range reported in the literature (e.g., AASHTO, 2008).

6.3 Recommendations for Modeling of Subgrade

- Three approaches for modeling the subgrade can be adopted:

1. Enable the EICM module and use as input a value of M_R that represents the optimum condition. This value will then be reduced within the EICM to reflect actual site conditions.
2. Disable the EICM module and introduce an input M_R that already accounts for moisture changes and reflects the in situ conditions.
3. Disable the EICM module and introduce an input M_R with seasonal reduction that reflects the in situ conditions.

- Changes of the subgrade M_R due to seasonal variations of the water table, modeled by placing it at 2, 4, 6, and 9 ft below the pavement surface, resulted in an average reduction of ~43% that is almost constant during the four seasons (winter, spring, summer, and fall). Hence, it appears that the third approach, i.e., using seasonal reduction, is less meaningful in Indiana and the first two approaches seem more practical.
- Similar to the subgrade, the M_R input into the MEPDG for the treated layer should be a constant (i.e., not affected by EICM) and with PI and P_{200} values that are representative of the soil after treatment, given that the fines content and plasticity of a chemically treated soil tend to decrease with treatment.

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

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