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Evaluation of Dynamic Modulus of Modified and Unmodified Asphalt Mixes for Different Input Levels of the MEPDG

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Abstract: The Mechanistic Empirical Pavement Design Guide (MEPDG) provides three levels of input (i.e. Level 1, Level 2, and Level 3) for the design and analysis of flexible pavements. The selection of a particular level of input depends on the amount of information available to the designer and the criticality of the project. For all three input levels, the dynamic modulus (|E*|) of hot mix asphalt (HMA) is used as an important parameter to evaluate the stress-strain characteristics of an asphalt layer associated with its performance (i.e. rutting and fatigue cracking). The present study was undertaken to compare |E*| for these three levels of inputs for modified and unmodified HMA mixes. Two different mixes having a similar nominal maximum aggregate size of 19 mm were collected from the production plant. The mixes were prepared with a styrene-butadiene-styrene (SBS)-modified binder of performance grade (PG)70-28 and an unmodified binder of PG64-22. Specimens were prepared for each mix at four different levels of air voids, namely, 6%, 8%, 10%, and 12%. For Level 1, |E*| values were measured in the laboratory at different temperatures and frequencies in accordance with the AASHTO TP62-06 standard. |E*| values for Level 2 and Level 3 were predicted using the Witczak 1999 model provided in the MEPDG. Analyses of the results show that the prediction accuracy of this model for Level 2 and Level 3 varies with the type of mix, temperature, and level of air voids. In addition, it was discovered that this model performs differently for modified and unmodified HMA mixes. To address this variability, correction factors were developed for each type of mix, resulting in more accurate |E*| values comparable to those obtained at Level 1.

Key words*: Binders, Dynamic modulus, Hot mix asphalt, MEPDG.*

Introduction

The long term performance of a pavement depends, to a large extent, on the properties of the materials comprising the asphalt mix. The Mechanistic Empirical Pavement Design Guide (MEPDG) developed under the National Cooperative Highway Research Program (NCHRP) project 1-37A recommends the dynamic modulus (|E*|) of hot mix asphalt (HMA) as an important input parameter for the design and analysis of flexible pavements [1]. Several researchers reported that the |E*| of a HMA mix is highly correlated to pavement distresses (i.e. rutting, fatigue, and low temperature cracking) over a wide range of traffic and climatic conditions [2-8]. A high |E*| (high stiffness) improves the load carrying ability of asphalt layers and reduces the stress-strain on the underlying layers. However, excessive stiffness can reduce the durability of the pavement and increase the possibility of thermal cracking in surface layers. On the other hand, low |E*| (low stiffness) decreases the load bearing capacity and possibly results in the rutting failure of the pavement. Therefore, an accurate estimation of |E*| is important for designing a structurally sound pavement.

The MEPDG uses a hierarchical approach for the selection of |E*| depending on the desired reliability and available information. It offers three levels of input, known as Level 1, Level 2, and Level 3. Of the three specified levels, Level 1 is considered the most accurate, while Level 2 and Level 3 are assumed to be an intermediate and the lowest level of accuracy, respectively. |E*| values for Level 1 are measured in the laboratory at selected combinations of temperature and loading frequency. |E*| values for Level 2 and Level 3, on the other hand, are predicted using the Witczak 1999 model [1, 9-11]. Although the measurement of |E*| in the laboratory (i.e. Level 1) is highly desirable, it is not always feasible to conduct this test because of its tedious and time consuming nature [10, 12]. Consequently, predictions of |E*| (i.e. Level 2 and Level 3) using the Witczak 1999 model is an alternative choice for designers [1, 3, 9-10]. The Witczak 1999 model was developed by Andre et al. [11] using 2,750 test data points from 205 HMA mixes. This model uses the volumetric properties of the mix, aggregate gradation, binder viscosity, and loading frequencies to determine |E*| of a mix.

Several studies have been conducted in the past to check the predictive power of this model for modified and unmodified mixes. For example, Bennert [13] reported that percent differences between the measured and the predicted |E*| increases with highly modified asphalt binders. Consequently, caution should be taken while predicting |E*| for modified asphalt binders. One reason for such discrepancy might be due to the fact that the Witczak 1999 model was developed using very few polymer-modified asphalt binders. Insufficient binder information can result in this model performing poorly for modified mixes [13-14]. Zeghal et al. [15] compared the predictions of this model for Level 3 designs for mixes prepared with PG58-22, PG64-34, and PG52-34 asphalt binders. It was reported that this model over-predicted |E*| with an average error of approximately 100% and 300% at an intermediate temperature and high temperatures, respectively. Similarly, for Level 2 and Level 3,

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Harran et al. [16] reported that the predicted |E*| ranged from 65% to 250% of the values measured in the laboratory at intermediate and high temperatures. However, their study was limited to unmodified asphalt mixes.

Tran et al. [10] compared the measured (i.e. Level 1) and the predicted (i.e. Level 3) |E*| of several HMA mixes prepared with modified binders PG70-22 and PG76-22. It was found that this model resulted in significant error for Level 3. Consequently, calibration factors were suggested to reduce the error in this model. However, they did not study the performance of this model for Level 2. In another study, Azari et al. [17] compared the predictions for Level 3 designs for mixes prepared with unmodified, an air blown, and polymer-modified asphalt binders. It was reported that |E*| for all kinds of mixes were over-predicted. However, the research was limited to one air void level (i.e. 7%), and the accuracy of the model at Level 2 was not evaluated. Similarly, Mohammad et al. [18] studied the performance of this model for the modified and unmodified mixes for Level 3 and reported that the model over-predicted |E*|. However, their conclusions were based on the combined dataset of modified and unmodified mixes for samples compacted at 7% air void.

In a recent study, Zhu et al. [19] studied the performance of this model for different polymer-modified asphalt mixes. It was reported that this model may be applicable for polymer-modified asphalt mixes. However, the research was limited to one air void level (i.e. 4%). Moreover, results were based on the combined dataset of all four mixes, which might result in the change in prediction power of the model. Furthermore, it was not clear from their reported results if the accuracy of the model was checked at Level 2 or Level 3. In a similar study, Singh et al. [20] evaluated the strengths and weaknesses of this model for Level 3 and reported that this model over-predicted |E*|. However, the findings were based on the combined dataset of modified and unmodified mixes.

The results from the literature presented above conclusively demonstrates that the accuracy of input Level 2 and Level 3 |E*| is largely dependent on the type of mix, binder, air voids, and test temperature. The predictive model performs differently for modified and unmodified HMA mixes. Such a significant difference between the measured and the predicted |E*| values may produce inaccurate designs and discourage users from implementing the proposed guide [15]. Therefore, it is important for state agencies and pavement designers to study the different hierarchical levels of the MEPDG for predicting |E*| for modified and un-modified HMA mixes. Furthermore, correction factors need to be developed to improve the accuracy of the predictive models for the asphalt mixes used in a particular state.

In the present study, the |E*| of modified and unmodified mixes that are commonly used in the construction of pavements in Oklahoma was evaluated for three levels of inputs (i.e. Level 1, Level 2, and Level 3) of the MEPDG. Comparisons were made by estimating the relative errors and by comparing the master curves constructed for these levels. Correction factors to reduce the prediction errors were developed for both mixes. It is anticipated that the present study will provide the designer more insight into the effect of modified mixes on pavement stiffness, hopefully resulting in the accurate estimation of |E*|.

The rest of the paper is organized as follows: First, the selection of the materials and the preparation of the specimens is discussed. The measurement and prediction of |E*| values are then discussed, followed by the construction of master curves for both the modified and unmodified mix. Later, the results and discussion section is presented, followed by the development of correction factors. The paper concludes with a discussion of experimental results and direction of future research.

Material and Specimens Preparation

Two Superpave® HMA mixes that are commonly used for the construction of flexible pavements in Oklahoma were collected from the production plant of Haskell Lemon Construction Company in Norman, Oklahoma. The nominal maximum aggregate size of both mixes was 12.5 mm. One mix was prepared with 4.5% of styrene-butadiene-styrene (SBS)-modified asphalt binder with performance grade (PG)70-28, and it was named modified mix (MM). The second mix was prepared using 5.1% unmodified PG64-22 grade binder, and it was designated as an unmodified mix (UM).

The asphalt binders used in this study were obtained from the Valero Refinery in Ardmore, Oklahoma. These are commonly used binders for the construction of flexible pavement in Oklahoma. The aggregates in the MM mix contained primarily granite with approximately 38% of 15.6 mm chips, 27% manufactured sand, 24% C-33 screening, and 11% sand. Similarly, the aggregates in the UM mix contained primarily rhyolite with approximately 25% of 15.6 mm chips, 38% manufactured sand, 22% screening, and 15% sand. The composition of aggregates in the mixes and their gradation are given in Table 1.

Loose HMA mixes were preheated in an oven to their compaction temperature. Specimens were compacted using a Superpave® Gyratory Compactor (SGC) at 6%, 8%, 10%, and 12% target air voids (± 0.5%). It is expected that this selection of air voids will cover a practical range of compaction density (i.e. 94% to 88% of the theoretical maximum density) encountered during the construction of a flexible pavement. Three replicates of the specimens were compacted at each level of air void. First, specimens with proportions 150 mm diameter by 167.5 mm height were prepared. Then, the test specimens sized 100 mm in diameter and 150 mm height were cored and sawed from the center of the gyratory compacted specimens. These specimens have the most consistent air void distribution in both vertical and radial directions [21]. Moreover, these are the specimen geometries currently recommended for the simple performance test and are used in the constitutive modeling of asphalt concrete in tension and compression [7, 22-24]. Volumetric analyses were conducted to obtain effective binder content (V_{beff}), voids in mineral aggregates (VMA), voids filled with asphalt (VFA), and air voids (V_a) for both mixes (Table 2).

Measurement of |E*| for Input Level 1

|E*| values for input Level 1 were measured in the laboratory in accordance with AASHTO TP62-03 specification [25]. All tests were performed using a MTS servo-hydraulic testing system. |E*| test matrix for both mixes is given in Table 3. Each mix was tested

Table 1. Aggregate Gradations and Mix Property.

Material	Modified Mix (MM) (%)	Unmodified Mix (UM) (%)
15.6 mm Chips	38	25
Manufactured Sand	27	38
C-33 Screenings	24	22
Sand	11	15
Sieve Size (mm)	Gradation (% Passing)	
19	100	100
12.5	97	98
9.5	89	87
4.75	69	62
2.36	49	40
1.18	35	28
0.6	25	21
0.3	15	13
0.15	7	5
0.075	2.5	3.2
Volumetric Properties		
G_{mm}	2.463	2.477
G_{se}	2.658	2.681
G_{sb}	2.634	2.669
G_b	1.01	1.02
Binder Type	PG70-28	PG64-22
P_b (%)	4.5	5.1
Aggregate Type	Granite	Rhyolite
Mix Type	Virgin	Virgin

G_{mm} = Max. Theoretical Sp. Gr. Mix
G_{sb} = Bulk Sp. Gr. of Agg. G_b = Sp. Gr. of Binder
P_b = Binder Content G_{se} = Effective Sp. Gr. of Agg.

for different levels of air voids, as mentioned above. The test was conducted on each test specimen at four different temperatures (4°C, 21°C, 40°C, and 55°C) and at six different frequencies (25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz, and 0.1 Hz). The test specimen was placed in an environmental chamber and allowed to reach equilibrium within ±0.5°C of the specified test temperature. The temperature of the specimen was monitored using a dummy specimen with a thermocouple mounted at the center. The deformation of the specimen was measured using two linear variable differential transducers (LVDTs) mounted on the specimen. To reduce the friction, Teflon papers were placed between the specimen ends and loading plates. Prior to testing, the specimen was conditioned through the application of 200 cycles of load at a frequency of 25 Hz. The load magnitude was adjusted based on the material stiffness, air void content, temperature, and frequency to keep the strain response within 50-150 micro-strains [26]. The data was recorded for the last five cycles of each sequence. |E*| was calculated using Eq. (1) for a combination of temperature and frequency [7]. A total of 576 |E*| values (2 mixes × 3 specimens × 4 air voids × 4 temperatures × 6 frequencies) were measured in the laboratory.

$$|E^*| = \frac{\sigma_o}{\varepsilon_o} \tag{1}$$

where σ_o is the applied stress amplitude and ε_o is the measured strain amplitude.

Prediction of |E*| for Input Level 2 and Level 3

|E*| values for input Level 2 and Level 3 are predicted using the Witczak 1999 model (Eq. (2)). The predictions are based on mix volumetric properties, aggregate gradation, binder viscosity, and loading frequencies.

$$Log\,|E|^* = -1.249937 + 0.029232\,\rho_{200} - 0.001767\,(\rho_{200})^2 - 0.002841\,\rho_4 - 0.058097\,V_a - 0.8022\,\frac{V_{beff}}{(V_{beff}+V_a)} + \frac{3.87197 - 0.0021\,\rho_4 + 0.003958\,\rho_{38} - 0.000017\,(\rho_{38})^2 + 0.00547\,\rho_{34}}{1+\exp(-0.603313 - 0.31335\log(f) - 0.393532\log(\eta))} \tag{2}$$

Table 2. Volumetric Properties of Compacted Specimens.

Air Voids (%)	Specimen No.	MM V_a (%)	MM VMA (%)	MM VFA (%)	MM V_{beff} (%)	UM V_a (%)	UM VMA (%)	UM VFA (%)	UM V_{beff} (%)
6	1	6.2	16.2	58.7	9.5	6.1	16.8	67.3	11.3
	2	6.3	16.4	58.1	9.5	5.9	16.6	68.1	11.3
	3	6.2	16.2	58.8	9.5	6.3	16.9	66.5	11.3
8	1	7.9	17.7	52.8	9.4	8.2	18.7	59.0	11.0
	2	7.9	17.7	52.7	9.4	7.8	18.3	60.5	11.1
	3	8.3	18.1	51.4	9.3	8.2	18.6	59.3	11.0
10	1	10.2	19.9	45.9	9.1	9.9	20.2	53.7	10.8
	2	10.3	19.9	45.7	9.1	9.6	19.9	54.6	10.9
	3	10.2	19.8	45.9	9.1	9.9	20.2	53.7	10.8
12	1	11.9	21.4	41.8	8.9	12.1	22.1	47.7	10.6
	2	12.2	21.6	41.4	8.9	11.6	21.7	49.0	10.6
	3	12.1	21.5	41.5	8.9	11.7	21.7	48.9	10.6

V_a = Air Voids VMA = Voids in Mineral Aggregates
VFA = Voids Filled with Asphalt V_{beff} = Effective Binder Content, % Volume

Table 3. Dynamic Modulus Test Matrix.

Mix Type	Air Voids (%)	Temperature (^{o}C)	Frequency (Hz)	No. of Specimens	|E*| values
MM	6	4, 21, 40, 55	25, 10, 5, 1, 0.5, 0.1	3	72
	8			3	72
	10			3	72
	12			3	72
UM	6	4, 21, 40, 55	25, 10, 5, 1, 0.5, 0.1	3	72
	8			3	72
	10			3	72
	12			3	72

Table 4. Laboratory Measured Viscosity and A-VTS Values for Both Binders.

Temperature (^{o}C)	PG64-22	PG70-28
	Viscosity (cP)	
135	667	1747
150	313	842
165	163	415
180	89	204

Asphalt Type	Laboratory Measured (Level 1 and Level 2)		MEPDG Default (Level 3)	
	A	VTS	A	VTS
PG64-22	10.59	-3.537	10.98	-3.68
PG70-28	9.78	-3.233	9.715	-3.217

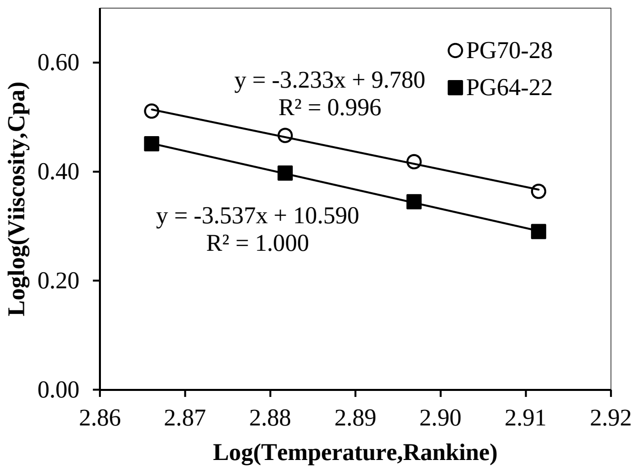


Fig. 1. Temperature-Viscosity Relationship for PG64-22 and PG76-28 Asphalt Binders.

where |E*| is the dynamic modulus in 10^5 psi; η is the viscosity of binder in 10^6 poise; f is the loading frequency in Hz; V_a is the air voids in the mix (percentage by volume); V_{beff} is the effective binder content (percentage by volume); ρ_{200} is the percentage passing # 200 (0.075 mm) sieve; ρ_4 is the cumulative percentage retained on # 4 (4.75 mm) sieve; ρ_{38} is the cumulative percentage retained on 3/8 in (9.5 mm) sieve; and ρ_{34} is the cumulative percentage retained on 3/4 in (19 mm) sieve.

The viscosity of an asphalt binder used as an input in the model can be determined from the viscosity-temperature relationship, shown in Eq. (3) [27]. This equation needs two inputs: the intercept (A) and slope (VTS) pertaining to the temperature susceptibility line of an asphalt binder. Level 2 designs use the laboratory measured A and VTS values, while Level 3 uses default values provided in the MEPDG [1]. Viscosity of both asphalt binders (i.e. PG64-22, and PG70-28) was measured in the laboratory using a Brookfield rotational viscometer in accordance with AASHTO T-316 [28]. Prior to measuring the viscosity, binders were subjected to short-term aging in a rolling thin film oven (RTFO) in accordance with AASHTO T-240 [29]. The viscosity was measured at four temperatures (135^{o}C, 150^{o}C, 165^{o}C, and 180^{o}C). Table 4 lists the results of the Brookfield rotational viscometer test. It can be seen from Table 4 that at a given temperature, PG70-28 asphalt binder is more viscous compared to PG64-22 asphalt binder.

$$\log\log(\eta) = A + VTS \log T_R \tag{3}$$

where η is the viscosity of binder (cP); T_R is the temperature, Rankine; A is the regression intercept; and VTS is the regression slope of viscosity temperature susceptibility.

Fig. 1 shows the relationship of temperature and viscosity for PG70-28, and PG64-22 binders. The A and VTS values for PG70-28 and PG64-22 were calculated as (9.78, -3.233) and (10.590, -3.537), respectively. The default A and VTS values were taken from the MEPDG guide as (9.7515, -3.217) and (10.98, -3.68) for PG70-28 and PG64-22, respectively [1]. Table 4 lists the laboratory measured and default A and VTS values for both binders. The model input parameters, namely V_{beff}, VMA, VFA, V_a, and the gradation of the mixes, are listed in Table 1 and Table 2. |E*| values were predicted for Level 2 and Level 3 for both mixes at different air voids, temperature, and frequencies, as mentioned above. A total of 576 |E*| values were estimated for each level. In the next section, the procedure is discussed to construct the master curves for all three levels of the MEPDG for both mixes.

Construction of Master Curves

Master curves provide a comparison of |E*| on a wide range of temperatures and frequencies. They were developed for all three input levels (i.e. Level 1, Level 2, and Level 3). Level 1 and Level 2 require laboratory measured A-VTS values, while Level 3 uses the default binder properties provided in the MEPDG (Table 4). Master curves were generated at a reference temperature of 21^{o}C using the procedure outlined in Bonaquist et al. [30]. This procedure eliminates the lower temperature requirement so that the time required in conducting |E*| testing and master curve construction can be reduced. The limiting maximum modulus is estimated based on binder stiffness and mix volumetric data using the Hirsch model [31]. Eqs. (4) and (5) show the sigmoidal function and the shift

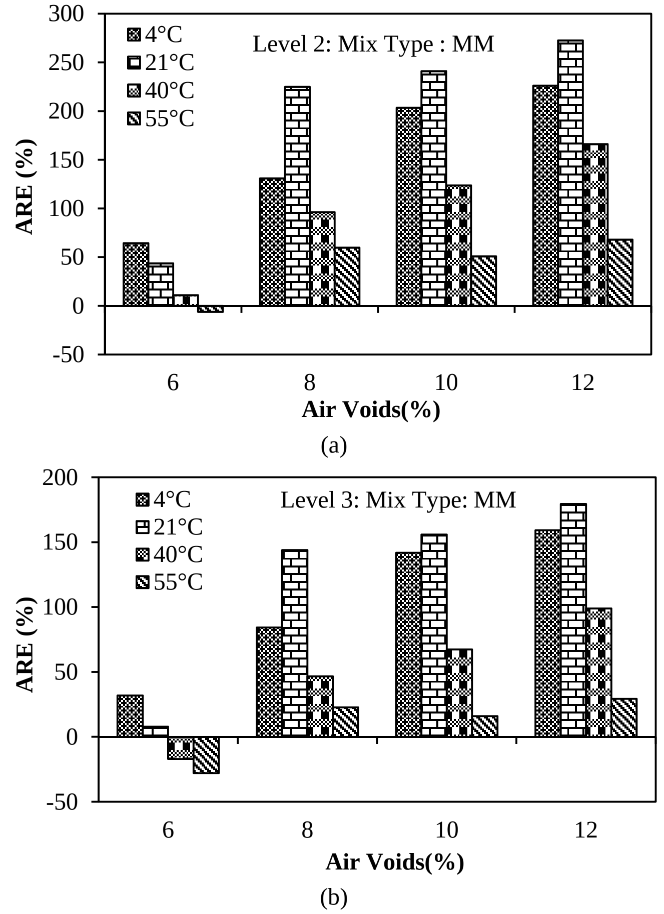


Fig. 2. Average Relative Error for MM Mix with Temperature and Air Voids at (a) Level 2 and (b) Level 3.

factor used for fitting a master curve. A nonlinear optimization program available in Microsoft Excel® was used for simultaneously solving these unknown parameters.

$$Log\left|E^*\right| = \delta + \frac{Max - \delta}{1 + \exp(\beta + \gamma\left[\log(f) + c(10^{(A+VTS\log(T_R))} - \log\eta_{t=r})\right]} \quad (4)$$

$$a(T) = \frac{f_r}{f} \quad (5)$$

where Max is the maximum $|E^*|$ for a particular mix; T_R is the temperature in Rankine; f_r is the reduced frequency at reference temperature; f is the frequency at a particular temperature; $\eta_{t=r}$ is the binder viscosity at reference temperature; β, δ, γ are the fitting coefficients and A, VTS are the parameters pertaining to the temperature-viscosity graph of binder (Table 4).

Results and Discussion

The modulus values obtained for both MM and UM mixes for Level 1, Level 2, and Level 3 of the MEPDG design are compared in this section to determine the relative accuracy of each method in determining the stiffness of the mix specimen. In addition, the master curves were compared for all three levels of the MEPDG.

Average Relative Error (ARE) for MM and UM Mixes

To better assess the performance of this model, it is necessary to estimate the percentage average relative error (ARE) for each air void and temperature level. For this purpose, |E*| data for a particular mix (i.e. MM or UM mix) was separated into four levels of air voids (i.e. 6%, 8%, 10%, and 12%). For each air void, the data was further partitioned into four temperature groups (i.e. 4°C, 21°C, 40°C, and 55°C). For example, at 6% air voids, the measured and the predicted |E*| were divided into 4°C, 21°C, 40°C, and 55°C group. The ARE was estimated for each temperature using Eq. (6).

$$\text{ARE} = \frac{\sum_{i=1}^{N} \frac{\left(\left|E^*\right|_p - \left|E^*\right|_m\right)}{\left|E^*\right|_m} \times 100}{N} \quad (6)$$

where $|E^*|_p$ is the predicted dynamic modulus in MPa for Level 2 or Level 3, $|E^*|_m$ is the laboratory measured dynamic modulus in MPa (Level 1), and N is number of observations.

MM Mix

Fig. 2 shows the plot of ARE for the MM mix estimated at Level 2 and Level 3 for all four air voids and test temperatures. It can be seen from Fig. 2 that the accuracy of both levels varies with air voids and temperature. Both levels resulted in the lowest ARE at 6% air voids, indicating that predictions are good at this air void. This plot also shows that the model resulted in significant error at higher air voids (i.e. air voids >6%) for both levels.

At each air void, the model prediction is influenced by the test temperature. The results show that the model over-predicted |E*| at all test temperatures for both levels of the MEPDG. For example, this model shows the highest error at 21°C, followed by 4°C, 40°C, and 55°C, indicating that the model deviates significantly at low and intermediate temperatures. Surprisingly, Level 3 results exhibit a comparatively smaller error compared to Level 2. Thus, although the MEPDG considers Level 2 more accurate compared to Level 3 [1], the same is not seen for the modified mix used in the present study.

UM Mix

Fig. 3 shows the ARE (%) plot for the UM mix. At low air voids (i.e. 6%), the model under-predicted |E*| values significantly for all test temperatures. The model exhibited less error for high air voids. The highest error ranged from -10% to -40% for high temperatures, indicating that the model under-predicted |E*| at this temperature. Such errors at high temperatures limit the ability of this model to capture the rutting behavior of a pavement. Level 2 predictions show slightly less magnitude of error compared to Level 3, showing that the predictions are similar to those mentioned in the MEPDG.

Comparison of MM and UM Mixes

Figs. 4 -7 show a comparison of MM and UM mixes at Level 2 and

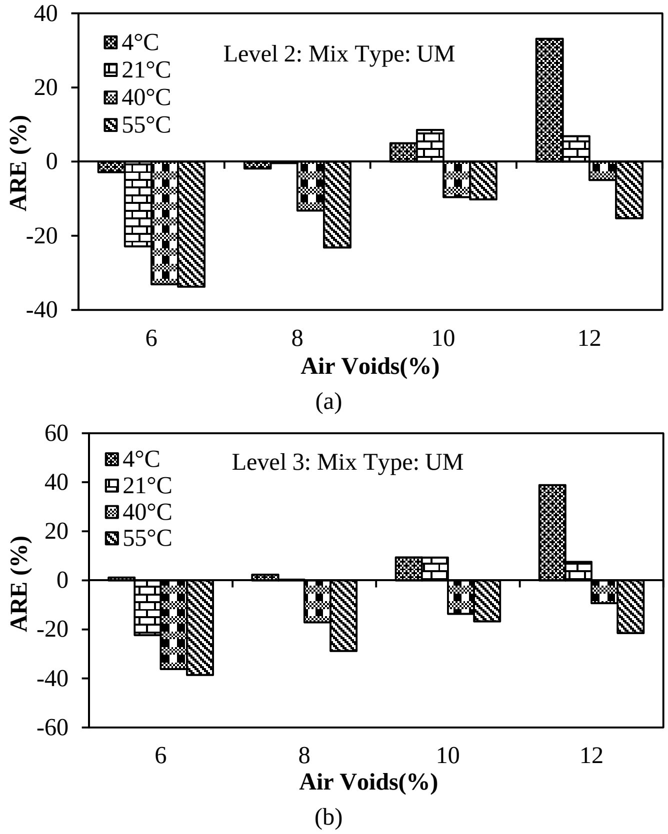


Fig. 3. Average Relative Error for UM Mix with Temperature and Air Voids for (a) Level 2 and (b) Level 3.

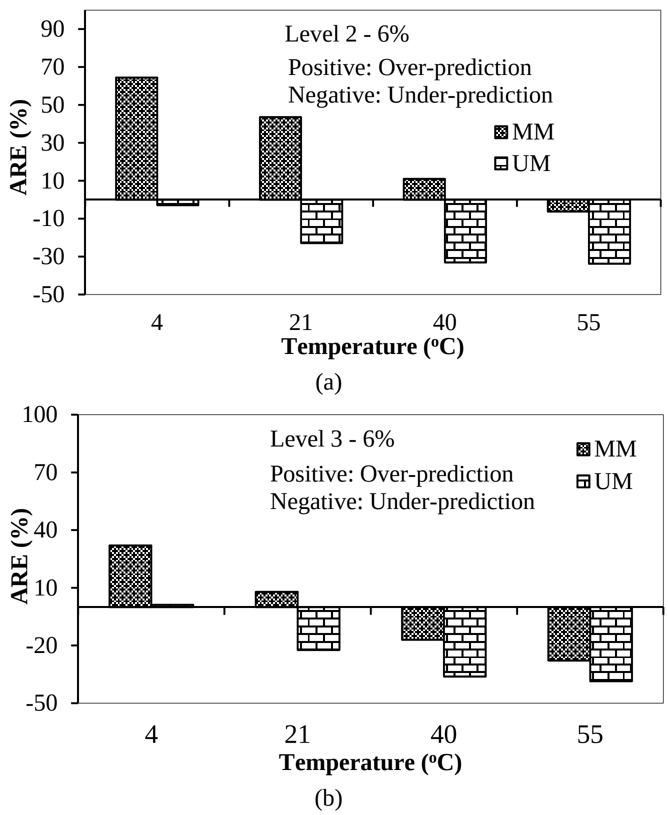


Fig. 4. Comparison of MM and UM Mix at 6% Air Voids for (a) Level 2 and (b) Level 3.

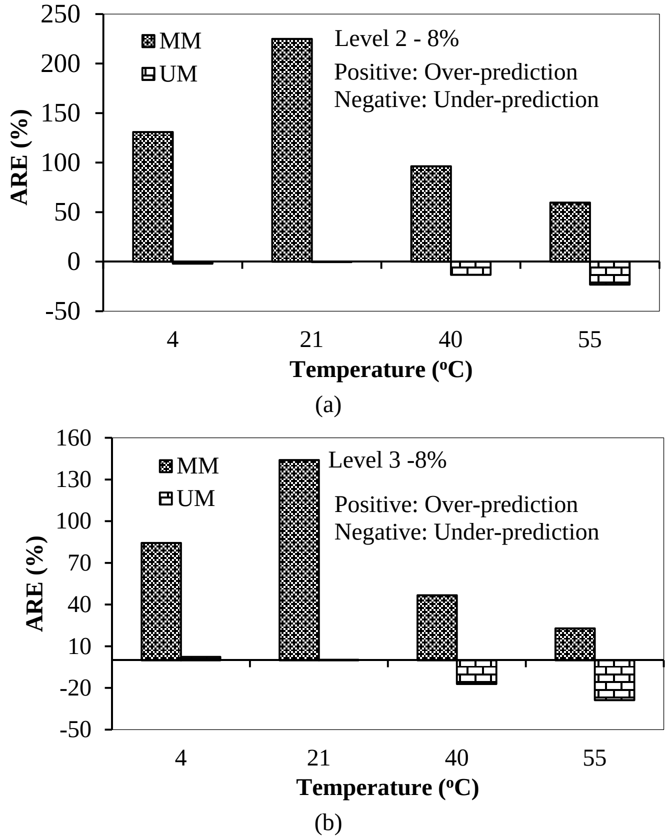


Fig. 5. Comparison of MM and UM Mix at 8% Air Voids for (a) Level 2 and (b) Level 3.

Level 3 for all four levels of air voids and test temperatures. These plots are helpful in understanding the accuracy of the predicted |E*| as a function of the mix type. Fig. 4 depicts the ARE (%) for Level 2 and Level 3 designs at 6% air voids. For both of these levels, at low and intermediate temperatures (i.e. 4^{o}C and 21^{o}C) the model under-predicted |E*| for the UM mix, while it over-predicted |E*| for the MM mix. The resulting magnitude of error for the UM mix was found to be smaller compared to the error for the MM mix, indicating that the model performs better for the UM mix. On the other hand, at a high temperature (i.e. 55^{o}C), the model works better for the MM mix compared to the UM mix. It can be concluded that at 6% air voids and high temperature, the model performs better for the MM mix.

Similarly, Fig. 5 shows the distribution of ARE (%) for Level 2 and Level 3 for 8% air voids. It is important to see that the performance of the model is different for both mixes. The model over-predicted |E*| significantly for the MM mix with ARE (%) ranging from 20% to 130%, while it resulted in a smaller magnitude of error (i.e. < 30%) for the UM mix. This indicates that the model works better for the UM mix compared to the MM mix. Similar trends were observed for 10% and 12% air voids (Fig. 6 and Fig. 7). The model over-predicted |E*| for the MM mix, while it predicted reasonably well for the UM mix. This can be due to the fact that the database used to develop this model primarily contains the unmodified mixes [13, 24]. Consequently, its performance is better for unmodified mixes.

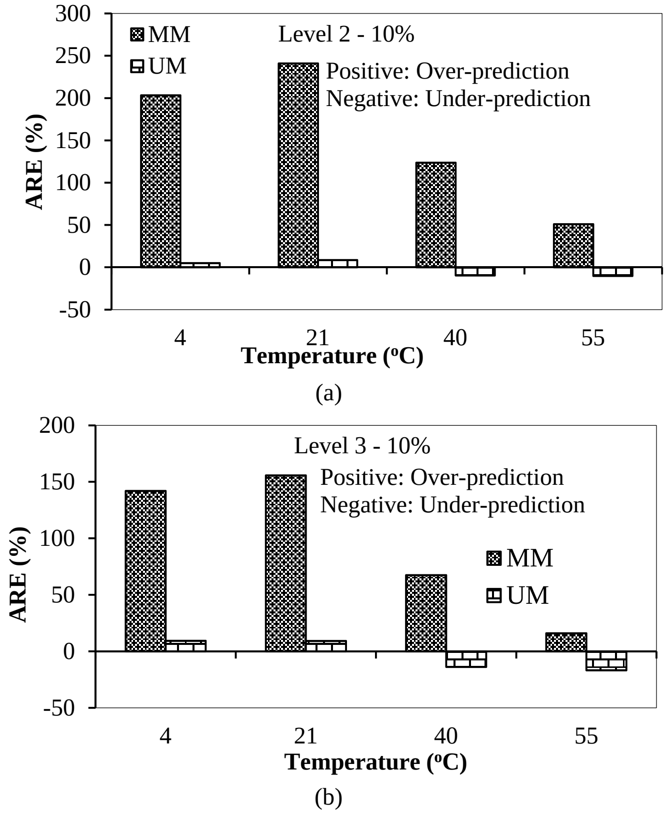


Fig. 6. Comparison of MM Mix and UM Mix at 10% Air Voids for (a) Level 2 and (b) Level 3.

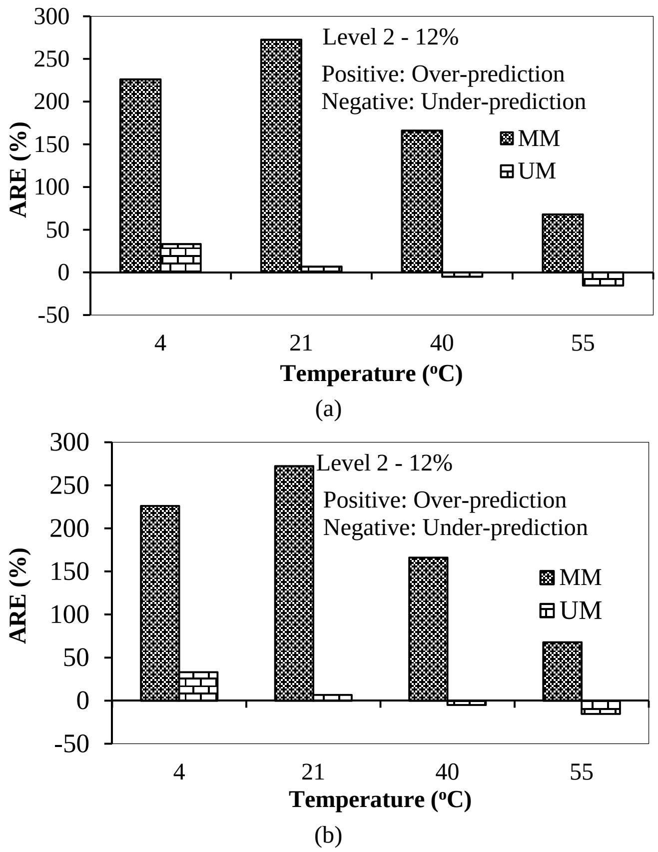


Fig. 7. Comparison of MM Mix and UM Mix at 12% Air Voids for (a) Level 2 and (b) Level 3.

Comparison of the Master Curves for MM and UM Mixes

The master curve can be used for the comparison of |E*| for a wide range of temperatures and frequencies. For this comparison, the master curves were generated for all three levels (i.e. Level 1, Level 2, and Level 3) at 21^{o}C reference temperature. Figs. 8-11 show the master curves for MM and UM mixes generated for different levels of air voids. It is seen from the figures that for the MM mix, the master curves at Level 2 and Level 3 did not match the master curve developed for Level 1. Also, the master curve for Level 2 lies above Level 3, indicating that Level 2 results in higher error compared to Level 3. For the UM mix, the Level 2 and Level 3 predictions match with Level 1, indicating that the model performs better for this mix. At low frequency (high temperature), the model under-predicts |E*| for both mixes. It is expected that at high temperatures the aggregate shape parameters dominate. Consequently, the modulus at this temperature indicates an elastic modulus of aggregates [32]. Since the model does not include any shape parameters, that may be a reason for this model to under-predict |E*| at high temperatures.

Such errors in the estimation of |E*| can result in performance issues. For example, a higher predicted value would result in a thinner pavement section and, consequently, the premature rutting failure of a pavement. Similarly, lower predicted |E*| would result in thicker pavement section that will increase the possibility of the pavement's rutting failure while simultaneously increasing the cost of its construction. Therefore, prior to the use of the predictive model for the Level 2 and Level 3 designs of the MEPDG, it is important to understand the nature of the prediction error and its magnitude.

Development of Correction Factors

An accurate estimation of |E*| is important to enhance the performance of pavements. Selection of |E*| can significantly affect the thickness of pavement and its response characteristics. As discussed in the previous sections, the prediction of |E*| for Level 2 and Level 3 varies with type of mix, air voids, and temperatures. Consequently, correction factors are required to account for the variability in the model. The correction factors were calculated for each test temperature using Eqs. (7) through (10). First, the slope (m) was determined by fitting a regression line passing through the origin for combinations of temperatures and air voids (Eq. (7)). This slope represents the calibration factor that is used to multiply the predicted |E*| to get a range of modulus close to the laboratory measured |E*|. Second, the relationship between "m" and air voids (Eq. (9)) was developed to estimate coefficients "a" and "b". Eq. (10), along with factors "a" and "b" listed in Table 5, can be used to estimate |E*| at the selected air voids and temperature.

$$|E^*|_{\text{Measured (Level 1)}} = m|E^*|_{\text{Predicted (Level 2 or Level 3)}} \tag{7}$$

$$m = f(T, V_a) \tag{8}$$

For a constant temperature, T = Constant, Eq. (8) can be written in form of Eq. (9).

$$m = f(V_a) = a(V_a)^b \tag{9}$$

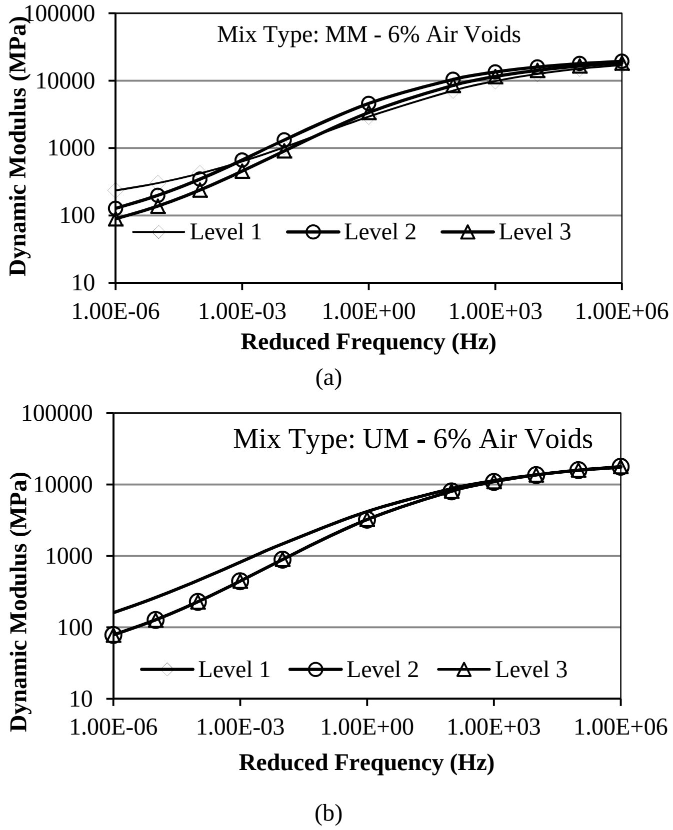


Fig. 8. Master Curve Comparisons for Level 1, Level 2, and Level 3 at 6% Air Voids for (a) MM Mix and (b) UM Mix.

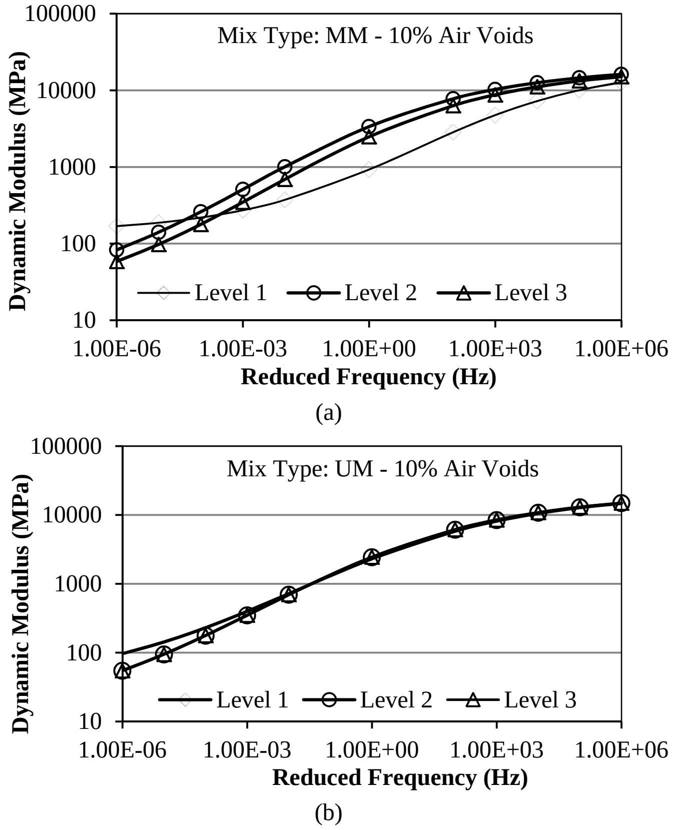


Fig. 10. Master Curve Comparisons for Level 1, Level 2, and Level 3 at 10% Air Voids for (a) MM Mix and (b) UM Mix.

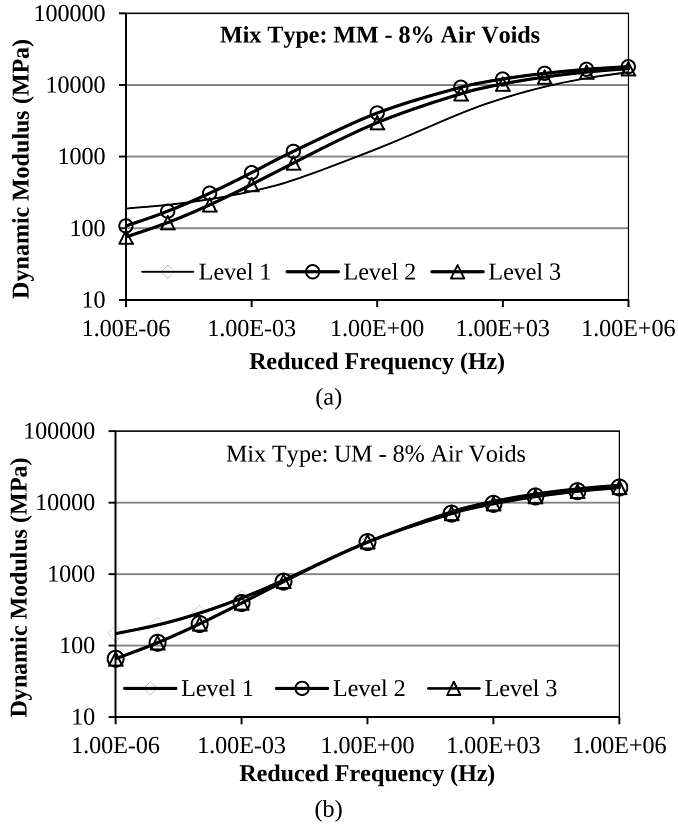


Fig. 9. Master Curve Comparisons for Level 1, Level 2, and Level 3 at 8% Air Voids for (a) MM Mix and (b) UM Mix.

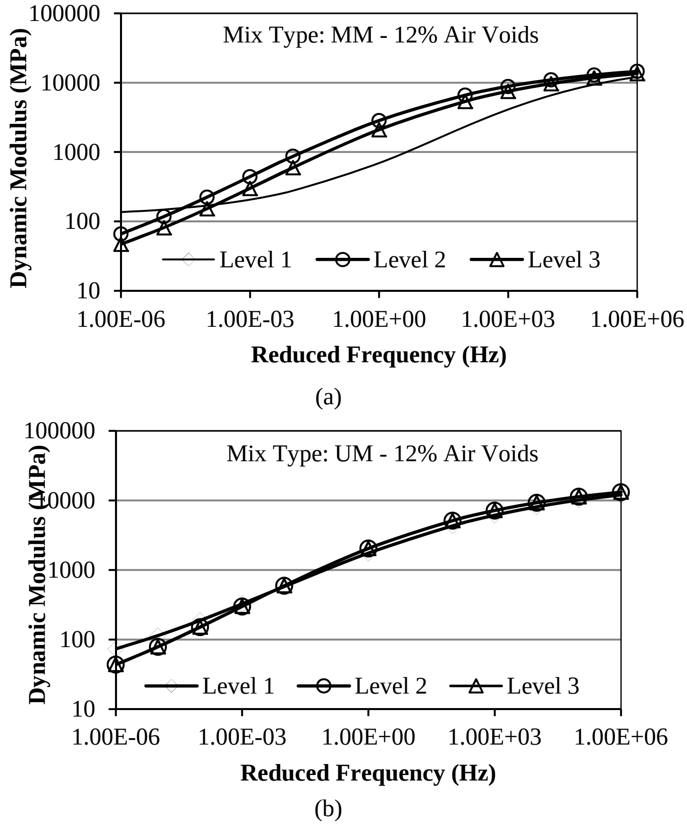
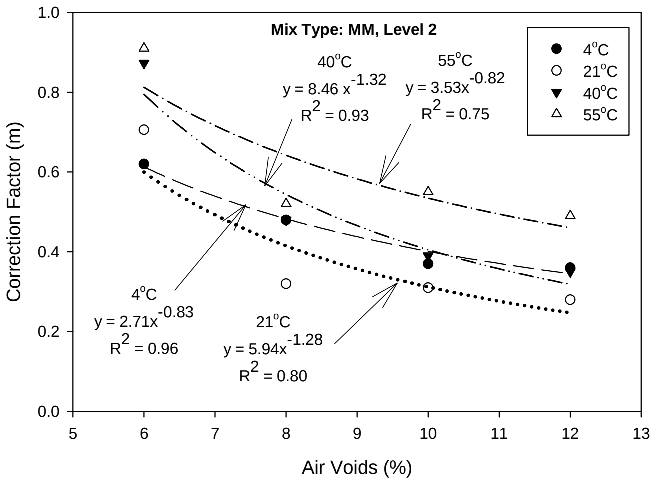


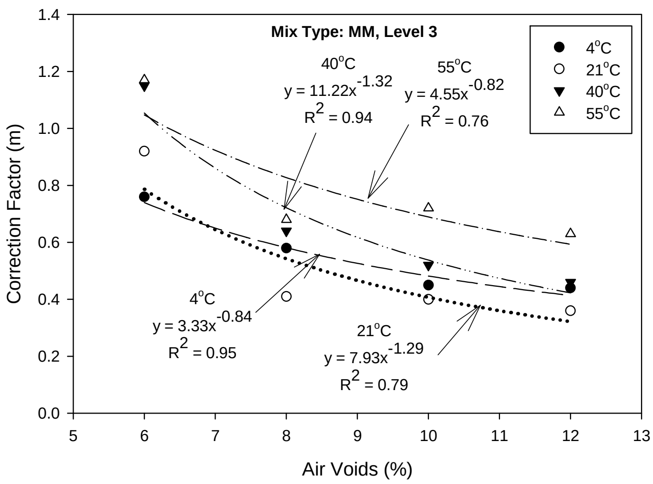
Fig. 11. Master Curve Comparisons for Level 1, Level 2, and Level 3 at 12% Air Voids for (a) MM Mix and (b) UM Mix.

Table 5. Correction Factor Parameters for Level 2 and Level 3.

T	Level 2			Level 3		
(^{o}C)	a	b	R^2	a	b	R^2
Mix Type : MM						
4	2.71	-0.83	0.96	3.33	-0.84	0.95
21	5.94	-1.28	0.80	7.93	-1.29	0.79
40	8.46	-1.32	0.93	11.22	-1.32	0.94
55	3.53	-0.82	0.75	4.55	-0.82	0.76
Mix Type : UM						
4	2.02	-0.35	0.63	1.94	-0.35	0.63
21	2.53	-0.41	0.80	2.51	-0.41	0.80
40	3.48	-0.51	0.87	3.64	-0.51	0.87
55	2.80	-0.41	0.92	3.01	-0.41	0.92



(a)

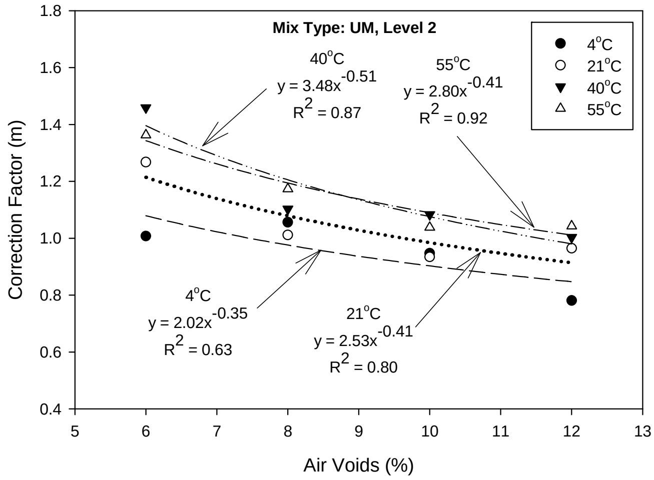


(b)

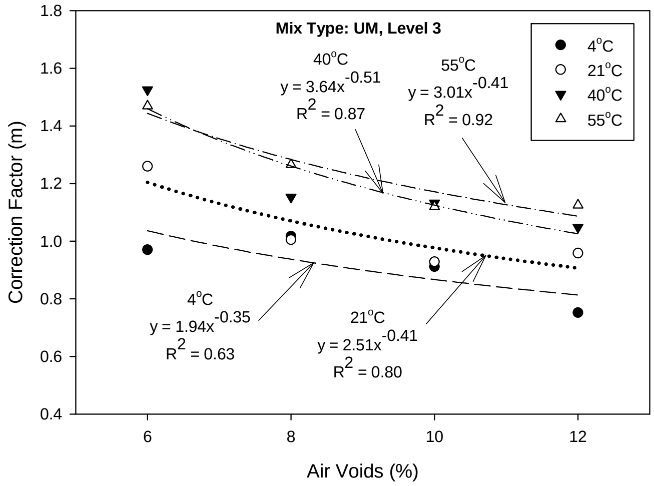
Fig.12. Correction Factor for MM Mix (a) Level 2, and (b) Level 3.

Substituting the value of "m" from Eq. (9) into Eq. (7), the relationship between different levels of the MEPDG can be written in form of Eq. (10).

$$|E^*|_{\text{Measured (Level 1)}} = a(V_a)^b\,|E^*|_{\text{Predicted (Level 2 or Level 3)}} \quad (10)$$



(a)



(b)

Fig. 13. Correction Factor for UM Mix (a) Level 2 and (b) Level 3.

where m is the slope of the regression line, T is temperature, V_a is air voids, |E*| is the dynamic modulus, and a, b are the fitting coefficients for any particular temperature (Table 5). Fig. 12 and Fig. 13 show the relationship between correction factor and air voids at different temperatures for MM and UM mixes, respectively. It is anticipated that the use of calibration factors will be helpful in estimating |E*| accurately without conducting actual modulus tests in the laboratory. Calibration factors are useful for estimating a reasonable range of |E*| used for input Level 2 and Level 3 of the MEPDG.

Conclusions and Recommendations

The present study was undertaken to compare |E*| for three input levels (i.e. Level 1, Level 2, and Level 3) of the MEPDG for modified and unmodified mixes. The analyses of results show that the performance of the Witczak model varies with the type of mix, air voids, and temperature. The accuracy of the model was evaluated by calculating the average relative error (%) and by plotting master curves. The following conclusions can be drawn from the results and discussions presented in the preceding sections.

- At low air voids, for example 6%, the model works better for the modified mix than the unmodified mix.
- For higher air voids (i.e. 8%, 10%, and 12%), the model over-predicted and under-predicted |E*| for modified and unmodified mixes, respectively. This indicates that the performance of the model changes with type of mix.
- For the modified mix, Level 2 resulted in a higher magnitude of error compared to Level 3, which is contrary to the expectation that Levels 1, 2, and 3 are in reducing order of accuracy.
- For the unmodified mix, Level 2 resulted in lesser error compared to Level 3, indicating that use of default viscosity values from the MEPDG may work well for unmodified mix.
- The Witczak model is very sensitive to input parameters pertaining to the viscosity-temperature relationship.
  Correction factors developed in this study for both mixes at different temperatures and air voids can be used as correction factors in estimating |E*|, resulting in |E*| values comparable to Level 1.
- It is recommended that similar studies be conducted for mixes from different sources with different types of binders and aggregates. Furthermore, different mixes should be tested to develop common correction factors applicable for a wide range of mixes.

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