Effects of Asphalt Mixture Properties on Permanent Deformation Response

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The hot-mix asphalt (HMA) rutting prediction model in the *Mechanistic–Empirical Pavement Design Guide* (MEPDG) uses a relationship that includes the effects of mix characteristics only through the resilient strain, which in turn is a function of the dynamic modulus ($|E^*|$) of the mix. However, increasing evidence suggests that the use of $|E^*|$ alone may be insufficient to characterize completely the permanent deformation behavior of HMA. In addition to effects already considered by the MEPDG model with $|E^*|$, the effects of mix characteristics on permanent deformation are analyzed with the use of the results of repetitive axial permanent deformation tests from laboratory-compacted HMA specimens. Results of multiple linear regression analysis indicate that binder type, effective binder content, and air void content have significant effects on model parameters for permanent deformation. The potential effects of mix characteristics on these parameters are analyzed with the use of the MEPDG model and an HMA pavement section with four levels of compaction. Scenarios in which the mixture characteristics are incorporated solely by means of $|E^*|$ are compared with scenarios in which the effects of air void content and asphalt content are incorporated into the rutting prediction model by adjusting its parameters according to relationships established in the laboratory. Empirical laboratory evidence supports the hypotheses that, regardless of mixture properties, universal values for permanent deformation model parameters do not fully account for mixture-specific contributions to rutting and that other mix characteristics (e.g., air void content) may be needed to supplement $|E^*|$ for the appropriate characterization of the permanent deformation of asphalt mixtures.

In the *Mechanistic–Empirical Pavement Design Guide* (MEPDG) model, the contribution of each layer is considered in computing permanent deformation (*1*). In particular, for hot-mix asphalt (HMA) layers, a relationship is used that includes the effects of mix characteristics only through the resilient strain, which in turn is a function of the dynamic modulus ($|E^*|$) of the HMA. However, increasing evidence suggests that the use of $|E^*|$ alone may be insufficient to completely characterize the permanent deformation behavior of HMA.

In addition to effects already considered by the MEPDG model through $|E^*|$, the effects of mix characteristics on permanent deformation are analyzed by using repetitive axial permanent deformation test results from laboratory-compacted HMA specimens. A clear understanding of the potential effects of mixture characteristics on parameters in the rutting prediction model incorporated into the MEPDG model would greatly enhance the model's acceptance and widespread implementation while significantly contributing to local calibration efforts.

BACKGROUND

In the MEPDG model, the prediction of permanent deformation uses results from both the dynamic modulus test ($|E^*|$) and repeated axial load tests. However, their use is asymmetric in the sense that project-specific $|E^*|$ values can be considered (measured or as a function of other mix properties), whereas the permanent deformation parameters enter only through the permanent deformation model, which is calibrated to local conditions at best. It is assumed that the effects of mixture properties such as air void content, effective binder content, and binder grade are already adequately incorporated into the permanent deformation simulation through $|E^*|$ values.

Different models trying to characterize the permanent deformation behavior of HMA have been developed and are reported in the literature (*2–4*). The model adopted for further field calibration in the MEPDG model for predicting rutting performance is essentially a modified power model, expressed in the form

$$\frac{\epsilon_p}{\epsilon_r} = 10^{k_1} T^{k_2} N^{k_3} \tag{1}$$

where

ϵ_p = permanent strain,
ϵ_r = resilient strain (calculated using the measured or estimated dynamic modulus of the mixture at the stress state corresponding to the permanent deformation test),
T = test temperature (°F),
N = number of load repetitions to reach ϵ_p, and
k_1, k_2, and k_3 = model parameters.

To calibrate the model in Equation 1 to actual field conditions, incorporated parameters include β_1, β_2, and β_3 (which multiply 10^{k_1}, k_2, and k_3, respectively) and a parameter to account for the effect of HMA thickness on the MEPDG rutting estimation.

The model in Equation 1 is based on the efforts of Leahy, who found that mixture properties such as binder viscosity, effective binder content, and air void content contributed significantly to the prediction of the ratio of plastic strain to resilient strain under repeated axial loading (*5*). Research conducted at Arizona State University involving the analysis of Leahy's data in combination with other data sets resulted in the model presented in Equation 1,

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Transportation Research Record: Journal of the Transportation Research Board, No. 2210, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 1–8.
DOI: 10.3141/2210-01

which summarizes mixture characteristics by means of the resilient strain alone. A detailed explanation of the rationale for simplifying Leahy's original model can be found elsewhere (*6*). However, a main argument is that including mix characteristics increased R^2 somewhat.

The simplicity and practicality of the model in Equation 1 must be commended. However, one limitation could be a matter of concern: Mixture properties are accounted for only by the elastic response (i.e., ϵ_r). As a result, it is possible that only a portion (instead of the full extent) of the variability induced from some mixture properties is being taken into account.

Limitations arising from the use of $|E^*|$ alone for rutting characterization have been reported in the literature. Mohammad et al. noted the inability of $|E^*|$ to properly rank the permanent deformation performance in a study involving six asphalt mixtures and suggest that the MEPDG rutting prediction model may not provide the true mixture performance (*7*).

Birgisson et al. report that no discernible relationship between $|E^*|$ and rutting was established for mixes of varying gradations and aggregate structure (*8*). As a result of observing rut development at the National Center for Asphalt Testing test track, Brown et al. suggest that there is no relationship between rutting and dynamic modulus (*9*). Similar conclusions regarding the limitations of $|E^*|$ alone to fully characterize rutting performance, particularly at higher temperatures, were reported by Myers et al., who note that more emphasis should be placed on evaluating the capabilities of the repeated load test for predicting in situ rutting performance (*10*).

With structural design methods moving toward mechanistic principles and given the reported limitations of using only the resilient strain from $|E^*|$ in the characterization of HMA rutting behavior, the direct incorporation of other mix characteristics into permanent deformation models may prove useful for characterizing permanent deformation and predicting rutting.

PERMANENT DEFORMATION

Evaluation

To analyze the effects of gradation, binder content and type, and compaction level on the resistance to permanent deformation under repeated axial loading (i.e., on the parameters from the permanent deformation model from Equation 1), 79 specimens were prepared in the laboratory. These specimens combined two gradations (identified herein as A and B), three asphalt contents (three for each gradation), a wide range of air void contents, and three types of asphalt (one neat PG 64-16 and two polymer-modified binders identified as PG 70-22 and PG 70-XX). Specimens, 170 mm high by 150 mm in diameter, were compacted by using the Superpave® gyratory compactor, then cored and sawed to obtain samples 150 mm high by 100 mm in diameter. The samples were evaluated with a simple performance tester.

The estimated optimum asphalt contents for Gradations A and B were 5.7% and 5.3%, respectively. For both gradations, the plan was to have one binder content at the optimum level, one at 0.5% below optimum, and one at 0.5% above optimum. As a result, binder content levels of 5.2%, 5.7%, and 6.2% were selected for Gradation A and of 4.8%, 5.3%, and 5.8% for Gradation B. These percentages correspond to variations that can be reasonably expected during production and fall within specifications. The idea was to cover a range of air void contents that reasonably could be expected in the field during normal operations, including some specimens slightly out of specification. Actual air void contents obtained were 2.3% to 10.1%.

After the specimens were compacted and prepared as described earlier, their dynamic modulus was determined at several temperatures (usually 4.4°C, 21°C, 45°C, and 54°C [40°F, 70°F, 113°F, and 129.2°F, respectively]) and at frequencies from 0.1 to 25 Hz. Next, samples were subjected to a confined axial repetitive permanent deformation test at 54°C with a load duration of 0.1 s, a rest period of 0.9 s, an axial deviator stress of 828 kPa (120 psi), a contact stress of 41.4 kPa (5.1 psi), and a confining stress of 138 kPa (20 psi). All tests were allowed to reach 100,000 microstrain or 20,000 load repetitions, whichever happened first (most specimens clearly entered the tertiary stage of permanent deformation). Detailed information about the binder and aggregates used in the study, as well as specific volumetric characteristics of each of the HMA specimens evaluated, can be found elsewhere (*11*).

Model Parameters

Results of the permanent deformation test were used to estimate the parameters k_1 and k_3 in Equation 1. Because the data were limited—all tests had been conducted at one temperature (54°C)—the parameter k_2 was assigned a value of 1.734, which is the laboratory-based value used to calibrate the MEPDG rutting prediction model (*1*). This assumption affects only the laboratory estimates of k_1 and has little effect on the main conclusions of this paper.

To estimate k_1 and k_3 from the laboratory test results, a dynamic modulus master curve first was developed for each specimen on the basis of the dynamic modulus test results. Then, consistent with the use of $|E^*|$ in the MEPDG model, the resilient strain corresponding to the state of stresses in the repetitive axial permanent deformation test was estimated using the $|E^*|$ corresponding to 54°C and a frequency of 10 Hz (which corresponds to the loading pulse duration in the permanent deformation test). This procedure made it possible to determine the ϵ_p-to-ϵ_r ratio for each observation on each specimen.

Parameters *a* and *b* of Equation 2 then were estimated by linear regression after a logarithmic transformation:

$$\frac{\epsilon_p}{\epsilon_r} = aN^b \tag{2}$$

The estimated value of *b* in Equation 2 is the direct estimate of k_3 in Equation 1 (Equation 3); the estimated k_1 in Equation 1 is derived from the estimated *a* in Equation 2 (Equation 4).

$$k_3 = b \tag{3}$$

$$\begin{aligned} k_1 &= \log_{10}(a) - k_2 \log_{10}(T) \\ &= \log_{10}(a) - 1.734 \log_{10}\left(\frac{9}{5}54 + 32\right) \end{aligned} \tag{4}$$

Because the power model excludes the tertiary stage of deformation and its parameter estimates can be affected by how many of the initial observations are included in the estimation, before the parameters *a* and *b* were estimated for each sample, the data were trimmed to exclude observations corresponding to the tertiary stage and some of the initial observations. For this purpose, the flow number (which determines the start of the tertiary stage) was determined with the method proposed by Archilla et al. (*12*). Furthermore, to ensure that the first stage of deformation was characterized from an extrapolation of the secondary stage of deformation (as indicated in the MEPDG) and to reduce the effect of the initial observations on the estimated parameters, the data series for each specimen were further trimmed by eliminating the first 10% of the remaining data in the series. The detailed procedures followed to prepare data for use in the regression analyses are beyond the scope of this paper, but complete descriptions can be found elsewhere (*12*, *13*).

EFFECTS OF MIXTURE PROPERTIES

Permanent Deformation Power Model Parameters

A model for k_1 and k_3 as a function of mix characteristics allows the default values in the MEPDG permanent deformation model to be adjusted to account for differences in mixture behavior due to particular mixture properties, such as binder type and content and air void content. In the following sections, the model parameter estimates that resulted from fitting the data generated for each of the samples to the permanent deformation model parameters are summarized. Due to space limitations, the specific values for each of the HMA specimens used to fit the models described in Equations 5 and 8 are not included in the present paper; however, these values and other specific details related with the statistical analyses can be found elsewhere (*11*). The same data set was used to estimate the parameters of the models presented next (Equations 5 and 8).

Parameter k_3

The results of preliminary data analyses indicated that the translog model, a flexible functional model form that can be estimated by using linear regression techniques, was appropriate to establish the relationship between k_3 and mix characteristics. This model accounts for interactions between air void and asphalt contents and considers the effect of binder type on k_3 through indicator variables (0, 1 variables). Although a more desirable approach to account for binder type would have involved the use of some measured characteristic of each binder (such as viscosity or dynamic shear rheometer test results), the fact that only three binder types were used in the experimental study justifies the treatment of the binder type as a factor from a statistical point of view. The use of indicator variables allows the capture of differences between binder types, and the marginal effects of air void content and effective binder content can be established at the same time without the confounding effect of binder type. The selected model has the form

$$\log(k_3) = \beta_1 + \beta_2 D_{\mathrm{B6416}} + \beta_3 D_{\mathrm{A70XX}} + \beta_4 D_{\mathrm{B70XX}} + \beta_5 D_{\mathrm{A7022}} + \beta_6 D_{\mathrm{B7022}} + \beta_7 \log(V_a) + \beta_8 \log(P_{\mathrm{beffVol}}) + \beta_9 \log(V_a)\log(P_{\mathrm{beffVol}}) \qquad (5)$$

where

D_{B6416} = 1 if Gradation B and binder is PG 64-16 and 0 otherwise,
D_{A70XX} = 1 if Gradation A and binder is PG 70-XX and 0 otherwise,
D_{B70XX} = 1 if Gradation B and binder is PG 70-XX and 0 otherwise,
D_{A7022} = 1 if Gradation A and binder is PG 70-22 and 0 otherwise,
D_{B7022} = 1 if Gradation B and binder is PG 70-22 and 0 otherwise,
V_a = air void content (%), and
P_{beffVol} = effective binder content by volume (%).

In addition to considering the effects of air void content, effective binder content, and their interaction, Equation 6 allows for different intercepts for the different binders and gradations for log(k_3) (β_1 for Gradation A with PG 64-16, $\beta_1 + \beta_2$ for Gradation B and PG 64-16, $\beta_1 + \beta_3$ for Gradation A and PG 70-XX, $\beta_1 + \beta_4$ for Gradation B and PG 70-XX, $\beta_1 + \beta_5$ for Gradation A and PG 70-22, and $\beta_1 + \beta_6$ for Gradation B and PG 70-22).

Data quality control was undertaken before model estimation, and as a result, some specimens were not included in the regression analysis because their dynamic modulus could not be reliably measured at 54°C and 10 Hz (conditions at which ϵ_r had to be determined to estimate the permanent deformation model parameters), because they showed unusually high permanent deformation readings at the start of the test, or because of mechanical issues with the simple performance tester operation during the permanent deformation tests. A complete explanation of the details involved in the quality control process can be found elsewhere (*11*). The parameters of the model described in Equation 5, including results from the regression analysis, are listed in Table 1.

Except for β_2 and β_6, the parameter estimates are statistically significant at a 95% confidence level. The low *p*-values for β_7, β_8, and β_9 statistically confirm the significance of the effects of air void content, effective binder content, and their interaction on k_3. The fact

TABLE 1 Parameter Estimates for log(k_3)

Parameter	Variable	Value	Standard Error	*t*-Value	*p*-Value	No. of Observations Associated
β_1	Intercept	−2.2228	0.6923	−3.2108	.0022	63
β_2	D_{B6416}	0.0177	0.0169	1.0416	.3022	16
β_3	D_{A70XX}	−0.1185	0.0195	−6.0827	.0000	10
β_4	D_{B70XX}	−0.1055	0.0179	−5.9055	.0000	14
β_5	D_{A7022}	−0.1105	0.0253	−4.3664	.0001	5
β_6	D_{B7022}	−0.0325	0.0266	−1.2180	.2285	4
β_7	$\log_{10}(V_a)$	2.3688	0.7934	2.9856	.0042	63
β_8	$\log_{10}(P_{\mathrm{beffVol}})$	2.3548	0.6696	3.5169	.0009	63
β_9	$\log_{10}(V_a)\ \log_{10}(P_{\mathrm{beffVol}})$	−1.9065	0.7731	−2.4661	.0169	63

NOTE: Residual standard error = 0.04625 on 54 degrees of freedom. Multiple R^2 = .8362. *F*-statistic = 34.45 on 8 and 54 degrees of freedom, *p*-value = 0; sample size = 63.

that the estimated β_2 is not statistically significantly different from zero simply indicates that there is no discernible difference between mixes with unmodified binder prepared with either gradation. This finding is not surprising because the responses from mixes prepared with either of the two gradations selected in this study do not appear to be very different.

A somewhat surprising result is that the estimate of parameter β_6 is not statistically significant, which would indicate that there is no difference between a mix prepared with Gradation A and the PG 64-16 binder (or, given that β_2 was not statistically significantly different from zero, a mix with Gradation B and PG 64-16) and another mix prepared with Gradation B and the PG 70-22 binder. This result is believed to be an anomaly in one or more of the only four data points available for the combination of Gradation B and the PG 70-22 binder. [The authors recognize that by following the same logic (i.e., low number of data points), the conclusion drawn for the combination of Gradation A and the PG 70-22 binder could be challenged; however, these results indicate that the performance of the mixture with the modified binder is better than the one observed in the unmodified mixture, which is logical according to extensive literature reports and consistent with results obtained with the mixtures prepared with PG 70-XX binder, which have more experimental observations.]

The estimates for parameters β_3, β_4, and β_5 are all statistically significantly different from zero, which indicates that all these mixes performed better than the unmodified mixes. The three parameter estimates are similar, thus indicating that these mixes accumulate permanent deformation at comparable rates. The R^2 is 0.836, which indicates an acceptable fit.

The finding that the parameter k_3 is a function of mix characteristics is important. Currently, the MEPDG model assumes that the elastic response alone (ϵ_r), which is a function of $|E^*|$, can completely account for all the effects that individual mixture characteristics have on the permanent deformation response and, thus, assumes that k_3 is a constant; study results indicate that k_3 may not be a constant.

Parameter k_1

Recall that k_1 can be estimated from parameter a in Equation 2 by using Equation 4. Also, typically, parameters a and b of Equation 2 are estimated by using linear regression techniques because the equation can be written as

$$\log_{10}\left(\frac{\epsilon_p}{\epsilon_r}\right) = \log_{10}(a) + b\log_{10}(N) = a' + bX \qquad (6)$$

where

$a' = \log_{10}(a)$,
$X = \log_{10}(N)$, and
N = number of load repetitions.

From both statistical and engineering points of view, it is not surprising that the intercept in a power model has a poor fit. Statistically, it can be proved that the variation of the intercept $\log_{10}(a)$ increases with the separation of the location of the intercept from one-half the number of repetitions applied during the test. Because the intercept is found for $N = 1$ [i.e., for $\log(N) = 0$], it is always far away from one-half the number of repetitions, and therefore, high variability in its value should be expected. From an engineering point of view, it is expected that the extrapolated intercept, which represents (theoretically) the deformation after one load application, would be a small quantity. Therefore, any noise in the data would make the estimated quantity highly variable. These problems translate into unreliable predictions of k_1.

To avoid these potential drawbacks, the permanent deformation after 100 load repetitions (ϵ_{p100}) was estimated for each sample, then its value was modeled as a function of mix characteristics. The ϵ_{p100} was chosen for modeling for two reasons: Its value is farther from zero (compared with the intercept of the power model), and it is more representative of the actual mix behavior early in the loading process in the sense that particular specimen irregularities that could induce anomalies in the readings from the strain transducer under the initial load cycles are more likely to have disappeared after a few load cycles (e.g., $N = 100$). After parameters a and b of Equation 2 are estimated for each specimen, the value of ϵ_{p100} is computed as

$$\epsilon_{p100} = a(100)^b \epsilon_r \qquad (7)$$

where ϵ_r is the resilient strain computed with the master curves developed from dynamic modulus testing data. The model selected for ϵ_{p100} as a function of mix characteristics is entirely analogous to the one used to model k_3:

$$\begin{aligned}\log(\epsilon_{p100}) = {} & \lambda_1 + \lambda_2 D_{\mathrm{B6416}} + \lambda_3 D_{\mathrm{A70XX}} + \lambda_4 D_{\mathrm{B70XX}} + \lambda_5 D_{\mathrm{A7022}} \\ & + \lambda_6 D_{\mathrm{B7022}} + \lambda_7 \log(V_a) + \lambda_8 \log(P_{\mathrm{beffVol}}) \\ & + \lambda_9 \log(V_a)\log(P_{\mathrm{beffVol}}) \end{aligned} \qquad (8)$$

The parameters of the model described in Equation 8, including the results from the regression analysis, are summarized in Table 2. Interpretation of the results is analogous to the interpretation of the results for k_3. Again, the parameters for D_{B6416} and D_{B7022} (λ_2 and λ_6, respectively) are not statistically significant at a 95% confidence level. The fact that the estimated λ_2 is not statistically significantly different from zero simply indicates that there is no discernible difference between mixes with unmodified binder prepared with either gradation. As for λ_6, the same potential anomaly described for β_6 may affect this parameter estimate.

The essentially zero p-values for λ_7, λ_8, and λ_9 statistically confirm the significance of the effects of air void content, effective binder content, and their interaction on ϵ_{p100}. The estimates for the parameters λ_3, λ_4, and λ_5 are all statistically significantly different from zero and negative, which indicates that all of these mixes performed better than the unmodified mixes (i.e., they show smaller permanent deformations after 100 cycles). Parameters λ_3 and λ_4 have similar magnitudes, indicating that the mixes with PG 70-XX performed similarly regardless of whether Gradation A or Gradation B was used. In contrast, the absolute value of λ_5 is smaller than either λ_3 or λ_4, indicating that the mixes prepared with Gradation A and the PG 70-22 binder performed slightly worse than those with PG 70-XX but still better than those PG 64-16. The R^2 of almost 0.89 indicates again an acceptable fit for ϵ_{p100}.

Predicted Rutting

To evaluate the effects of mixture properties (specifically, air void content and binder content) on rutting prediction, a trial pavement design section with a mixture using the PG 64-16 binder for the HMA layer was analyzed by using the MEPDG software at four compaction levels and four binder contents under two scenarios (identified herein

TABLE 2 Parameter Estimates for $\log(\epsilon_{p100})$

Parameter	Variable	Value	Standard Error	*t*-Value	*p*-Value	No. of Observations Associated
λ_1	Intercept	–5.1695	1.690	–3.06	.0035	63
λ_2	D_{B6416}	–0.0500	0.041	–1.21	.2316	16
λ_3	D_{A70XX}	–0.3644	0.048	–7.66	.0000	10
λ_4	D_{B70XX}	–0.3529	0.044	–8.09	.0000	14
λ_5	D_{A7022}	–0.1325	0.062	–2.14	.0366	5
λ_6	D_{B7022}	–0.1170	0.065	–1.80	.0777	4
λ_7	$\mathrm{Log}_{10}(\mathrm{V_a})$	10.0005	1.937	5.16	.0000	63
λ_8	$\mathrm{Log}_{10}(\mathrm{P_{beffVol}})$	28.3943	1.635	5.14	.0000	63
λ_9	$\log_{10}(\mathrm{V_a})\ \log_{10}(\mathrm{P_{beffVol}})$	–8.6038	1.887	–4.56	.0000	63

Note: Residual standard error = 0.1129 on 54 degrees of freedom. Multiple R^2 = .8872. *F*-statistic = 53.11 on 8 and 54 degrees of freedom, *p*-value = 0; sample size = 63.

as Scenario I and Scenario II), and their corresponding rutting results were compared.

In Scenario I, the effect of mixture characteristics on rutting was incorporated solely by means of the HMA $|E^*|$ master curve (i.e., through the resilient strain ϵ_r), and the permanent deformation model parameters used correspond to nationally calibrated rutting prediction model parameters (i.e., $k_1 = -3.4488$, $k_2 = 1.5606$, and $k_3 = 0.479244$) considered to be independent of mixture characteristics (i.e., constant). In Scenario II, a pavement section identical to that of Scenario I was evaluated, but the effect of mixture characteristics was incorporated into the MEPDG rutting model by adjusting parameters k_1 and k_3 according to the relationships established in Equations 5 and 8.

The MEPDG model provides a mechanism to adjust the required permanent deformation model parameters (k_1, k_2, and k_3) for calibration purposes. By default, the MEPDG model multiplies the laboratory-derived values for k_1, k_2, and k_3 (–3.2536, 1.734, and 0.3994, respectively), obtained during the course of MEPDG development, by the field adjustment factors β_1, β_2, and β_3 (1.06, 0.9, and 1.2, respectively), which were derived by using Long-Term Pavement Performance data to better match the MEPDG predictions with field observations. Because no local field information currently exists to estimate similar field calibration factors, the same values are used in this study; however, instead of using the default k_1 and k_3 used in Scenario I, the parameters k_1 and k_3 to be used during the Scenario II simulation were estimated as described below.

The k_3 value was estimated with the use of Equation 5. The k_1 value was calculated by first estimating the value of ϵ_{p100} (Equation 8); then solving for *a* in Equation 7 (by replacing the estimated ϵ_{p100}), *b* (which corresponds to the estimated k_3 from Equation 5), and the resilient strain ϵ_r (obtained from the dynamic modulus master curve of the mixture); and finally replacing the calculated value of *a* in Equation 4. Because the data were limited—all tests had been conducted at one temperature (54°C)—the parameter k_2 was assigned a value of 1.734, which is the laboratory-based value used to calibrate the MEPDG rutting prediction model. The laboratory-derived model parameters k_1, k_2, and k_3 were then multiplied by their corresponding field adjustment factors and used as input to the MEPDG model.

To consider the effects of air void content and binder content on $|E^*|$, dynamic modulus values were estimated with a dynamic modulus prediction model, described elsewhere (*11, 14*). As an example, for a mixture with Gradation A, the PG 64-16 binder, 7% air voids, and 5.3% asphalt content, the estimated values for k_1 and k_3 are –3.4659 and 0.4947, respectively. (The default laboratory value for k_2 is 1.734.) Multiplying these values by their respective field adjustment factors (1.06, 0.9, and 1.2) yields values of –3.6739 for k_1, 1.5606 for k_2, and 0.5936 for k_3, which are used as input to the MEPDG model.

The estimated values for k_1 and k_3 for each simulated mix combination in Scenario II, in which the effect of mixture characteristics was incorporated into the MEPDG rutting prediction model by adjusting these parameters, are listed in Table 3. Results from simulations under this scenario were compared with simulation results from Scenario I, in which the effects of mix characteristics on rutting were considered exclusively by means of the dynamic modulus through the resilient strain ϵ_r and the rutting model parameters were assumed to be constant (i.e., independent of mixture properties, with values of –3.4488, 1.5606, and 0.479244 for k_1, k_2, and k_3, respectively).

TABLE 3 Estimated Field Values for MEPDG Rutting Prediction Model Parameters k_1 and k_3 Used in Scenario II Simulations with Air Void Contents of 3% to 9%

Gradation	Binder	Asphalt Content (%)	3%		5%		7%		9%	
			k_1	k_3	k_1	k_3	k_1	k_3	k_1	k_3
A	PG 64-16	4.8			–3.6550	0.4240	–3.5920	0.5360	–3.5865	0.6219
		5.3	–3.7492	0.3695	–3.6795	0.5035	–3.6739	0.5936	–3.7068	0.6633
		5.8	–3.6917	0.4653	–3.7214	0.5711	–3.7405	0.6430	–3.8083	0.6991
		6.3	–3.6390	0.5489	–3.7094	0.6301	–3.7943	0.6854		

TABLE 4 Input Values Used in Simulations with MEPDG Model

MEPDG Input Variable	Scenario I	Scenario II
Location	Honolulu, Hawaii	
Traffic		
Annual average daily truck traffic	1,250	
No. of lanes in design direction	3	
% of trucks in design direction	50	
% of trucks in design lane	95	
Asphalt layers		
Thickness	7 in.	
$\lvert E^* \rvert$	Estimated with $\lvert E^* \rvert$ model published (*14*)	
Permanent deformation model parameters		
k_1	–3.4488	See Table 3
k_2	1.5606	
k_3	0.479244	See Table 3
HMA volumetric characteristics		
Air void content (V_a; %)	See Table 3 (same for both scenarios)	
Asphalt content (P_b; %)	See Table 3 (same for both scenarios)	
Unit weight (pcf)	Variable, depending on V_a and P_b	
Binder		
PG grade	Unmodified binder—PG 64-16	
Base		
Thickness	15 in.	
Type	A-1-b	
Subgrade		
Thickness	Semi-infinite	
Type	Clay of low plasticity	

The input parameter values used in the MEPDG model for all simulations are listed in Table 4.

The results obtained are summarized in Figure 1, where patterns represent different air void contents. The analysis in the present paper focuses on permanent deformation of the asphalt layer alone as predicted by the MEPDG model. Given that the purpose of the simulations was to evaluate whether accounting for specific HMA mixture characteristics directly in the MEPDG rutting prediction model has a significant effect on HMA rutting prediction, the authors consider that the relative comparison between the results of Scenarios I and II is valid. Simulations considering extreme conditions were not included in the analysis (such as HMA layers exhibiting simultaneously low air void and low binder contents, or high air void and high binder contents) because they rarely happen in practice. In Table 3, the cells that correspond to such combinations are empty.

As illustrated in Figures 1*a* and 1*b*, the estimated rutting in most cases is considerably higher if HMA characteristics are taken into account explicitly in the permanent deformation model (Scenario II), particularly when air void content exceeds 5%. In addition, the variation in estimated rutting attributable to variations in air void content, binder content, or both is significantly lower when the effect of mixture characteristics is not considered directly in the HMA rutting prediction model (Scenario I).

When the scale of the Scenario I results (Figure 1*a*) is enlarged, as in Figure 1*c*, it becomes evident that the dynamic modulus alone can capture only some of the effects that particular HMA characteristics have on the mixture's resistance to permanent deformation. In addition to having a significant effect on the dynamic modulus of the mixture, air void content V_a and binder content P_b have a crucial effect on the rutting resistance of HMA, as evidenced by the observed performance of the mixtures during permanent deformation testing in the laboratory. Even though this fact was statistically demonstrated earlier in this paper, the authors consider it extremely important to highlight this situation, given that it is currently not considered in the MEPDG permanent deformation prediction model.

The effect of air void content on the mixture's rutting increases as the binder content increases, as suggested by trends illustrated in Figure 1*b*. For instance, the increase in accumulated rutting when the air void content increases from 5% to 7% for a mixture with P_b equal to 5.8% is greater than the rutting increase between mixtures with the same air void contents when P_b is equal to 5.3%.

Not considering the effects of HMA characteristics on rutting accumulation is not critical for low air void contents (e.g., 3%) because considering mixture effects solely by means of the dynamic modulus at this level actually yields a somewhat higher rutting estimate than the one obtained in Scenario II. Even though such an estimate could be considered an advantage of the current MEPDG procedure (as the rutting estimate would be on the conservative side), these high compaction levels are rarely achieved in the field during construction. In reality, HMA design procedures usually require that mixture air void contents be around 4%, but after additional compaction from traffic loading. In practice, compaction requirements during construction usually demand air void contents from 7% to 8%, a situation that strengthens the importance of explicitly considering mixture characteristics in the MEPDG permanent deformation model.

To illustrate the relevance of this situation, the expected rutting in a mixture like the one used in the simulations after 20 years of service, compacted to 93% of maximum theoretical specific gravity (i.e., with $V_a = 7\%$) and a binder content of 5.8%, would be 5.6 mm in Scenario I and 25.6 mm in Scenario II. The practical implication would be that if mixture-specific characteristics are not taken into account explicitly in the permanent deformation model parameters, this mixture could be approved for use during construction.

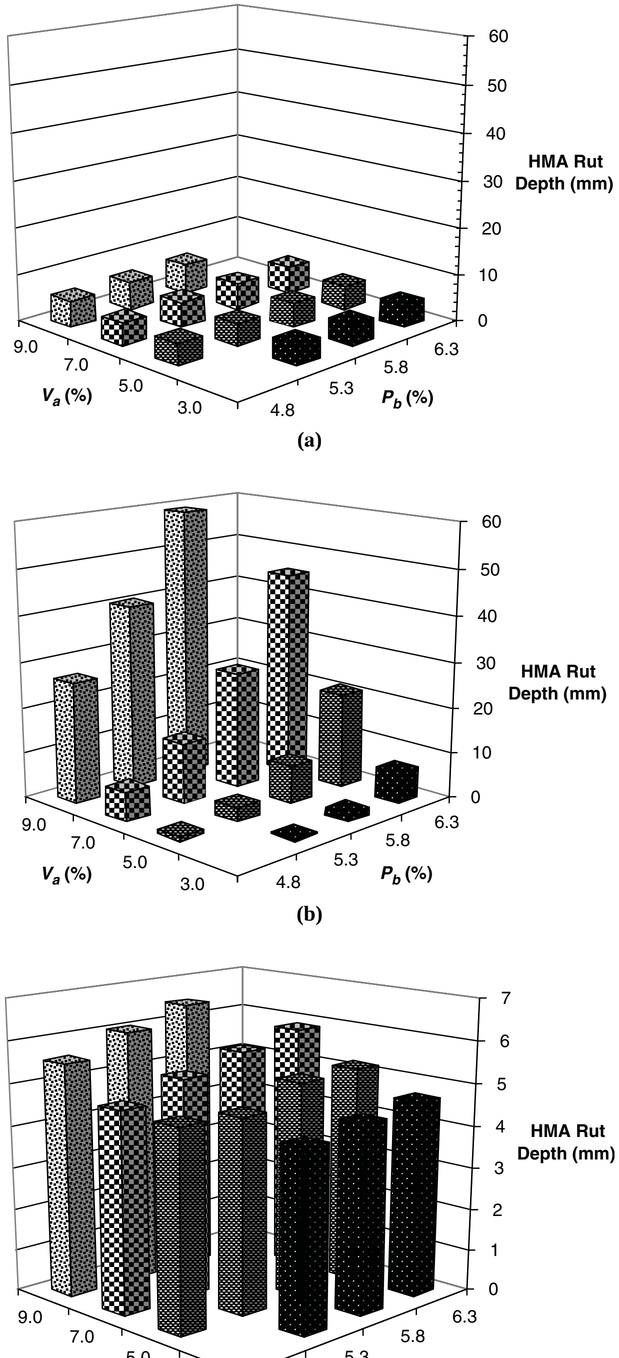

FIGURE 1 HMA rutting (50% reliability) after 20 years in (*a*) Scenario I, (*b*) Scenario II, and (*c*) Scenario I with vertical scale modified.

Results suggest that variation in air void content is more critical to rutting than variations in binder content. This finding implies that higher compaction levels (i.e., lower air void contents) should be specified during construction. Lower air void contents are desirable as long as they are attained through compaction, not artificially by increasing binder content.

In terms of permanent deformation, a mixture with a binder content slightly under the optimum is less problematic than a mixture slightly over the optimum. Even though this approach could be economically favorable, rutting is only one distress that could be present in an HMA, and low binder contents could negatively affect HMA durability and fatigue resistance.

The authors recognize that the conclusions drawn in the present paper are based on laboratory work and that variables such as stress levels and temperature were not considered. However, the conclusions presented highlight the potentially significant effects on rutting that could arise by not considering specific HMA characteristics in the parameters for the MEPDG permanent deformation prediction model.

If the conclusions presented herein and in prior investigations undertaken by Leahy (*11*) had been corroborated in the laboratory and in the field but not somehow incorporated into the MEPDG model (*1*), one of the greatest advantages of mechanistic design methods (i.e., the direct use of material testing results to determine material fundamental properties used in pavement structural design) would have been wasted.

CONCLUSIONS AND RECOMMENDATIONS

Results of the present study suggest that predicting rutting performance by means of elastic response alone (universal values for permanent deformation model parameters, regardless of mixture properties) does not fully take into account mixture-specific contributions to rutting. The empirical laboratory evidence in this study is in agreement with numerous findings reported in the literature (*7–10*) and supports the hypothesis that other mix characteristics must be used in addition to the dynamic modulus ($|E^*|$) to appropriately characterize the permanent deformation of asphalt mixtures.

In particular, results show that the air void content, effective asphalt content, and binder type of the mixture have significant effects on the permanent deformation model parameters k_1 and k_3 incorporated into the MEPDG model. With the specific objective of facilitating the use of the results presented herein in the MEPDG model, models were developed to estimate these parameters as a function of mixture characteristics. The data used in the models' development were obtained by testing the resistance to permanent deformation under repeated axial loading with the simple performance tester in laboratory-compacted HMA specimens.

To evaluate the practical implications of ignoring the specific effects that HMA characteristics potentially could have on rutting prediction, the results obtained from MEPDG simulations in two scenarios were compared. Results indicate that, in general, rutting variability is significantly higher if HMA characteristics are considered explicitly in the parameters of the MEPDG permanent deformation prediction model (Scenario II). Furthermore, air void content and binder content have significant effects not only on a mixture's dynamic modulus $|E^*|$ but also on its rutting resistance. In general, high air void content combined with high binder content leads to poor performance.

Simulation results suggest that the effect of variations of the degree of compaction is not linear (i.e., a 2% increase in air voids has a greater impact on predicted rutting as the air void content increases) and that variations in air void content have a more critical effect on rutting than variations in binder content do. Given that compaction acceptance criteria during construction for a mixture similar to the one used to run the simulations is around 93% (i.e., mixes with approximately 7% air void content are deemed acceptable during construction), consideration should be given to promoting low air void contents in a properly designed HMA solely through compaction. The results reported herein are extremely relevant in the sense that if mixture characteristics are not considered explicitly in a mixture's performance evaluation, the mixture could be deemed acceptable for use in a project, with significant negative consequences.

The authors believe that a better understanding of the potential effect that HMA characteristics have on the parameters of the MEPDG permanent deformation prediction model could significantly enhance the guide's prospects for acceptability and implementation while facilitating local calibration efforts. They recommend that a large database of laboratory permanent deformation tests—including additional stress levels, temperatures, binder grades, and mix designs—be used to confirm the laboratory observations in this study.

ACKNOWLEDGMENTS

The financial support of the Hawaii Department of Transportation in cooperation with the Federal Highway Administration is greatly appreciated and acknowledged.

REFERENCES

1. ARA, Inc., ERES Consultants Division. *Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures.* Final report, NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, D.C., 2004. http://www.trb.org/mepdg/guide.htm.
2. Biligiri, K. P., K. E. Kaloush, M. S. Mamlouk, and M. W. Witczak. Rational Modeling of Tertiary Flow for Asphalt Mixtures. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2001,* Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 63–72.
3. Zhou, F., and T. Scullion. Three Stages of Permanent Deformation Curve and Rutting Model. *International Journal of Pavement Engineering,* Vol. 3, No. 4, 2002, pp. 251–260.
4. Zhou, F., T. Scullion, and L. Sun. Verification and Modeling of Three-Stage Permanent Deformation Behavior of Asphalt Mixes. *Journal of Transportation Engineering,* Vol. 130, No. 4, 2004, pp. 486–494.
5. Leahy, R. B. *Permanent Deformation Characteristics of Asphalt Concrete.* PhD dissertation. University of Maryland, College Park, Md., 1989.
6. Kaloush, K. *Simple Performance Test for Permanent Deformation of Asphalt Mixtures.* PhD dissertation. Arizona State University, Tempe, Ariz., 2001.
7. Mohammad, L. N., Z. Wu, S. Obulareddy, S. Cooper, and C. D. Abadie. Permanent Deformation Analysis of Hot-Mix Asphalt Mixtures Using Simple Performance Tests and 2002 Mechanistic–Empirical Pavement Design Software. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1970,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 133–142.
8. Birgisson, B., R. Roque, J. Kim, and L. Viet Pham. *The Use of Complex Modulus to Characterize the Performance of Asphalt Mixtures and Pavements in Florida.* Final report. Report No. 4910-4504-784-12. Florida Department of Transportation, Tallahassee, Fla., 2004.
9. Brown, E., L. Cooley, Jr., D. Hanson, B. Powell, B. Prowell, and D. Watson. *NCAT Test Track Design, Construction, and Performance.* NCAT Report 2002-12. National Center for Asphalt Technology, Auburn University, Auburn, Ala., November 2002.
10. Myers, L. A., J. Gudimettla, J. D'Angelo, S. Gokhale, and B. Choubane. Evaluation of Performance Data from Repeated Load Test. *Proc., 50th Annual Conference of the Canadian Technical Asphalt Association,* Victoria, British Columbia, Canada, 2005, pp. 207–224.
11. Archilla, A. R. *Effect of Polymer Modified Asphalt Binders on the Performance of Asphalt Concrete Mixes Used in Hawaii.* Final report. Prepared for the Hawaii Department of Transportation, Honolulu, 2008.
12. Archilla, A. R., L. G. Diaz, and S. Carpenter. Proposed Method to Determine the Flow Number in Bituminous Mixtures from Repeated Axial Load Tests. *Journal of Transportation Engineering,* Vol. 133, No. 11, 2007, pp. 610–617.
13. Diaz, L. G., and A. R. Archilla. Effect of Laboratory Data Range Selection in Permanent Deformation Characterization of Asphalt Mixtures. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2057,* Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 126–133.
14. Archilla, A. R. Developing Master Curve Predictive Equation Models for Local Conditions: A Case Study for Hawaii. *Journal of the Association of Asphalt Paving Technologists,* Vol. 79, 2010, pp. 325–364.

The Characteristics of Asphalt Paving Mixtures to Meet Structural Requirements Committee peer-reviewed this paper.