01 Jan 2010

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Mohamed Attia

Magdy Abdelrahman
Missouri University of Science and Technology, abdelrahmanm@mst.edu

Recommended Citation

M. Attia and M. Abdelrahman, "Variability in Resilient Modulus of Reclaimed Asphalt Pavement as Base Layer and its Impact on Flexible Pavement Performance," *Transportation Research Record*, no. 2167, pp. 18-29, National Research Council (U.S.), Jan 2010.
The definitive version is available at https://doi.org/10.3141/2167-03

Variability in Resilient Modulus of Reclaimed Asphalt Pavement as Base Layer and Its Impact on Flexible Pavement Performance

Mohamed Attia and Magdy Abdelrahman

The use of reclaimed asphalt pavement (RAP) as a base layer is gaining popularity, but there are gaps in the literature about its material performance. One problem not well investigated is the variability in the resilient modulus (M_R) of RAP as a base layer, as compared with typical granular material, and the impact of this variability on pavement performance. Selection of one M_R value has its own variability, beyond the expected variability in the base layer M_R that results from the use of aggregates with different qualities. This paper investigates the effect of three sources of variability to determine the base layer resilient modulus in the laboratory for RAP as compared with granular material. The three sources considered were (*a*) the variability in the material and sample preparation for the M_R testing, (*b*) the constitutive model used to predict the resilient modulus, and (*c*) the state of stress used to predict the base layer modulus. The study compared the variability of the M_R of RAP with the M_R of unbound granular materials on the basis of actual test results. The impact of M_R variability on the flexible pavement distresses for RAP as compared with granular material was investigated using the *Mechanistic–Empirical Pavement Design Guide.*

The use of reclaimed asphalt pavement (RAP) as a base layer is increasing as a result of the scarcity and high cost of quality aggregates. Resilient modulus (M_R) is the basic property that defines the structural capacity of the unbound base layer in the pavement analysis and design process (*1*). It is the property currently used in AASHTO 1986, AASHTO 1993, and in the new *Mechanistic–Empirical Pavement Design Guide* (MEPDG) to define the structural capacity of the base layer. The resilient modulus test is a commonly conducted laboratory test to define the stiffness of the base material (*1–3*). The resilient modulus is defined in Equation 1.

$$M_R = \frac{\sigma_d}{\epsilon_r} \tag{1}$$

Limited work has been conducted to evaluate the variability in the M_R of RAP as a base layer, compared with typical granular material, and the impact of this variability on the predicted pavement distress.

Department of Civil Engineering, North Dakota State University, Department 2470, P.O. Box 6050, Fargo, ND 58108-6050. Corresponding author: M. Abdelrahman, m.abdelrahman@ndsu.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2167, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 18–29.
DOI: 10.3141/2167-03

In 2007, Westover et al. conducted a brief survey of Minnesota's neighboring states and other states that frequently used recycled materials as a base layer (*4*). They found that the use of resilient modulus in design was limited, although considerable research was being conducted. They also found that the departments of transportation (DOTs) of some states assigned one typical value to the granular and recycled materials that they used as a base layer. Michigan's DOT, for example, used 30 ksi as the M_R for a dense-graded base. South Dakota's DOT used 21 ksi for virgin aggregate and 30 ksi for aggregate containing recycled material. This practice needs to be adjusted. To produce a reliable design, designers need to understand for the same material the main factor that affects the M_R of the base layer. A gap exists between DOT practice and the state of the art for determining base layer stiffness. This paper presents the importance of accurate determination of the M_R and the impact of its variability on the predicted pavement distress.

The MEPDG has three levels to define the M_R of the base layer. MEPDG level 1 input makes use of a stress-dependent finite element (FE) to present unbound layer properties, but it has not yet been implemented up to MEPDG V1.0. Currently in the MEPDG only one value can be used to present the M_R of the unbound layer, which can be adjusted within the software for environmental impact. MEPDG level 2 estimates the M_R based on correlations between soil index, strength properties, and resilient modulus. MEPDG level 3 uses a default value for the M_R of the base layer (*5*). Sensitivity analysis for MEPDG models showed that the predicted pavement distresses with MEPDG were affected by base layer modulus and subgrade modulus (*6–9*). Base rut depth and alligator cracking decreased as the base M_R increased (*6–9*). Normally, variability in the M_R of the base layer results from the use of materials that have different qualities. Selection of one M_R value for the same material may, however, contribute to its variability.

The M_R test does not provide one single value for the modulus, because the M_R depends on the state of stress. Determining one single value for M_R includes three main steps: (*a*) conduct the M_R test on a sample representing the field conditions (density and moisture) or at optimum moisture content (OMC) and maximum dry density (MDD), as defined in the lab; (*b*) model the testing results with an appropriate constitutive model; and (*c*) select an appropriate state of stress that presents the stress state within the base layer to define one single modulus for the base layer. The state of stress within the base layer depends on the hot-mix asphalt (HMA) stiffness, asphalt thickness, and subgrade resilient modulus (*1*).

The resilient modulus of granular material is nonlinear and varies with state of stress (*1, 2, 10–14*). Several researchers reported that the M_R depended on the bulk stress (first stress invariant, θ) applied to the sample, as presented in Equation 2 (*2, 12–18*). In reality, most soils are affected by confining pressure and shear stress (*19*). Uzan proposed a model that accounted for the shear stress effects (*2, 11, 13*). A modified form of the Uzan equation is used by the MEPDG as presented in Equation 3 (*5, 7*). Witczak evaluated 14 constitutive models for their capabilities of predicting the resilient behavior of different granular materials (*20*). The author recommended a five-parameter model for its overall goodness-of-fit statistic (*20*). The Witczak model is presented in Equation 4. Many variables should be considered during the selection of one single M_R value to define the stiffness of the base layer.

$$M_R = K_1 \cdot p_a \left(\frac{\theta}{p_a}\right)^{K_2} \tag{2}$$

$$M_R = K_1 \cdot p_a \left(\frac{\theta}{p_a}\right)^{K_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{K_3} \tag{3}$$

$$M_R = K_1 \cdot p_a \cdot \left(\frac{\theta - 3K_4}{p_a}\right)^{K_2} \cdot \left(\frac{\tau_{oct}}{p_a} + K_5\right)^{K_3} \tag{4}$$

where

M_R = resilient modulus,
K_i = multiple regression constants evaluated from resilient modulus tests,
p_a = atmospheric pressure = 14.7 psi (101.5 kPa),
ϵ_R = peak axial resilient strain after 100 loading cycles,
θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3 = \sigma_d + 3\sigma_3$,
σ_3 = confining pressure,
σ_d = peak axial deviator (cyclic) stress after 100 loading cycles, and
τ_{oct} = octahedral shear stress
$= \frac{1}{3}\sqrt{\left\{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2\right\}}$

OBJECTIVES

The present study was to investigate the effect of sources of variability on the resilient modulus of RAP as a base layer as compared with granular material. Three sources of variability were considered in the study: (*a*) from the material and sample preparation, (*b*) from the constitutive model used to predict the resilient modulus, and (*c*) from the state of stress used to predict the modulus of the base layer. The impact of those sources of variability on M_R and the flexible pavement distresses was investigated using the MEPDG for RAP as compared with granular material. The research results offer insights into the most critical elements in the selection of a base layer M_R.

RESEARCH METHODOLOGY

This study used the results of M_R testing on one source of granular material—Minnesota Class 5 (Class 5)—and laboratory blends consisting of 50% RAP + 50% Class 5, 75% RAP + 25% Class 5, and 100% RAP material. The first step was to conduct the M_R test for one sample and a replicate for each material in the laboratory. Both samples were prepared at OMC and MDD. Test results were used to find the regression coefficients for the constitutive models presented in Equations 2–4.

To investigate the effect of variability in M_R prediction as the result of model selection, the M_R value was predicted using three models (Equations 2–4). Because the K-θ model (Equation 2) was the most popular, and the Witczak model was the best-fitting (Equation 4), the M_R predicted from them was used as an input in the MEPDG to investigate the effect of the model selection on the predicted pavement distresses.

NCHRP 1-28A recommends calculating and reporting a summary M_R using the Witczak model for aggregate base materials at $\sigma_3 = 5$ psi and $\sigma_d = 15$ psi (*21*). This was equivalent to a bulk stress of 30 psi. The bulk stress within the base layer varied between 5 and 30 psi for asphalt thickness from 6 in to 2 in; the thicker the asphalt concrete (AC) layer, the lower the bulk stress (*1*). To investigate the effect of stress on M_R variability and hence on predicted distress, the M_R at different states of stress {($\sigma_3 = 5$ psi and $\sigma_d = 15$ psi) and ($\sigma_3 = 2$ psi and $\sigma_d = 4$ psi)} was compared with the predicted M_R values for different materials. High bulk stress was defined as $\sigma_3 = 5$ psi and $\sigma_d = 15$ psi after Witczak (*21*) and was equivalent to 30 psi, which placed it within the base layer suggested in the literature (*1*). Low bulk stress within the base layer was defined as $\sigma_3 = 2$ psi and $\sigma_d = 4$ psi and was equivalent to 10 psi. Analysis was done using Kenlayer software (*1*) for different sections. The low-bulk stress case presented stresses at the middle of the base layer under single-axle, single-tire loading, with a tire pressure of 80 psi, an asphalt layer 6 in. thick, and an HMA stiffness of 600 ksi.

The effect was investigated of the selected M_R on asphalt layer rutting, base rutting, subgrade rutting, international roughness index (IRI), and alligator cracking. The variation in the resilient modulus was defined by Equation 5. The variation of the predicted distress was defined by Equation 6. The change in the predicted pavement life was defined by Equation 7. The change of pavement life at 90% reliability was used to present the impact of resilient modulus variation on pavement performance. The failure criteria were alligator cracking that exceeded 18% of the area, IRI that exceeded 160 in. per mile, and total rutting that exceeded 0.75 in. at the reliability level.

$$\text{percent MR change or variability} = \left|\frac{M_R \text{ of reference case} - M_R \text{ of analyzed case}}{M_R \text{ of reference case}}\right| * 100 \tag{5}$$

$$\text{percent distress change or variability} = \left|\frac{\text{distress of reference case} - \text{distress of analyzed case}}{\text{distress of reference case}}\right| * 100 \tag{6}$$

$$\text{change of pavement life} = \left[\text{pavement age (reference case)} - \text{pavement age (analyzed case)}\right] \tag{7}$$

The M_R of the reference case is equal to the M_R calculated on the basis of the Witczak model and on sample 1, as illustrated in Tables 1 and 2. The distress of reference case is the distress after 20 years, calculated on the basis of reference M_R. The research methodology and the cases used in the MEPDG are presented in Figure 1. Table 1 presents the input data for all the cases used in the MEPDG analysis.

EXPERIMENTAL CONSIDERATIONS

The M_R samples were prepared by using a gyratory compactor at OMC and MDD. The OMC and MDD were determined by the gyratory compactor at 50 gyrations, 600 kPa, 30 revolutions per min, and

TABLE 1 Variables Used in MEPDG Analysis

Parameter	Variables	Source of Data
Traffic	Traffic volume AADTT (vehicle/day) 1,000 (medium traffic) 7,000 (high traffic)	Witczak et al. (*7*)
HMA	Thickness[a] 2 in. 6 in.	The 2 in. was analyzed only for the medium traffic
Base layer material	Class 5 (0% RAP) M_R = 28,540[b] M_R = 24,971[c] M_R = 12,700[d] M_R = 24,100[e] 50% RAP M_R = 42,232[b] M_R = 35,940[c] M_R = 23,400[d] M_R = 43,900[e] 75% RAP M_R = 37,200[b] M_R = 31,600[c] M_R = 19,800[d] M_R = 37,700[e] 100% RAP M_R = 59,500[b] M_R = 48,500[c] M_R = 33,600[d] M_R = 60,100[e]	Predicted by different models at different states of stresses based on data from laboratory testing

NOTE: AADTT = average annual daily truck traffic; HMA = hot mix asphalt layer; GWT = ground water table height from pavement surface.
[a]Arbitrary selected thicknesses to present thin and thick AC layer.
[b]State of stress: σ_3 = 5 psi and σ_d = 15 psi, calculated using K-θ model, Sample 1 results.
[c]State of stress: σ_3 = 5 psi and σ_d = 15 psi, calculated using Witczak model, Sample 1 results (reference case for each material).
[d]State of stress: σ_3 = 2 psi and σ_d = 4 psi, calculated using Witczak model, Sample 1 results.
[e]State of stress: σ_3 = 5 psi and σ_d = 15 psi, calculated using Witczak model, Sample 2 results.

1.25 angle of gyration. This procedure was recommended in the literature for RAP aggregate blends (*3, 22*). More details about testing can be found in Mallick et al. (*23*).

The M_R test was conducted immediately after sample compaction. The sample was subjected to 1,000 load cycles for preconditioning followed by 30 load sequences as specified by NCHRP 1-28A protocol, procedure 1A (*21*). The resilient modulus test was conducted inside a triaxial pressure chamber, capable of maintaining the required confining pressure. Air was used as the confining fluid. The axial deformation was measured internally using three linear variable differential transducers (LVDTs). A closed-loop electrohydraulic materials testing machine was used to apply repeated cycles of a haversine-shaped load pulse. Each pulse had a 0.1-s loading duration followed by a rest period of 0.9 s. The axial load was measured with a 5,000-lb electronic load cell, located inside the triaxial chamber.

EFFECT OF DIFFERENT SOURCES OF VARIABILITY ON THE PREDICTED M_R

For each material, one resilient modulus test and a replicate were conducted at the OMC and MDD. Figure 2 presents the resilient modulus testing results, with the coefficient of variation (COV) between the two samples of each material. The procedure for calculating COV is presented in Equations 8 and 9.

$$\text{COV}_i = \frac{\text{Stdev}_i}{\text{average}_i} * 100 \tag{8}$$

$$\text{COV} = \text{average}\left(\text{COV}_i\right) \tag{9}$$

where

average = average of M_R for two samples at same sequence i of M_R test,
Stdev_i = standard deviation of M_R for two samples at same sequence i of M_R test,
COV_i = coefficient of variation at test sequence i, and
COV = average coefficient of variation for material.

Class 5 had the lowest average COV of 7% between samples at different states of stress. The 75% RAP samples had an average COV of 11%. The 50% RAP and the 100% RAP samples had an average COV of 14%. Figure 2 shows that all RAP and aggregate blends had a higher M_R than did Class 5 material. The resilient moduli of RAP samples did not relate well to the bulk stress. R^2 for the power relation between bulk stress and M_R varied from 0.56 to 0.72 for RAP and aggregate blends, whereas it was 0.87 for Class 5 material. RAP samples had little shear softening, whereas

TABLE 2 MEPDG Data Input for All Analyzed Cases

Parameter	Variables		Source of Data
Traffic	Other traffic parameters	Default MEPDG Level 3	
Climate	Location GWT height	Minneapolis–St. Paul airport 2 ft	Witczak et al. (*7*)
HMA	Air voids Effective binder content VFA (%) % retained ¾″ % retained ⅜″ % retained #4 % passing #200 PG grade Other HMA parameters	7% 11% 61% 11 35 52 7 58-28 Default MEPDG Level 3	Medium mix (*7*)
Base	Thickness	12 in.	Selected typical value
Subgrade	M_R PI	15,000 psi 16	Medium subgrade support (*7*)

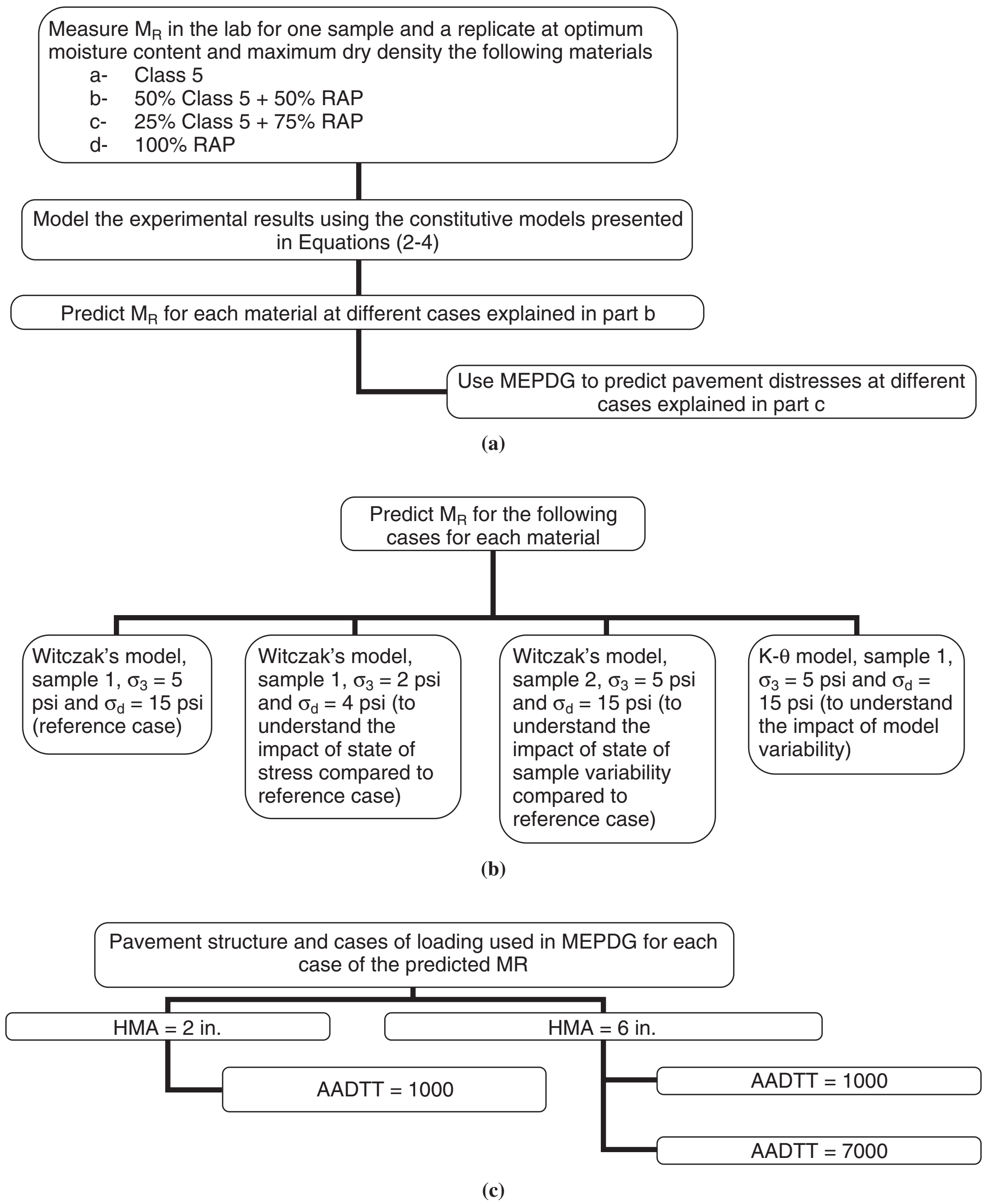

FIGURE 1 Research methodology.

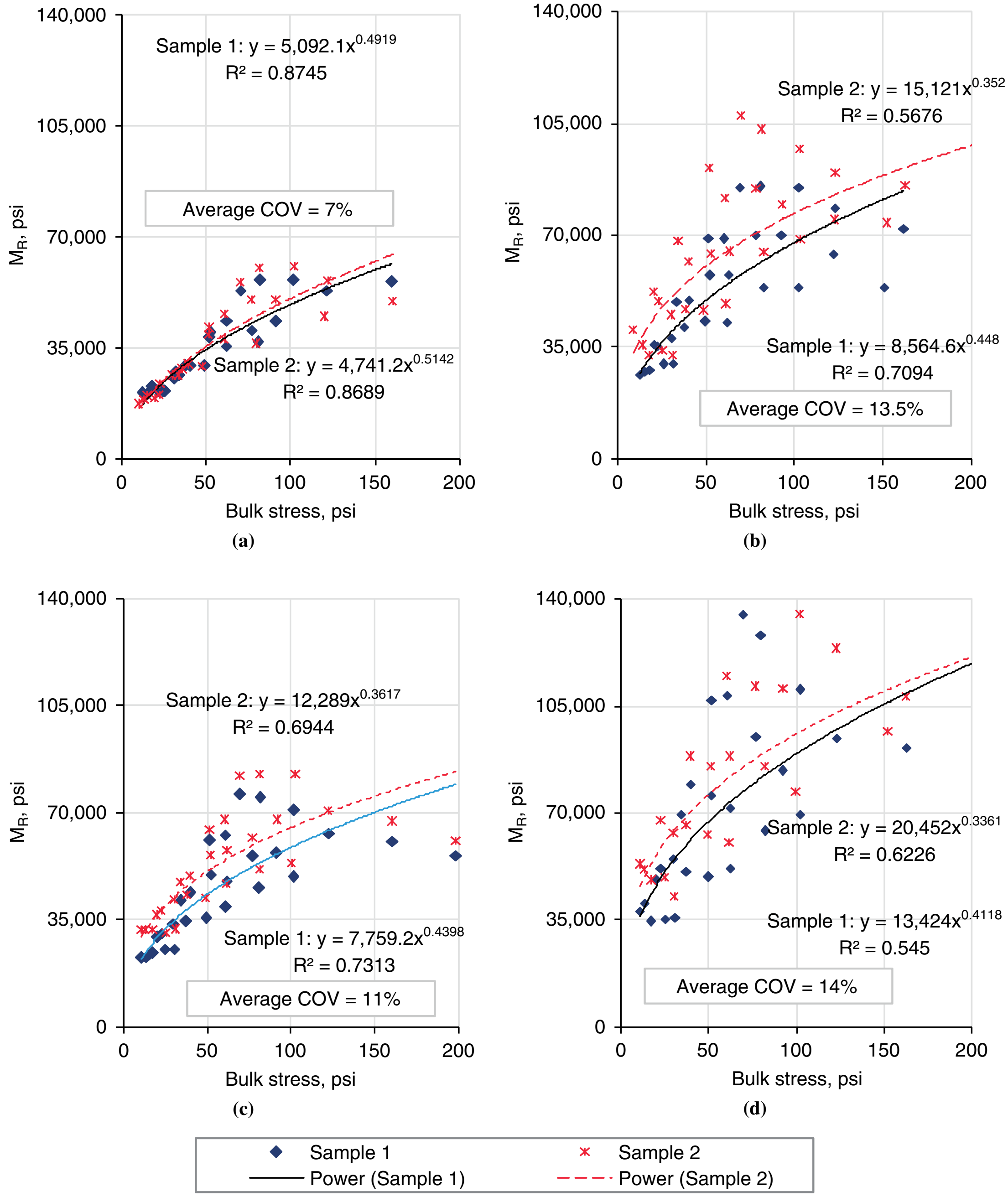

FIGURE 2 Resilient modulus versus bulk stress: (*a*) Class 5, (*b*) 50% RAP, (*c*) 75% RAP, and (*d*) 100% RAP.

the K-θ model was appropriate for material with strain-hardening behavior.

Figure 3 shows the predicted M_R for the evaluated materials, based on three constitutive models at two states of stress. The variability in testing caused M_R to vary by 4% for Class 5 material and by 26% for 50% RAP material. These percentages were calculated by using Equation 5. The use of different constitutive models caused 14% to 17% variation in the M_R. For the investigated samples, the K-θ model overestimated the M_R at the high bulk stress. The variation of the state of stress caused 34% to 50% variation in the M_R. The variation was higher in Class 5 material. The selected state of stress had the highest impact on the M_R. How such variation could affect predicted pavement distress is discussed in the following sections.

EFFECT OF M_R VARIABILITY ON ALLIGATOR CRACKING

Fatigue failure results from elastic deflection in the pavement component (*24*). Fatigue cracking (alligator cracking), as a percent of wheel path area, is assumed to depend on the tensile strains at the bottom of the bound layers and, consequently, on all conditions

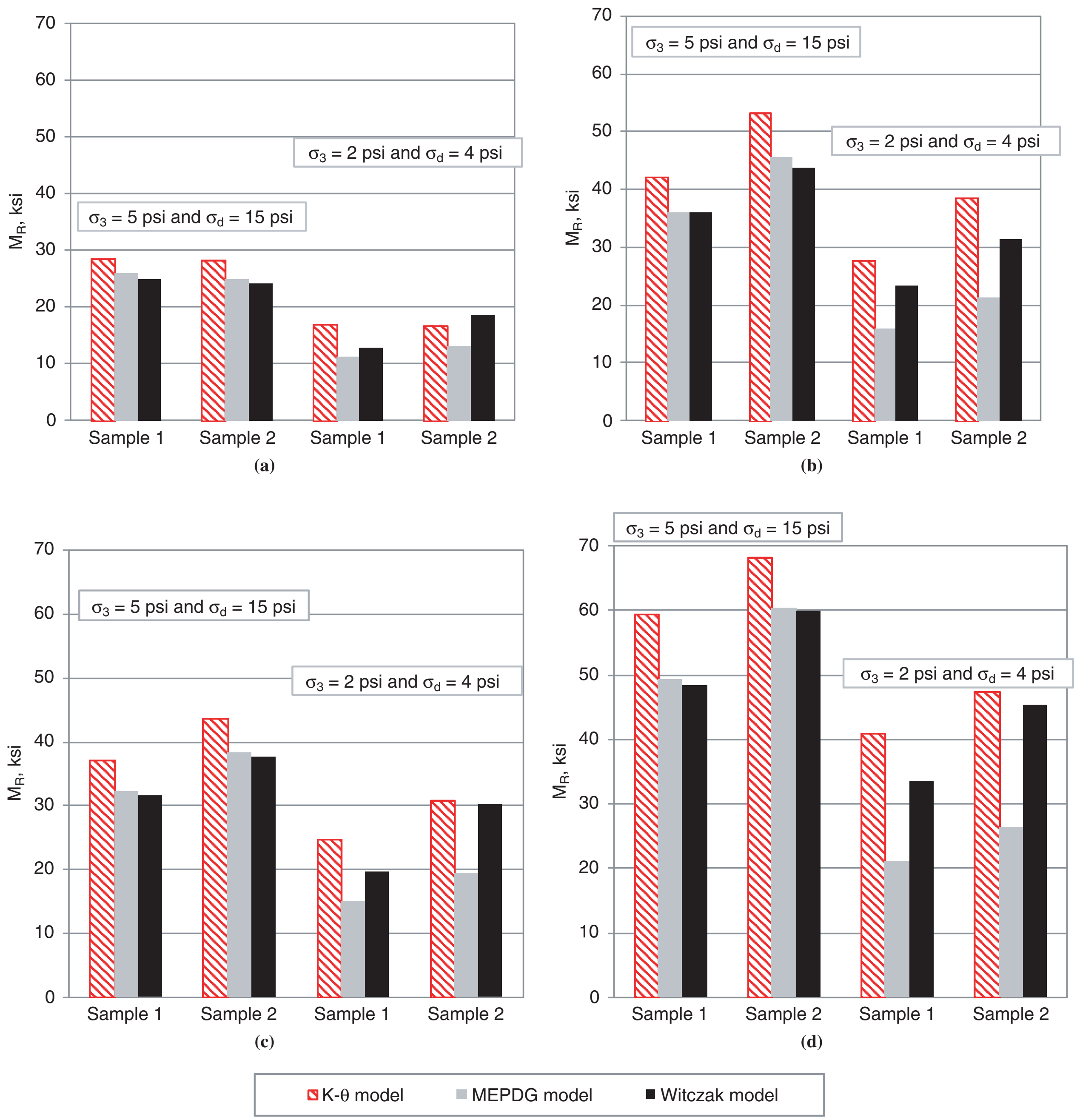

FIGURE 3 Comparison between predicted M_R by different models at two states of stress for one sample and a replicate: (*a*) Class 5; (*b*) 50% RAP + 50% Class 5; (*c*) 75% RAP + 25% Class 5; and (*d*) 100% RAP.

affecting this pavement response (*25*). NCHRP 1-37A has documented that alligator cracking is sensitive to the subgrade layer modulus. The analysis was conducted only for AC at a thickness of 4 in (*6*).

Figure 4 shows that alligator cracking is highly sensitive to base layer M_R. For thick pavement, 1% variation in base layer M_R was reflected as 2% variation in alligator cracking. For thin pavement, the effect of M_R variability was similar to that of thick pavement, as the variability of M_R was less than 25%. As the variability of M_R increased, however, the effect on alligator cracking increased rapidly: a 50% variation in base layer M_R resulted in a 500% variation in predicted alligator cracking (Figure 4*a*). The level of traffic did not have an effect on the variability produced. Whether heavy truck traffic [average annual daily truck traffic (AADTT) = 7,000] or medium truck traffic (AADTT = 1,000) was used, the resulting error as a percentage of the predicted distress was found to be the same.

An attempt to distinguish the variability caused by each source is shown in Figure 4*b* and *c*. Variability caused by a state of stress had the greatest impact on M_R. It also had the greatest impact on alligator cracking. The sample variability had limited impact on the M_R

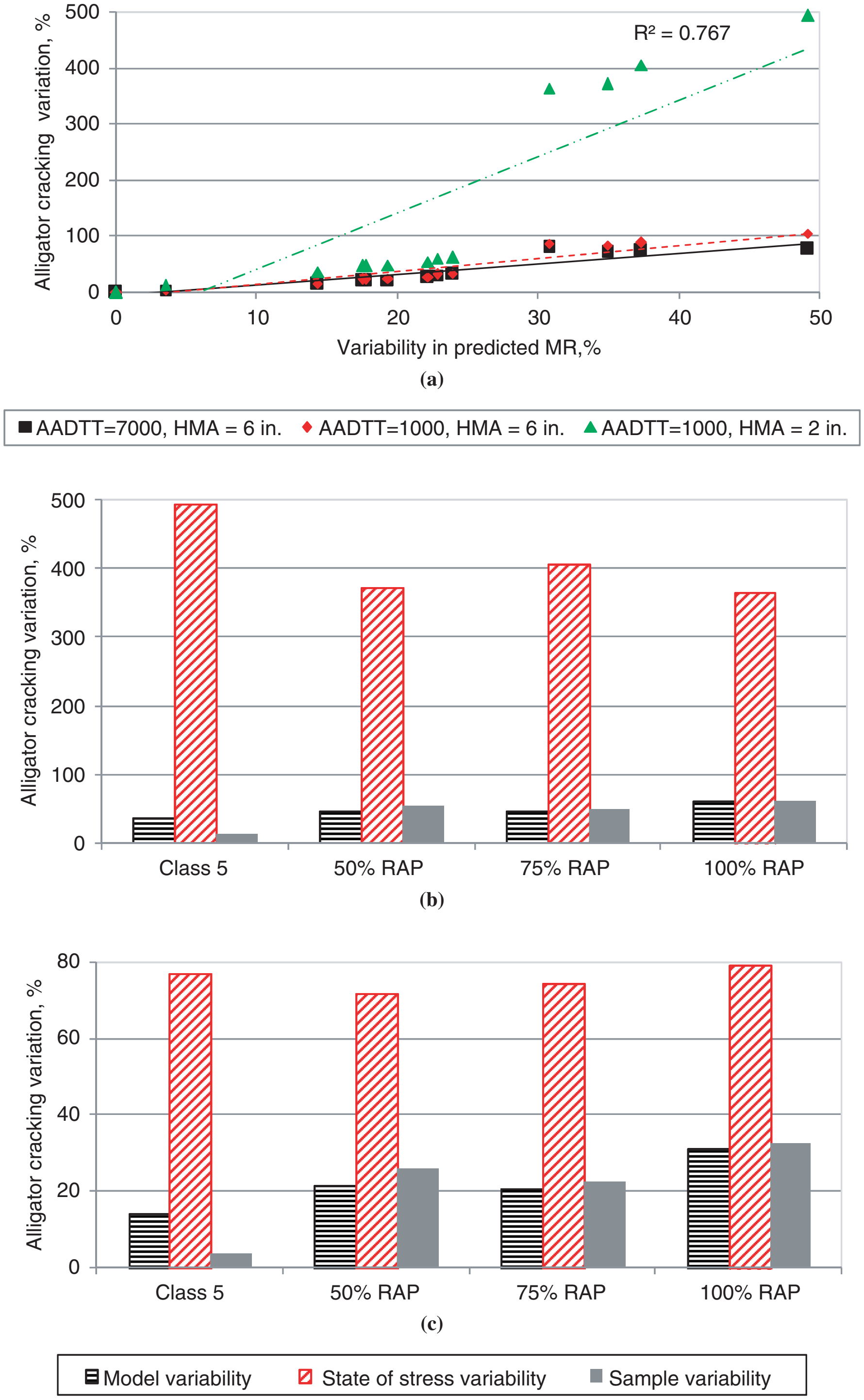

FIGURE 4 Effect of M_R variability on alligator cracking: (*a*) alligator cracking variability; (*b*) thin AC layer (HMA = 2 in., AADTT = 1,000); and (*c*) thick AC layer (HMA = 6 in., AADTT = 7,000).

for Class 5, and no apparent impact on alligator cracking. For RAP and aggregate blends, it caused a 50% to 60% variation in predicted alligator cracking in thin AC pavement, and a 20% to 30% variation in thick AC pavement. All the variations were calculated as a percentage of a reference value. Arguably this variation as a difference in alligator cracking was insignificant, for thin pavement alligator cracking varied from 1% to 6%. Considering the reliability of the design, however, the ratio reflects the error that would be introduced as the result of variation in the base layer modulus.

Change of pavement life at failure was another way to quantify the impact of different sources of M_R variability on pavement performance. The failure criterion selected was that alligator cracking exceeded 18% of the area at 90% reliability. It was reported that the number of load repetitions to failure on the basis of fatigue cracking for flexible pavement (following the asphalt institute method) resulted in 20% fatigue cracking in the total area as observed on AASHO Road test (*1*). Some of the sections that underwent comparison did not reach 20% fatigue after 20 years (the period of analysis used in the MEPDG) at the reliability level. The failure criterion was reduced to 18% to compare sectional behavior without the need to extrapolate the MEPDG results. Figure 5 presents the results of the analysis and shows that error in the state of stress can cause a variation of up to 7 years in the predicted pavement life of thin pavement and up to 5 years in thick pavement. Results also show that sample variability in Class 5 had negligible impact on pavement life, whereas pavement variability for RAP samples caused about 4 years of variation in predicted pavement life.

Analysis showed that alligator cracking was highly sensitive to base layer M_R and that thin pavement was more sensitive to the base layer modulus than was thick pavement. The impact of base layer M_R on alligator cracking of thin AC pavement can be explained. For thin AC pavement, major structural capacity is gained from the underlying layers, which will affect the tensile strains at the bottom of the AC layer. The tensile strain at the bottom of the AC layer controls the development of the alligator cracking (bottom-up fatigue). The nonlinearity of the effect of base layer M_R variability on the alligator cracking can be understood by investigating the alligator cracking model within MEPDG. The MEPDG alligator cracking model calculates the number of load repetitions to failure, calculates the percentage of damage after a specific number of load repetitions, and uses a function to transfer the damage into the percentage of the area that will experience alligator cracking. All models used

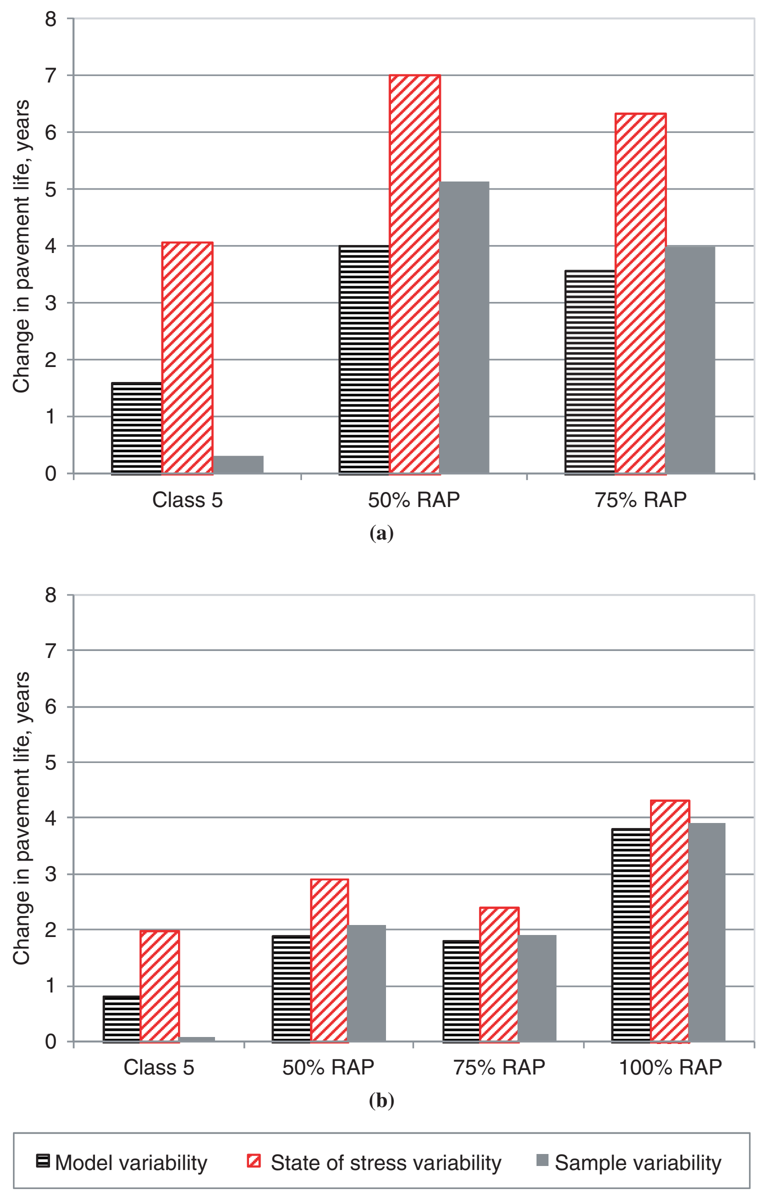

FIGURE 5 Change in pavement life based on alligator cracking criterion: (*a*) thin AC layer (HMA = 2 in., AADTT = 1,000); and (*b*) thick AC layer (HMA = 6 in., AADTT = 7,000).

during those steps were nonlinear. Default calibration factors based on the MEPDG national calibration were used in this analysis (i.e., the number of load repetitions up to failure was a function of the tensile strain to the power of −3.9), which means that a 10% variation in the tensile strain at the bottom of the AC layer would change the number of load repetitions to failure by 50%.

EFFECT OF M_R VARIABILITY ON RUTTING AND IRI

The effect of the base layer quality on AC rutting, base rutting, and subgrade rutting was investigated in the literature (*7–9*). The effect of the base modulus on the AC rutting was reported as small. Base rut depth decreased as the base quality increased. Limited impact of the base layer modulus on subgrade rutting has been reported (*7–9*).

Figure 6 presents the variability in pavement rutting as a result of base layer variability. For thick pavement, a 50% variation in the base layer M_R was reflected as a 4% variation in the AC rutting. For thin pavement, a 50% variation in the base layer M_R was reflected as a 40% variation in the AC rutting (Figure 6*a*). Base rutting variability results are presented in Figure 6*b.* For thin and thick pavement, a 50% variation in base layer M_R was reflected as a 45% and a 60% variation in base rutting, respectively. The subgrade rutting was not sensitive to variability in base layer modulus. For thin and thick pavement, a 50% variation in the base layer M_R was reflected as a 10% variation in subgrade rutting (Figure 6*c*). This finding agrees with the

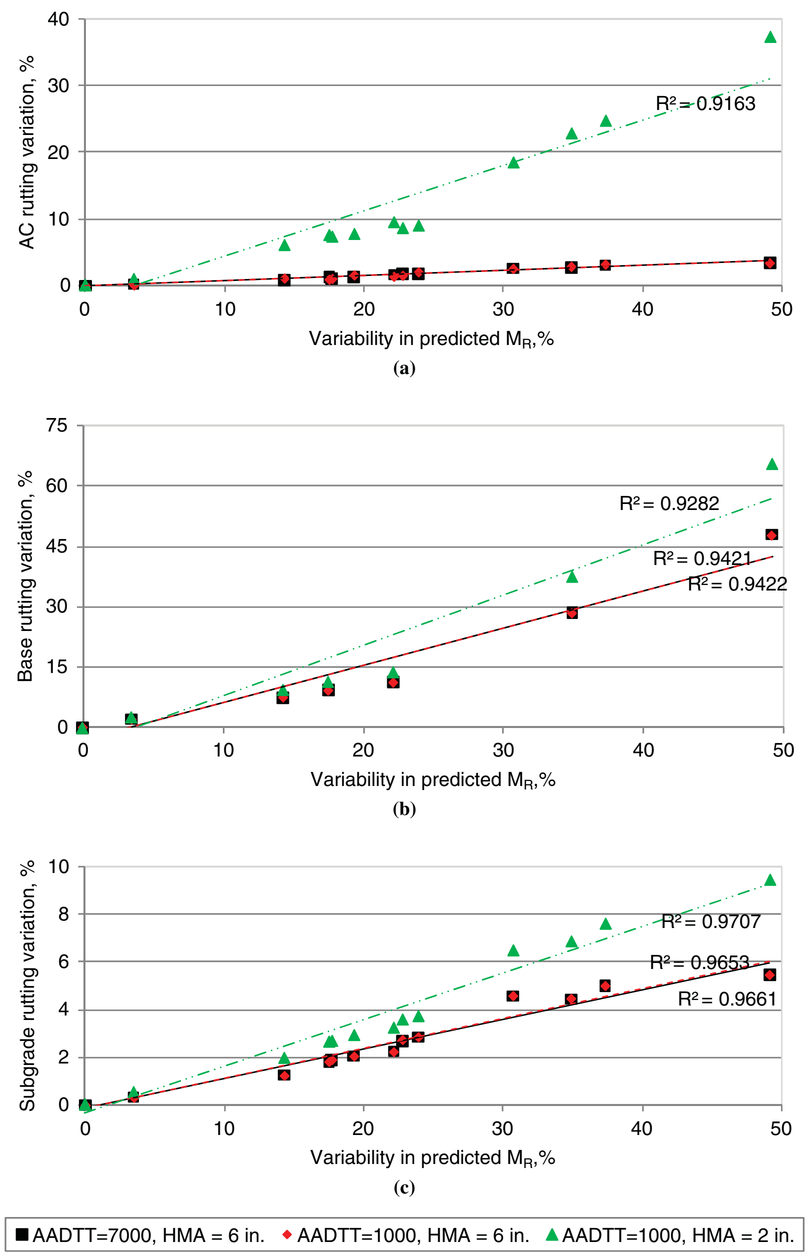

FIGURE 6 Variability in pavement rutting as a result of base layer M_R variability: (*a*) AC rutting variability, (*b*) base rutting variability, and (*c*) subgrade rutting variability.

literature. It was reported that a variation from 20 ksi to 50 ksi in base layer M_R did not have a significant impact on subgrade rutting (*7*).

The impact of each source of variability was considered for its effect on the total rutting. The impact was assessed by evaluating the change in pavement life up to failure as a result of the change in the M_R. The selected failure criterion was 0.75 in. of total rutting at 90% reliability, which was the default total rutting failure criterion in the MEPDG and similar to the Shell permanent deformation failure criterion of 0.7 in. (*1*). Figure 7 presents part of the analysis results. Variability caused by state of stress had the greatest impact on M_R and on total rutting. In thin AC pavement, the variability from state of stress caused 2.5 years to 5.5 years of variation in the predicted pavement life for different materials, with a high variation in RAP (a result of a 30% to 40% variation in M_R.) Sampling variability had changed the predicted pavement life for RAP material by 2.8 years to 4 years, whereas it had a negligible effect on Class 5. The effect of base layer variability can be ignored in thick pavement (based on rutting criterion). All sources of variability caused about 1 year of variability in pavement life in thick AC pavement (Figure 7*b*).

The impact of each source of variability on the IRI was analyzed. The impact of M_R variability on IRI was assessed by evaluating the change in pavement life up to failure as a result of the change in base layer modulus. The selected failure criterion was 160 in. per mile at 90% reliability. This failure criterion was equivalent to a pavement serviceability rating (PSR) of 2.6 based on the relationship between IRI and PSR developed by Al-Omri and Darter (*26*). Figure 8 presents partial results of the analysis. Thin AC pavement was more sensitive to base stiffness than thick AC pavement. For thin pavement, the

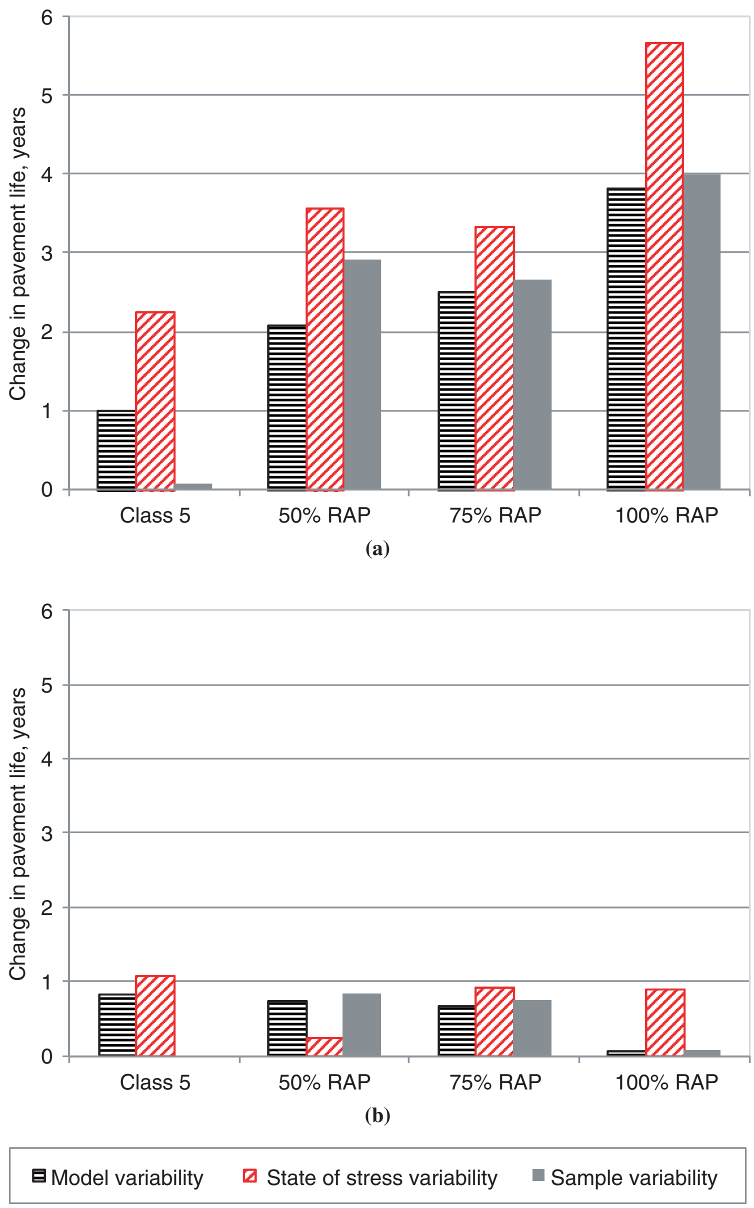

FIGURE 7 Change in pavement life based on total rutting criterion: (*a*) thin AC layer (HMA = 2 in., AADTT = 1,000); and (*b*) thick AC layer (HMA = 6 in., AADTT = 7,000).

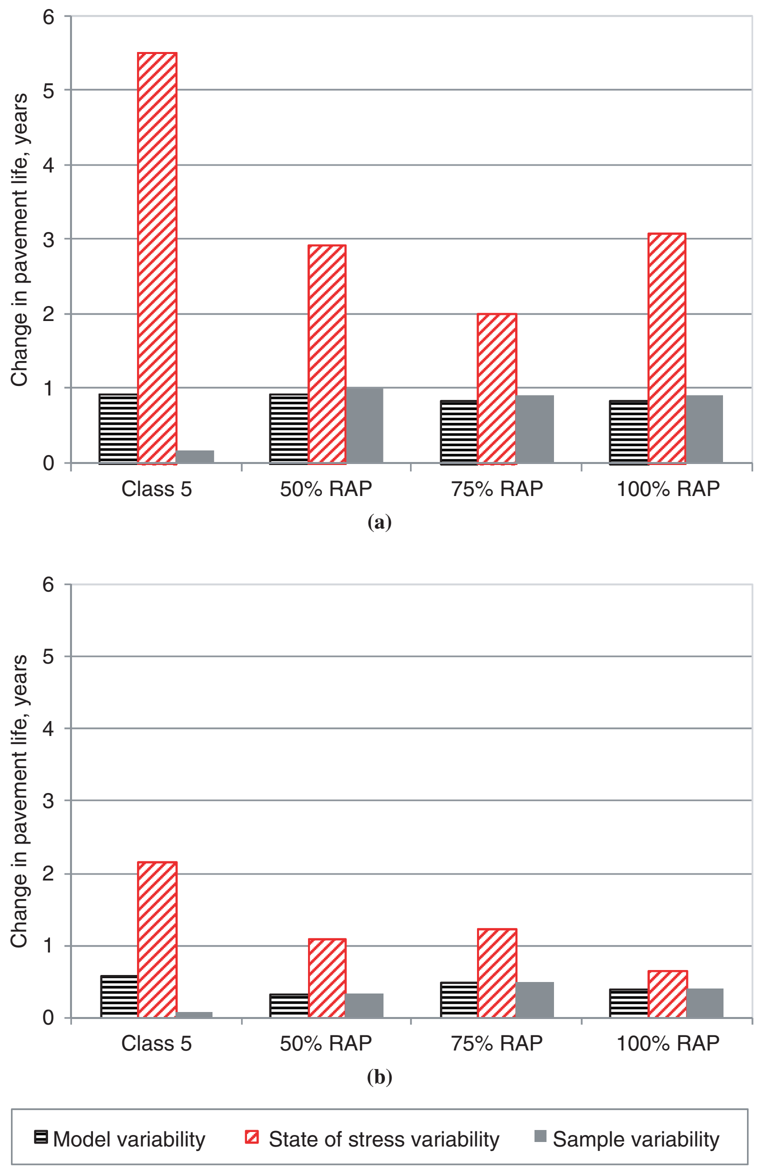

FIGURE 8 Change in pavement life based on IRI criterion: (*a*) thin AC layer (HMA = 2 in., AADTT = 1,000); and (*b*) thick AC layer (HMA = 6 in., AADTT = 7,000).

variation of state of stress caused variations from 2 years to 5.5 years in predicted pavement life. Variability in M_R caused by sample variability and model selection had no impact on the IRI for all materials; there was less than 1 year of variation in pavement life for both thin and thick AC pavement.

DISCUSSION AND CONCLUSIONS

This paper investigated the effects of three sources of variability in determining in the laboratory the base layer resilient modulus for RAP as compared with granular material. The three sources of variability were (*a*) the material and sample preparation for the M_R test, (*b*) the constitutive model used to predict the resilient modulus, and (*c*) the state of stress used to predict the base layer modulus. On the basis of actual test results, the study compared the M_R variability of RAP with that of unbound granular materials. The impact of M_R variability on flexible pavement performance for RAP as opposed to granular material was investigated by using the MEPDG. The selected state of stress was found to be the most critical element to affect the base layer M_R and hence predicted pavement distress. The MEPDG needs to include guidelines to define the state of stress to calculate the M_R to be used during analysis, unless and until the nonlinear, stress-dependent FE module is implemented. The variability in the state of stress caused as much as a 50% variation in the predicted M_R. This variation caused in some cases as many as 7 years of difference in the predicted pavement life.

The effect of the constitutive model used to predict M_R value caused moderate changes in the predicted modulus and hence in the predicted pavement distress. The predicted pavement life varied as much as 4 years as a result of differences in the constitutive model used to present the modulus of the material. This effect could be reduced by using a model that fits the testing results for each material. Models like Witczak's are more relevant than the K-θ model.

Sample variability had less impact on the resilient modulus than the other two factors. This effect can be ignored for Class 5. For RAP material, however, sample variability had a clear impact on pavement performance; it caused as many as 4 years of variation in predicted pavement life.

Base layer M_R variability had more impact on thin AC pavement than on thick. Alligator cracking was more sensitive to the change in M_R than rutting was. The difference of the predicted M_R under two states of stress reflected a difference of 10% to 500% on predicted alligator cracking and a difference of 3 to 7 years on the life expectancy of different pavement sections.

The results of this research indicate the importance of accurately defining the base layer resilient modulus throughout its study—from accurate testing to proper modeling to accurate selection of the state of stress to be incorporated into the analysis. This conclusion pertains to virgin and recycled material used as a base layer.

ACKNOWLEDGMENTS

The authors acknowledge the Minnesota Department of Transportation and the National Science Foundation for their partial support of this research. This material is based on work supported by the National Science Foundation.

REFERENCES

1. Huang, Y. *Pavement Analysis and Design.* Prentice Hall, Inc., Englewood Cliffs, N.J., 1993.
2. Lekarp, F., U. Isacsson, and A. R. Dawson. State of the Art. I: Resilient Response of Unbound Aggregates. *Journal of Transportation Engineering,* Vol. 126, No. 1, Jan.–Feb. 2000, pp. 66–75.
3. Kim, W., and J. F. Labuz. Resilient Modulus and Strength of Base Course with Recycled Bituminous. Minnesota Department of Transportation, Report MN/RC-2007-05, Jan. 2007.
4. Westover, T. M., J. F. Labuz, and B. B. Guzina. Resilient Modulus Development of Aggregate Base and Subbase Containing Recycled Bituminous and Concrete for 2002 Design Guide and Mn/Pave Pavement Design. Minnesota Department of Transportation, Report MN/RC-2007-25, Jan. 2007. http://www.lrrb.org/PDF/200725.pdf. Accessed July 2009.
5. ARA, Inc., ERES Consultants Division. *Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures. Part 2. Design Inputs.* Final report, NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, D.C., 2004. http://www.trb.org/mepdg/Part2_Chapter2_Materials.pdf. Accessed July 2008.
6. Witczak, M. W., M. M. El-Basyouny, and S. El-Badawy. *Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures.* Appendix II-2: Sensitivity Analysis for Asphalt Concrete Fatigue Alligator Cracking. Transportation Research Board of the National Academies, Washington, D.C., 2004.
7. Witczak, M. W., M. M. El-Basyouny, and S. El-Badawy. *Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures.* Appendix GG-2: Sensitivity Analysis for Permanent Deformation for Flexible Pavements. Transportation Research Board of the National Academies, Washington, D.C., 2004. http://www.trb.org/mepdg/2appendices_GG.pdf. Accessed July, 2008.
8. Ceylan, H., S. Kim, M. Heitzman, and K. Gopalakrishnan. Sensitivity Study of Iowa Flexible Pavements Using the Mechanistic–Empirical Pavement Design Guide. Presented at 85th Annual Meeting of the Transportation Research Board. Washington, D.C., 2006.
9. Masad, S. A. Sensitivity Analysis of Flexible Pavement Response and AASHTO 2002 Design Guide for Properties of Unbound Layers. Master's thesis. Texas A&M University, May 2004.
10. Kim, M., and E. Tutumluer. Nonlinear Pavement Foundation Modeling for Three-Dimensional Finite Element Analysis of Flexible Pavements. Presented at 86th Annual Meeting of the Transportation Research Board. Washington, D.C., 2007.
11. Tutumluer, E., and R. W. Meier. Attempt at Resilient Modulus Modeling Using Artificial Neural Networks. In *Transportation Research Record 1540,* TRB, National Research Council, Washington, D.C., 1996, pp. 1–6.
12. Hicks, R. G., and C. L. Monismith. Factors Influencing the Resilient Properties of Granular Materials. In *Highway Research Record 345,* HRB, National Research Council, Washington, D.C., 1971, pp. 15–31.
13. Uzan, J. Characterization of Granular Materials. In *Transportation Research Record 1022,* TRB, National Research Council, Washington, D.C., 1985, pp. 52–59.
14. Santha, B. L. Resilient Modulus of Subgrade Soils: Comparison of Two Constitutive Equations. In *Transportation Research Record 1462,* TRB, National Research Council, Washington, D.C., 1994, pp. 79–90.
15. Witczak, M. W., and J. Uzan. *The Universal Airport Pavement Design System. Report I of V: Granular Material Characterization.* Department of Civil Engineering, University of Maryland, College Park, 1988.
16. Rada, G., and M. W. Witczak. Comprehensive Evaluation of Laboratory Resilient Moduli Results for Granular Material. In *Transportation Research Record 810,* TRB, National Research Council, Washington, D.C., 1981, pp. 23–33.
17. Wen, H., J. Warner, and T. B. Edil. Laboratory Comparison of Crushed Aggregate and Recycled Pavement Material with and Without High-Carbon Fly Ash. Presented at 87th Annual Meeting of the Transportation Research Board. Washington, D.C., 2008.
18. Garg, N., and M. R. Thompson. Lincoln Avenue Reclaimed Asphalt Pavement Base Project. In *Transportation Research Record 1547,* TRB, National Research Council, Washington, D.C., 1996, pp. 89–95.
19. Andrei, D., M. W. Witczak, C. W. Schwartz, and J. Uzan. Harmonized Resilient Modulus Test Method for Unbound Pavement Materials. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1874,* Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 29–37.
20. Witczak, M. W. Harmonized Test Methods for Laboratory Determination of Resilient Modulus For Flexible Pavement Design. Project No. NCHRP 1-28A, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, May 2003.
21. Witczak, M. W. *Research Results Digest 285: Laboratory Determination of Resilient Modulus for Flexible Pavement Design.* TRB, National Research Council, Jan. 2004. http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rrd_285.pdf. Accessed July 2008.
22. Mallick, R., P. Kandhal, E. Brown, R. Bradbury, and E. Kearney. Development of a Rational and Practical Mix Design System for Full Depth Reclaimed (FDR) Mixes. Final Report, Project (Subcontract 00-373). Recycled Materials Resource Center, University of New Hampshire, 2002.
23. Attia, M., M. Abdelrahman, and T. Alam. Investigation of Stripping in Minnesota Class 7 (RAP) and Full-Depth Reclamation Base Materials. Minnesota Department of Transportation, Report MN/RC-2009-05, Jan. 2009. http://www.lrrb.org/PDF/200905.pdf. Accessed June 2009.
24. Seed, H. B., C. K. Chan., and C. E. Lee. Resilience characteristics of subgrade soils and their relation to fatigue failures in asphalt pavement. *Proc., 1st International Conference on Structural Design of Asphalt Pavements,* University of Michigan, Ann Arbor, 1962.
25. Mallela, J., M. Ayres, L. Khazanovich, C. Rao, L. Titus-Glover, M. Witczak, and M. Darter. *Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures.* Appendix BB: Design Reliability. Transportation Research Board of the National Academies, Washington, D.C., 2004. http://www.trb.org/mepdg/2appendices_bb.pdf. Accessed July 2009.
26. Al-Omri, B., and M. I. Darter. Relationships Between International Roughness Index and Present Serviceability Rating. In *Transportation Research Record 1435,* TRB, National Research Council, Washington, D.C., 1994, pp. 130–136.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

The Mineral Aggregates Committee peer-reviewed this paper.