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Assessment of analytical tools used to estimate the stiffness of asphalt concrete

Morched Zeghal and ElHussein H. Mohamed

Abstract: This paper presents the results of an assessment performed on the empirical model used in level 3 input of the proposed mechanistic–empirical pavement design guide (MEPDG) developed under the National Cooperative Highway Research Program (NCHRP) project 1-37A. The empirical formula estimates the stiffness (dynamic modulus) of asphalt concrete mixes used in paving roads. The assessment revealed that analytically estimated dynamic modulus differs substantially from the actual value determined in the laboratory. Errors are high at elevated service temperatures and for mixes prepared with engineered binders. An alternative approach is presented in this paper based on the use of generic modulus values. Generic asphalt concrete dynamic modulus values were generated from tests performed on typical Marshall and SuperPave mixes. Results were compiled in a database (material library) to provide users of the MEPDG with estimates of the dynamic modulus that will yield more accurate predictions of performance until dynamic modulus laboratory testing capabilities are established locally.

Key words: asphalt concrete, dynamic modulus, predictive model, material library.

Résumé : Cet article présente les résultats d'une évaluation effectuée sur le modèle empirique utilisé dans les intrants de niveau 3 du Guide de conception mécanisto-empirique des chaussées (« MEPDG ») produit lors du projet « National Cooperative Highway Research Program » (« NCHRP ») 1-37A. La formule empirique estime la rigidité (module dynamique) des mélanges de béton bitumineux utilisés dans les chaussées. L'évaluation a montré que le module dynamique estimé par analyse diffère grandement de la valeur réelle déterminée en laboratoire. Les erreurs sont grandes à des températures de service élevées et pour des mélanges préparés avec des liants artificiels. Une autre approche, basée sur l'utilisation des valeurs du module générique, est présentée dans cet article. Les valeurs du module générique dynamique du béton bitumineux ont été générées à partir de tests effectués sur les mélanges « Marshall » et « SuperPave » typiques. Les résultats ont été compilés dans une base de données (bibliothèque de matériaux) afin de fournir aux utilisateurs du « MEPDG » des estimations du module dynamique qui permettront d'avoir des prévisions plus exactes du rendement tant que les capacités d'essai en laboratoire du module dynamique n'auront pas été établies localement.

Mots-clés : béton bitumineux, module dynamique, modèle prédictif, bibliothèque de matériaux.

[Traduit par la Rédaction]

Introduction

Effective characterization of pavement materials is a key element in the application of mechanistic design procedures to produce cost-effective and reliable design of pavements. The characterization of pavement materials has undergone many developments in the last three decades. Characterization of unbound materials changed from the physical approach to the resilient modulus approach. This parameter (i.e., modulus) is sufficient for conducting the structural analysis necessary for establishing the state of stresses and strains in unbound layers as influenced by the physical state

of the material related to its moisture content and density. Developments related to asphalt concrete (AC) materials resulted in abandoning reliance on Marshall stability, flow, and other physical properties (air voids and voids in the mineral aggregates) in favour of a mechanistic characterization approach based on the complex modulus.

These developments facilitated the evolution of mechanistic design techniques, such as the new mechanistic–empirical pavement design guide (MEPDG) developed under the National Cooperative Highway Research Program (NCHRP) project 1-37A (NCHRP 2004). The MEPDG is expected to replace the current American Association of State Highway and Transportation Officials (AASHTO) design that has been widely used in Canada. The complex modulus concept was incorporated in the MEPDG to support structural analysis so that the outcome can be used to empirically predict performance.

Mechanistic characterization of AC in the laboratory targets capturing the material response, which is known to include elastic, viscous, and plastic components. The complexity of the response hampered material development and the establishment of an effective laboratory characterization technique. Today, the most effective scheme is based on a simplified linear viscoelastic approach, which can be consid-

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ered satisfactory at low strain amplitude of pavement deformations (Di Benedetto and De La Roche 1998). Only the elastic component of the response (dynamic modulus) has been considered in the MEPDG. The dynamic modulus is measured at different temperatures and loading frequencies to construct a master curve that integrates various design factors, such as temperature, material aging, and traffic (loading frequency). The new MEPDG offers users a choice of three hierarchical levels of input. Each level requires a different method for estimating the dynamic modulus. At the first level, the dynamic modulus is measured in the laboratory at different temperatures and loading frequencies, which the MEPDG model uses to develop a master curve that accurately describes the time-temperature dependency of the mix response. Knowing that the majority of users do not yet have necessary laboratory testing capabilities, second and third levels for estimating the dynamic moduli were incorporated in the MEPDG. An empirical equation, known as the predictive equation, is used to construct the master curve. Direct measurement in the laboratory remains the most accurate method for determining the dynamic modulus, but the use of the predictive equation will be relied upon by many because of the high cost and complexity of laboratory testing and the lack of personnel trained to conduct the test. As it is anticipated that a significant number of Canadian agencies adopting the new MEPDG will be using level 3 input, there is a need to assess the effectiveness of the predictive model, which is the subject of this paper.

The effectiveness of the predictive model was assessed using results of a comprehensive laboratory testing program that covered a wide range of AC mix types prepared using different aggregate gradations, binder types, and mix design methods (Marshall and SuperPave). The review process considered the history of predictive models through their evolution over the last 40 years.

Predictive models

Given the complexity and the time-consuming nature of the laboratory test procedure designed for the determination of the dynamic modulus under sinusoidal loading, many predictive equations have been proposed to estimate its value for various asphalt mixes. The first predictive equation was proposed 40 years ago, and several equations were proposed subsequently. Witczak and Fonseca (1996) summarized the most important of these models developed since 1967 (Table 1) and reported that they have several limitations. In their evaluation, they found that the major drawback of these equations is associated with classical statistical principles regarding model extrapolations of parameters outside the range of variables used to develop the model. Further, all the test data were generated within a temperature range of 5 to 40 °C. They concluded that these limitations resulted in unrealistically large and small predictive moduli for very cold and very hot conditions, respectively outside this range. Witczak and Fonseca also observed that the majority of these predictive equations were based on the original bitumen properties, with the test temperature being the most important variable in the system. However, these predictive equations do not account for the hardening effects on the binder, and, consequently do not account for the AC properties associated with long-term aging.

Witczak and Fonseca (1996) proposed a new predictive equation for estimating the dynamic modulus of AC materials based on a statistical study conducted on data consisting of 1429 points from 149 separate AC mixes. In this equation, they included improvements over earlier models (shown in Table 1) by taking into account hardening effects from short- and long-term aging and extreme temperature conditions. The equation is based on the gradation of aggregates in the mix and asphalt binder properties and has the following form:

$$[1] \quad \log E^* = -0.261 + 0.008225p_{200} - 0.00000101(p_{200})^2 + 0.00196p_4 \\ - 0.0315V_a - 0.415 \left(\frac{V_{\text{beff}}}{V_{\text{beff}} + V_a} \right) + \frac{3.87 + 0.002808p_4 + 0.00000404p_{3/8} - 0.0001786(p_{3/8})^2 + 0.0164p_{3/4}}{1 + \exp[-0.716 \log(f) - 0.7425 \log(\eta)]}$$

where E^* is the asphalt mix complex modulus (in $\text{psi} \times 10^5$, where 1 $\text{psi} = 6.985 \text{ kPa}$); η is the bitumen viscosity (in $\text{P} \times 10^6$, where $\text{P} = 0.1 \text{ Pa}\cdot\text{s}$); f is the loading frequency (in Hz); V_a is the percentage of air voids in the mix, by volume; V_{beff} is the percentage of effective bitumen content, by volume; $p_{3/4}$ is the percentage retained on the 3/4 in. (1 in. = 25.4 mm) sieve by total aggregate weight (cumulative); $p_{3/8}$ is the percentage retained on the 3/8 in. sieve by total aggregate weight (cumulative); p_4 is the per-

centage retained on the No. 4 sieve by total aggregate weight (cumulative); and p_{200} is the percentage passing the No. 200 sieve by total aggregate weight.

Later, more data were introduced in the analysis, and the predictive model (given in eq. [1]) for calculating the dynamic modulus was modified to the following equation (NCHRP 2004):

$$[2] \quad \log E^* = 3.750063 + 0.02932p_{200} - 0.001767(p_{200})^2 - 0.002841p_4 \\ - 0.005809V_a - 0.802208 \left(\frac{V_{\text{beff}}}{V_{\text{beff}} + V_a} \right) + \frac{3.871977 - 0.0021p_4 + 0.003958p_{3/8} - 0.000017(p_{3/8})^2 + 0.005470p_{3/4}}{1 + \exp[-0.603313 - 0.313351 \log(f) - 0.393532 \log(\eta)]}$$

Table 1. Dynamic modulus predictive models (after Witczak and Fonseca 1996).

Model No.	Model form
1	$\log_{10} E^* = a_0 + a_1 p_{200} + a_2 V_a + a_3 \eta_{70:10^6} + a_4 p_{ac}^{a_5} t_p^{a_6}$
2	$\log_{10} E^* = b_0 + b_1 p_{200} + b_2 V_a + b_3 p_{ac}^{b_4} (\log \eta_t)^{b_5}$
3	$\log_{10} E^* = c_0 c_1 p^{-(t/c_2)}$
4	$\log_{10} E^* = d_0 + d_1 (p_{200})^{d_2} + d_3 V_a + d_4 \eta_{70:10^6} + d_5 [t_p^{(d_6+d_7 \log f)} p_{ac}^{d_8}] + d_9 [t_p^{(d_6+d_7 \log f)} p_{ac}^{d_8} f^{d_{10}}] + d_{11} f^{d_{12}}$
5	$\log_{10} E^* = e_0 + e_1 V_a + e_2 \eta_{70:10^6} + e_3 t_p^{e_4} V_{beff}^{e_5}$
6	$\log_{10} E^* = g_0 + g_1 (p_{200})^{g_2} + g_3 V_a + g_4 \eta_{70:10^6} + g_5 f^{g_6} + [g_7 t_p^{(g_8+g_9 \log f)} + g_{10} f^{g_{11}} t_p^{(g_8+g_9 \log f)}] [p_{ac} - p_{opt} + g_{12}]^{g_{13}}$
7	$\log_{10} E^* = h_0 + h_1 V_a + h_2 p_{3/4} + h_3 \eta_{70:10^6} + h_4 t_p + h_5 \log f + h_6 (\log f t_p^2) + h_7 (V_{beff} - V_{beffopt} + h_8) t_p^{h_9} + h_{10} (V_{beff} p_4) + h_{11} (p_{200} p_{abs})$
8	$\log_{10} E^* = k_0 + k_1 V_{beff} + k_2 V_a + k_3 p_{200} + k_4 p_4 + k_5 p_{abs} + k_6 t_p + k_7 f + k_8 t_p^2 + k_9 V_{beff}^2 + k_{10} p_{200}^2 + k_{11} p_{3/4}^2 + k_{12} p_{3/8}^2 + k_{14} p_{abs}^2 + k_{13} p_4^2 + k_{14} p_{abs}^2 + k_{15} \eta_{70:10^6} + k_{16} f^2 + k_{17} p_{3/8} V_{beff} k_{18} p_{3/8} V_{beff} + k_{19} p_{3/4} p_4 + k_{20} p_{3/8} p_{abs}$
9	$\log_{10} E^* = l_0 + l_1 V_{beff} + l_2 V_a + l_3 p_{200} + l_4 p_{abs} + l_5 t_p + l_6 f + l_7 t_p^2 + l_8 V_{beff}^2 + l_9 p_{200}^2 + l_{10} p_{3/4}^2 + l_{11} p_{3/8}^2 + l_{12} p_{abs}^2 + l_{13} (\eta_{70:10^6})^2 + l_{14} f^2 + l_{15} p_{3/8} V_{beff} + l_{17} p_{3/4} p_4 + l_{18} p_{3/8} p_4 + l_{19} p_{3/8} p_{abs}$
10	$\log_{10} E^* = m_0 + m_1 V_{beff} + m_2 V_a + m_3 \eta_{70:10^6} + m_4 t_p + m_5 \log f + m_6 \log(f t_p^2) + m_7 (V_{beff} - V_{beffopt} + m_8) t_p^{m_9} + m_{10} (V_{beff} p_4) + m_{11} (p_{200} p_{abs})$

Note: $a_i, b_i, c_i, d_i, e_i, g_i, h_i, k_i, l_i, m_i$, regression coefficients; p_{abs} , percentage asphalt absorption; p_{ac} , percentage asphalt content, by weight of mix; p_{opt} , optimum asphalt content of mix, in percent by weight of mix; t_p , test temperature (in °F); $V_{beffopt}$, percentage effective optimum asphalt content of mix by volume; η_t , asphalt concrete viscosity at test temperature t (in P, where $1 \text{ P} = 0.1 \text{ Pa-s}$); $\eta_{70:10^6}$, asphalt concrete viscosity at 70°F (21.1 °C) (in $\text{P} \times 10^6$).

It should be noted that there was no change in the general form of eq. [2] compared with eq. [1]. However, the constant coefficients were changed to reflect calibration achieved with more data and to switch the units of the estimated dynamic moduli from 10^5 psi to psi.

The bitumen viscosity at a temperature of interest (η) is a key parameter in eqs. [1] and [2]. Improvements in terms of hardening and aging over the earlier models (given in Table 1) were achieved by adjusting the manner in which viscosity is captured in the equations. Viscosity of the binder is determined using the American Society for Testing and Materials (ASTM) viscosity temperature relationship (NCHRP 2004)

$$[3] \quad \log \log \eta = A + \text{VTS} \log T_R$$

where η is the bitumen viscosity (in cP, $1 \text{ cP} = 0.001 \text{ Pa-s}$), T_R is the temperature (Rankine), and A and VTS are the regression intercept and slope of the viscosity-temperature curve, respectively. It is recommended to determine the regression constants A and VTS using the results of the dynamic shear rheometer test to satisfy level 1 input requirements. However, no testing is recommended for level 3, and default values are provided as a function of the performance grade, the viscosity grade and the penetration grade of the binder used in the mix. The A and VTS values recommended as a function of the performance grade, were used in this study to determine the viscosity of the binder at the temperature of interest.

The experimental program conducted in this study focused on data required for assessment of the model given in eq. [2]. Limited applications of eq. [1] were made to delineate improvement brought by the inclusion of more data points in the statistical analysis performed to develop these two equations.

Experimental program

The experimental program was designed with the objective of generating dynamic modulus laboratory data for a

variety of asphalt mixes with known physical properties. Physical characteristics of aggregates, binders, and mixes were then used to estimate the dynamic moduli using eq. [2]. The estimated dynamic moduli were compared with those measured in the laboratory to assess the effectiveness of the predictive model.

Complex modulus testing technique

Specimens for complex modulus tests were compacted according to AASHTO standard T-312 (AASHTO 1993c) and exposed to short-term oven aging in accordance with the AASHTO standard R-30 (AASHTO 2002) procedure. All specimens underwent physical characterization. The bulk specific gravity (G_{mb}), maximum specific gravity (G_{mm}), and air voids (V_a) were determined according to AASHTO standards T166 (AASHTO 1993b), T209 (AASHTO 2005), and T269 (AASHTO 1997), respectively. Other properties evaluated included the binder content by total mass of mixture (P_b), voids in the mineral aggregate as percentage of bulk volume (VMA), and the effective bitumen content as percentage by volume (V_{beff}).

The complex modulus test setup consisted of a loading frame, an environmental chamber, measuring systems, and specimen end fixtures (Fig. 1). The loading frame was a servo-hydraulic testing machine capable of applying an axial sinusoidal strain load over a range of frequencies from 0.1 to 20 Hz and measuring stress levels up to 6.0 MPa (800 psi). The environmental chamber used to control specimen temperature is capable of controlling the temperature of the specimen over a temperature range of -10 to $+40$ °C (14 °F to 104 °F) to an accuracy of ± 0.5 °C (± 1 °F). The system is capable of measuring and recording the time history of applied deformations and the corresponding axial load. It consisted of an electronic load cell and two extensometers. The strain sensors were mounted with springs on the side of the sample at midheight (opposite to each other) and placed 180° apart as illustrated in Fig. 1.

Fig. 1. Complex modulus test setup. AC, asphalt concrete.

The protocol developed at the National Research Council Canada (NRCC) for performing the complex modulus test was used to determine the dynamic modulus (NRCC 2004). It is a tension-compression mechanical test performed using a strain-controlled approach. The strain-controlled mode was found to be more effective at ensuring that the assumed linear viscoelasticity is obeyed (Osman et al. 2007). In loading the specimen, a short rest period of 2 min was assigned after 20 and 10 Hz for tests performed at temperatures of -10 , 0 , and $+10$ °C. A rest period of 1 min was assigned after 5, 1, 0.3, and 0.1 Hz for tests performed at -10 , 0 , and $+10$ °C. Also, a rest period of 1 min. was assigned after all frequencies for testing at temperatures of $+20$, $+30$, and $+40$ °C. The adopted sampling rate was 100 points per cycle, which was found to be adequate for accurately plotting sinusoidal signals and for effectively capturing the peak stress and strain values. The commercial statistical package TableCurve was used to reduce the data and fit it to a waveform equation (sinusoidal) to assist in determining amplitudes of the stress and strain signals and the phase angle. Complex modulus tests were performed on samples that were 6 d old. A minimum of two replicates was used in each test.

Test matrix

The experimental testing program involved different binders, aggregates, and mix designs. Ministry of Transportation of Ontario (MTO) specifications (MTO 1990) were followed in determining the appropriate combinations of different aggregate fractions to achieve the job mix formulae that satisfied gradation requirements outlined for each specific hot-mix asphalt (HMA) type. The AASHTO specifications were followed to create job mix formulae that satisfied the gradation curves of SuperPave mix designs (AASHTO 1993a). Test specimens were prepared following HMA specifications (HMA1, HMA2, and HMA3) known in Ontario as HL8, HL4, and HL3 and commonly used as a stabilized base, binder, and surface course, respectively. Specimens were prepared using three performance-grade binders (PG 64-34, PG 52-34, and PG 58-22). SuperPave mixes prepared included coarse (SP1) and fine (SP2) mixes used as the binder and surface course, respectively. The SP1 and SP2 SuperPave mixes had nominal maximum aggregate sizes of 19.0 and 12.5 mm, respectively. All three binders used to prepare the HMA specimens were also used in the SuperPave mixes. Gradations used in all the

specimen types are given in Table 2. A gyratory compactor was used to prepare the specimens, and the specimens tested in this study were compacted to an air voids content of $5 \pm 0.5\%$.

Results and analysis

Physical characteristics determined for the mixes tested in this study are given in Table 3. These properties along with gradation and binder characteristics and loading frequency were used to estimate the dynamic modulus of each mix. The dynamic modulus values predicted for the different test temperatures and loading frequencies using eq. [2] were compared with those results from complex modulus tests performed in the laboratory. Predicted and laboratory-measured dynamic modulus values were compared for three different temperature conditions (-10 , $+20$, and $+40$ °C). These temperatures were chosen to represent cold, moderate, and warm service temperatures. Comparison involved three loading frequencies (0.1, 1, and 20 Hz) to represent slow, medium, and relatively fast vehicle speeds. To fully assess the capabilities of the predictive equation, the complex modulus values determined from laboratory tests and those estimated using the predictive equation were analyzed from different perspectives to examine the capabilities of the analytical model to delineate mix responses observed in the laboratory as they relate to the influence of binder type, temperature, and loading frequency.

Impact of binder type

Results of the experimental program were used to gauge the effectiveness of the dynamic modulus concept in characterizing AC materials and, more precisely, its ability to discriminate between mixes prepared with different binders. Dynamic modulus values determined in the laboratory at a frequency of 1 Hz for two HMA3 mixes prepared with two uniquely different binder types, namely PG 64-34 and PG 58-22, are shown in Fig. 2. The response of the engineered binder (PG 64-34) compared with that of the neat binder (PG 58-22) suggests that the objective behind engineering the binder is fulfilled, namely to reduce brittleness of the mix at low temperatures to minimize the potential for cracking. The measured dynamic modulus of the HMA3 mix prepared with the PG 64-34 binder is half that of the mix prepared with the PG 58-22 binder, as depicted in Fig. 2.

The dynamic moduli for the two aforementioned binders (PG 64-34 and PG 58-22) were estimated using the predictive model given in eq. [2]. The results are also shown in Fig. 2. It is clear that the predictive equation correctly rated the mix response at low temperatures as influenced by the properties of the two binders. However, the predictive equation was less successful in quantifying the difference between the two binders as measured in the laboratory using the complex modulus test. Predictions of the response made at -10 °C for the two binders suggest a difference of less than 10%, whereas the measured response reflected a difference of 100%.

The observed discrepancy between the analytical model estimates and actual laboratory test results was also assessed in terms of the percentage error defined by

Table 2. Aggregates gradation for asphalt concrete mixes.

Sieve size (mm)	Percent passing				
	HMA1	HMA2	HMA3	SP1	SP2
26.5	100.0	100.0	100.0	92.5	95.0
19.0	96.5	100.0	100.0	87.2	95.0
16.0	88.5	98.4	100.0	75.8	94.1
12.7	72.2	84.6	97.5	59.4	86.5
9.5	53.8	65.0	79.3	43.4	75.7
4.8	48.6	59.1	59.0	40.8	67.9
2.4	39.1	45.4	52.1	39.8	46.1
1.2	31.9	35.4	46.3	37.8	31.0
0.600	17.3	20.4	22.5	16.8	21.3
0.300	7.8	10.2	7.9	4.5	13.3
0.150	3.6	5.0	3.0	1.2	7.2
0.075	0.5	0.7	0.5	0.3	0.9

Note: HMA, hot-mix asphalt; SP, SuperPave.

Table 3. Physical properties determined for three SP2 SuperPave mixes.

Property	PG 58-22	PG 64-34	PG 52-34
P_b (%)	4.5	4.5	4.5
G_{mm}	2.577	2.590	2.570
G_{mb}	2.434	2.435	2.441
G_{sb}	2.755	2.755	2.755
VMA (%)	15.6	15.6	15.4
V_a (%)	5.1	5.0	5.0
V_{beff} (%)	10.1	9.6	10.4

Note: G_{sb} , bulk specific gravity of aggregates.

Fig. 2. Measured and predicted modulus for two HMA3 mixes prepared with different binders (1 Hz).

$$[4] \quad \text{percentage error} = \frac{[(\text{predicted} - \text{measured}) / \text{measured}] \times 100}{}$$

Three different temperatures and three frequencies were considered in this assessment. The discrepancy observed for the HMA3 mixes prepared using the neat binder PG 58-22 and the modified binder PG 52-34 is highlighted in Table 4. For the HMA3 mix prepared with the PG 52-34 binder, the results indicate an overprediction trend with a deviation of more than 200% at high temperatures. In contrast, estimates of the HMA3 mix modulus prepared using the PG 58-22

Table 4. Percentage error calculated at different temperatures and loading frequencies for HMA3 mixes prepared with neat binder (PG 58-22) and modified binder (PG 52-34).

Temperature (°C)	Percentage error		
	0.1 Hz	1 Hz	20 Hz
PG 58-22			
-10	-46	-37	-48
+20	-17	-43	-33
+40	145	106	34
PG 52-34			
-10	48	26	-9
+20	124	122	75
+40	999	625	268

binder resulted in a mix of an underprediction of up to 48% for tests performed at low to medium temperatures and an overprediction of up to 145% for tests performed at high temperatures.

A comparison was also made between the complex modulus test and the predictive equation for SuperPave mixes with a nominal maximum aggregates size of 19.0 mm and the same gradation. Results obtained from testing samples prepared with the PG 58-22 and PG 52-34 binders and loaded at a frequency of 0.1 Hz are plotted in Fig. 3. The results again confirmed the ability of the complex modulus test to properly rate the two mixes based on the response measured at a low temperature. The results of the laboratory tests discriminated effectively between the impacts of the two binders, where the mix prepared with the engineered binder (PG 52-34) showed lower stiffness than the neat binder (PG 58-22) at low temperatures. Dynamic modulus estimates produced using the predictive model given in eq. [2] are also shown in Fig. 3. The estimates made by the predictive equation produced an accurate rating. However, similar to the Marshall mixes, the predictive model was less successful in quantifying the difference between the two SuperPave mixes. The difference between dynamic modulus values at -10 °C estimated by eq. [2] was only 23%, whereas that calculated from results obtained from direct measurements made in the laboratory reached 112%.

Predictions at low and high temperatures

As older empirical models were criticized mainly for their limited ability to predict the modulus at very cold and very hot conditions, the assessment conducted in this study examined responses at two extreme temperatures, namely -10 and +40 °C. Laboratory-measured and model-predicted dynamic moduli of all mixes considered in this study were compared. The comparison between estimated and measured dynamic moduli at a low temperature of -10 °C is presented in Table 5. Equation [2] mainly underestimated the dynamic modulus regardless of the mix design method and the nature of the mix (fine or coarse). Underprediction is reflected in the negative percentage error for almost all mixes, which is expected to result in underestimating the potential thermal cracking at low temperatures and the road will not survive for its full design life. Modulus underprediction does not seem to be affected by changes in loading frequency. The

Fig. 3. Measured and predicted modulus for two coarse SuperPave mixes prepared with different binders (0.1 Hz).

viscosity of the binder at low temperatures is not affected by the loading frequency, as the material tends to be elastic.

The contrast between predicted and laboratory-measured dynamic modulus at +40 °C (see Table 6) showed a different picture from that observed at -10 °C. Overall, predictions made by eq. [2] overestimated the dynamic modulus and reflected a significant impact for the loading frequency. A higher overprediction was observed when the loading frequency was decreased. Overestimating the dynamic modulus value at high temperatures also has a negative effect because the analytical model will underestimate the potential for rutting. The results shown in Table 6 indicate that for all conventional mixes (HMA2, HMA3, SP1, and SP2), the discrepancy was higher for mixes prepared with the modified binders (PG 64-34 and PG 52-34) as compared with that prepared with the neat binder (PG 58-22).

Overall evaluation of the two models

Although eq. [2] is the one implemented in the MEPDG, which is the focus of this paper, assessment was extended to include eq. [1] to gauge the progress made by the introduction of eq. [2]. Analysis was intended to examine the effect of recalibration of eq. [1] using more data points. The outcome of evaluating the two equations is shown in Fig. 4 using the equality line. Points located above this line indicate that model predictions overestimated the dynamic modulus value and points below indicate underestimated values. Qualitatively, eq. [2] improved accuracy in estimating the dynamic modulus within the high modulus range (value greater than 15 000 MPa). Application of eq. [2] switched estimates of the modulus from predominantly underpredictions to a mix of overpredictions and underpredictions. However, predictions made with eq. [2] for moduli values lower than 15 000 MPa showed little or no improvements with respect to the laboratory determined modulus. Predictions made within modulus values ranging from 4000 to 15 000 MPa changed from underestimation when eq. [1] was used to overestimation of the modulus value with the application of eq. [2]. The overall improvement brought by eq. [2] was also apparent when the average percent error was evaluated for all data points generated in this study. The average percent error for eq. [1] was 97%, whereas application of eq. [2] resulted in an average percent error of 77%.

Alternative to the predictive model

The MEPDG is an important step forward in improving road design because of its more effective mechanistic approach, which will facilitate establishment of a performance-based practice. Problems identified in level 3 of the MEPDG, associated with inaccurate estimates of the dynamic modulus, will discourage users from implementing the new MEPDG as it produces unreliable designs. This section of the paper discusses an initiative for an alternative source (to the predictive equation) for obtaining modulus values. Instead of relying on the system implemented in the MEPDG, a material library, populated with results from laboratory tests conducted on local mixes, can be used to obtain modulus values as input for running level 1 of the software. Results of the pilot NRCC study that compared the use of the predictive equation and the use of generic data listed in the material library can be found in ElHussein H. Mohamed et al. (2006). The proposed approach is discussed briefly here using data for a typical HMA2 mix prepared using a PG 52-34 binder and designed in accordance with MTO specifications. For testing the material library approach, two aggregate gradations were selected, one to simulate the generic value listed in the material library and the other to represent an actual mix portrayed as the job mix formula. Physical and mechanical properties were determined in the laboratory to use as input for running the new MEPDG.

The dynamic modulus library values for the HMA2 mix, which represent the generic values, were plotted against the measured values for the job mix formula as shown in Fig. 5. Similarly, the actual dynamic modulus values measured in the laboratory and those estimated by the predictive equation were plotted in the same figure. From Fig. 5, it is clear that the error in estimating the dynamic modulus using the predictive equation far exceeds that resulting from the use of the generic values obtained from a typical mix. The average percentage error in estimating dynamic moduli from the pilot library at the low range (less than 4000 MPa) is 35% compared with 149% when the predictive equation is used. These differences reflected on performance predictions made by the proposed MEPDG. Rutting potential for the HMA2 mix was predicted with the MEPDG software using the three dynamic modulus scenarios to highlight the impact on predicted performance. The three values used included one that represents actual laboratory measurements (used as a reference for the two modulus estimate procedures), one that represents the library values, and one estimated using the predictive equation. Similar input values related to all other variables (road structure, traffic, environment, base, and subgrade materials, etc.) were used in the software runs. Rutting potentials estimated by the MEPDG software are shown in Fig. 6. Application of dynamic modulus values estimated by the predictive equation underestimated rutting potential by 43%. On the other hand, rutting potential was underestimated by only 13% when the dynamic modulus corresponding to the HMA2 mix listed in the pilot library was used as input to the MEPDG software. On another note, rutting in the base and subgrade layers was not sensitive to the method used to estimate the dynamic modulus of the AC layer.

Table 5. Percentage error calculated to assess predictive model effectiveness at -10°C .

Frequency (Hz)	Marshall mix design (% error)								SuperPave mix design (% error)				
	HMA1	HMA1	HMA2	HMA2	HMA2	HMA3	HMA3	HMA3	SP1	SP1	SP2	SP2	SP2
	58-22	52-34	58-22	64-34	52-34	58-22	64-34	52-34	58-22	52-34	58-22	64-34	52-34
0.1	-32	-38	-34	24	-21	-46	29	48	-26	25	-22	-23	-48
1	-32	-52	-43	11	-29	-37	32	26	-64	-46	-24	-24	-49
20	-39	-56	-70	-20	-46	-48	-19	-9	-66	-59	-32	-36	-53

Table 6. Percentage error calculated to assess predictive model effectiveness at $+40^{\circ}\text{C}$.

Frequency (Hz)	Marshall mix design (% error)								SuperPave mix design (% error)				
	HMA1	HMA1	HMA2	HMA2	HMA2	HMA3	HMA3	HMA3	SP1	SP1	SP2	SP2	SP2
	58-22	52-34	58-22	64-34	52-34	58-22	64-34	52-34	58-22	52-34	58-22	64-34	52-34
0.1	103	12	5	477	435	145	489	999	46	621	56	41	246
1	106	48	16	469	342	106	456	625	20	321	24	61	167
20	58	102	3	323	195	34	360	268	-17	123	-4	86	85

Fig. 4. Comparison between stiffness predictions made with eqs. [1] and [2]. **Fig. 5.** Modulus values from the material library and estimates from the predictive equation (HMA2, PG 52-34). **Fig. 6.** Impact of the modulus value (E^*) on the accuracy of predicted performance. AC, asphalt concrete.

Conclusions

The MEPDG produced under the NCHRP Project 1-37A, intended as the next AASHTO pavement design guide, represents a true step towards introducing performance-based road practices. The mechanistic based principles adopted for performing structural analysis have been made possible by the incorporation of effective material characterization techniques for unbound materials and AC. However, in view of the limited number of adequate facilities and expertise available nationwide for conducting the necessary laboratory tests, it is expected that the majority of Canadian road authorities will rely on levels 2 and 3 to generate the inputs necessary for running the design software. This paper evaluated level 3 input, which relies on the predictive model to estimate the stiffness of AC, which is required as input in the analysis and performance prediction models. Results of the evaluation and recommendations are summarized as follows:

- The comprehensive laboratory investigation performed in this study covered both Marshall and SuperPave mix design methods and included a variety of mix types prepared using neat and engineered binders. The mechanical test used followed a strain-controlled approach, and the results were used to determine the dynamic modulus of AC within a wide range of temperatures and loading frequencies that simulate traffic speed. Laboratory test results were compared with predictions made by the empirical equation included in level 3 of the MEPDG model to assess its effectiveness in estimating AC stiffness.
- Analysis revealed that estimates of AC dynamic moduli produced using the predictive model of the MEPDG differed substantially from those determined in the laboratory. In general, findings showed that the prediction model mainly underpredicted the dynamic modulus at low temperatures and overpredicted the laboratory value at high temperatures. Both trends are expected to produce unsatisfactory pavement design where (i) low stiffness at low temperature will result in underprediction of low temperature cracking, and (ii) falsely high stiffness at high temperatures will mask the potential for a critical level of rutting that will be induced because of the low actual stiffness.
- The percentage error detected at high temperatures increases with the decrease in the loading frequency (slower traffic). At high temperatures, the errors in model estimates were found to be higher for engineered binders than for neat binders.
- Given the shortcomings of the predictive model used to estimate AC stiffness in the MEPDG, an alternative approach is recommended in this paper. The proposed scheme involves building a database (material library) that will become the source for obtaining generic stiffness values. The National Research Council Canada has compiled a pilot library that was populated with generic dynamic modulus values for a limited number of mixes. Implementation of such generic properties using level 1 will produce lower design errors compared with those produced using moduli values estimated by the proposed MEPDG. It is recommended that the library be further populated with the addition of data from a wide variety of AC mixes.

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