Improving the prediction of the dynamic modulus of fine-graded asphalt concrete mixtures at high temperatures

Ghareib Harran and Ahmed Shalaby

Abstract: Predictive techniques for estimating the asphalt concrete dynamic modulus, |E*|, from mixture volumetric properties are widely used in pavement design and evaluation. The reliability of these techniques is lowest at high service temperatures above 35 °C. Rutting is one of the major distresses in asphalt pavements and is considered highly sensitive to |E*| at high temperatures. The objective of this paper is to improve the reliability in the prediction of |E*| at high temperatures using parameters that reflect the gradation of aggregates. A linear model is proposed to adjust the predicted |E*| for fine-graded mixtures using a new gradation parameter. The analysis was performed on 24 mixtures prepared from various aggregate gradations and types, and several binder grades. Reasonable results were predicted for the calibration data and a validation dataset from the literature. The correlation between |E*| at high temperatures and the gradation parameter improved when it was carried out independently on fine- and coarse-graded mixtures.

Key words: asphalt concrete, dynamic modulus, predictive technique, aggregate gradation, fine-graded mixtures, mechanistic-empirical pavement design guide (MEPDG).

Résumé : Les techniques de prédiction pour estimer le module dynamique des bétons bitumineux, |E^*|, à partir des propriétés volumétriques du mélange sont largement utilisées lors de la conception et de l'évaluation des chaussées. La fiabilité de ces techniques est plus faible à des températures d'utilisation supérieures à 35 °C. L'orniérage et l'un des principaux problèmes des chaussées en asphalte et il est considéré comme étant hautement sensible au |E^*| à de températures élevées. Le but de cet article était d'améliorer la fiabilité de la prédiction du |E^*| à des températures élevées en utilisant des paramètres qui reflètent la granulométrie des agrégats. Un modèle linéaire est proposé afin d'ajuster le |E^*| prévu pour les mélanges à grains fins en utilisant un nouveau paramètre de granulométrie. L'analyse a été réalisée sur 24 mélanges préparés à partir d'agrégats de granulométries et de types variés et de plusieurs qualités de liants. Des résultats acceptables ont été prévus pour les données d'étalonnage et un ensemble de données de validation trouvé dans la littérature. La corrélation entre |E^*| à de températures élevées et le paramètre de granulométrie s'est améliorée lorsqu'elle a été réalisée de manière indépendante des mélanges à grains fins ou grossiers.

Mots-clés : béton bitumineux, module dynamique, technique prédictive, granulométrie des agrégats, mélanges à grains fins, guide de conception mécanisto-empirique des chaussées (MEPDG).

[Traduit par la Rédaction]

Introduction

The dynamic modulus, |E*|, of asphalt concrete is a linear viscoelastic property that is integrated in mechanistic pavement design (NCHRP 2004). The modulus characterizes the response of asphalt concrete to various combinations of temperatures and loading rates, and correlates well with pavement performance indicators such as rutting and fatigue (Witczak et al. 2002*a*; 2002*b*).

The dynamic modulus is best estimated from nondestructive laboratory testing at various loading frequencies and test temperatures. There has been significant progress in developing predictive models that can estimate |E*| without the need for testing. Such models rely on material and mixture volumetric properties to predict |E*|. The models are widely used in planning and design of projects in which laboratory testing is unavailable. The Witczak |E*| predictive model (NCHRP 2004) is perhaps the most widely used one and it is incorporated in the mechanistic–empirical pavement design guide (MEPDG). Pellinen (2001) reported that the Witczak model does not capture the mixture performance with sufficient accuracy to be used as a simple performance test and that additional mixture volumetric evaluation is required to accurately predict the dynamic modulus. In another attempt, Schwartz (2005) concluded that this model understates the influence of the mixture parameters. According to Schwartz, the Witczak model may not be able to differentiate the performance of different mixtures under identical conditions. Dongré et al. (2005) evaluated the Witczak model for hot mix asphalt plant mixtures and concluded that the model loses accuracy if the mixture volumet-

Received 3 February 2008. Revision accepted 31 October 2008. Published on the NRC Research Press Web site at cjce.nrc.ca on 3 February 2009.

G. Harran[1] and A. Shalaby. Department of Civil Engineering, University of Manitoba, 15 Gillson St, Winnipeg, MB R3T 5V6, Canada.

Written discussion of this article is welcomed and will be received by the Editor until 30 June 2009.

[1]Corresponding author (e-mail: umaly@cc.umanitoba.ca).

ric properties, aggregate gradation, or binder content deviate from the mix design levels. They also found that the accuracy of the Witczak model was lowest at high temperature and that below an $|E^*|$ value of 125 000 psi (862 MPa) the model overpredicts the dynamic moduli. Therefore, they recommended measuring $|E^*|$ if the expected value is below 125 000 psi (862 MPa).

Rutting, one of the major pavement distresses, is considered highly sensitive to $|E^*|$ at high service temperatures. The low reliability of the $|E^*|$ predictive models at high temperatures understates the reliability of the predicted rutting. Therefore, considering the difficulty of obtaining high quality measurements of $|E^*|$, it is essential to improve the prediction models at high temperature.

Goodrich (1991) reported that the aggregate properties dominate on mixture response at high temperatures more than at low temperatures. Birgisson and Roque (2005) proposed a framework for optimizing aggregate gradation for high dynamic modulus. The aggregate gradation was represented with factors proposed by Birgisson and Ruth (2001) and Ruth et al. (2002). These gradation factors are the power law constants and exponents for the fine and coarse aggregate portions of the mixture. They are obtained by regression analysis for the percent passing and the sieve diameter for each portion. The framework relies on the exponents of the fine and coarse aggregate to classify fine-graded and coarse-graded mixtures as optimal or nonoptimal with respect to $|E^*|$ at high temperature (40 °C) and 1 Hz ($|E^*_{40}|$). This framework implies that aggregate gradation has a significant effect on the dynamic modulus at high temperatures. It ranks the mixtures according to their stiffness at high temperature but it does not quantify the effect of the aggregate gradation on $|E^*|$.

Schwartz (2005) performed a sensitivity analysis on the predicted $|E^*|$ for the input parameters of the Witczak model. The analysis was performed with the same data used to calibrate the Witczak model. The analysis showed that the aggregate gradation parameters have the strongest influence and, between the gradation parameters, the percent retained on the 4.75 mm sieve and the percent passing the 0.075 mm sieve have the strongest influence on the predicted $|E^*|$.

In the current study, a regression model was developed to adjust the predicted $|E^*|$ master curve using an aggregate gradation parameter. The model was developed from $|E^*|$ test results of mixtures tested at the University of Manitoba and others which are available in published literature. The model was verified with an independent dataset available in the literature.

Objectives

The main aim of this paper is to improve the reliability in the prediction of $|E^*|$ at high temperatures. The specific objectives of the research are:

- To evaluate the relationship between $|E^*|$ at 40 °C and the aggregate gradation parameters.
- To develop a statistical model that relates $|E^*|$ at 40 °C to the gradation parameters.
- To use the proposed model to improve the prediction models for $|E^*|$ master curves.

Mixtures tested

The analysis was conducted using four mixture groups that included a total of 24 mixtures (Table 1*a*). The first group, G1, consisted of six mixtures prepared from aggregates and binders that were obtained from recent highway projects in Manitoba. Four of the G1 mixtures, S1–S4, were specified for wear-resistant surface courses while the others, B3 and B4, were specified for binder courses. The surface mixtures contained crushed stone to meet the surface layer requirements while the binder asphalt mixtures contained fine river gravel. All G1 mixtures were classified as fine-graded and were tested in the University of Manitoba Pavement Research Laboratory. Gradations of fine-graded mixtures fall above the maximum density line (MDL) as given by the 0.45 power gradation chart while those of the coarse-graded mixtures are typically below the MDL.

The second group, G2, consists of six fine-graded mixtures and the third group, G3, consists of seven coarse-graded mixtures. The G2 and G3 mixtures were used in a project at the University of Florida to develop a gradation-based mixture design guideline. Additional information about these mixtures can be obtained from Birgisson and Roque (2005). The available information included volumetric properties and $|E^*_{40}|$. According to Birgisson and Roque, G2 and G3 consisted of laboratory and field prepared mixtures that contained limestone and granite aggregates with a wide range of gradations. These mixtures were prepared with a single binder grade, PG 67–22.

The fourth group, G4, was used to validate the proposed model. It consists of the five mixtures of the Minnesota Road Project (MnRoad) experimental test site, as reported by Pellinen (2001). The MnRoad mixtures include Cells 16–18, 20, and 22, which were prepared from materials sampled from the experimental test site and contained various aggregate gradations and two binder grades. Cells 16–18 contained an AC-20 binder while cells 20 and 22 contained a 120–150 penetration grade binder. A Superpave gyratory compactor was used to duplicate the field-compacted mixture properties.

Specimen preparation

The loose mixtures of G1 were short-time aged in the oven for 2 h. Three specimens from each mixture were compacted in a gyratory compactor to a design number of gyrations, N_{des}, selected according to the climate and traffic level as shown in Table 1*b*. Test specimens, which had dimensions 100 mm diameter and 150 mm height, were cored from the center of gyratory specimens and the ends were sawed prior to testing.

The specimen preparation and the dynamic modulus testing of G2 and G3 mixtures are presented in Birgisson and Roque (2005) and those of G4 mixtures are in Pellinen (2001). G2 and G3 mixtures were prepared based on the Superpave mix design method and compacted to N_{des} as shown in Table 1*b*. G4 mixtures were prepared according to the Marshall mix design except for cell 16 mixture which was designed according to the Superpave design method. Table 1*c* lists binder grades of G1 mixtures and their regression constants of viscosity (A) and temperature susceptibility (VTS).

Table 1(*a*). Description of the mixture groups.

Mixture group	Mixture source	Aggregate classification	No. of mixtures	Binder grade
G1	University of Manitoba	Fine-graded	6	PG58–28, PG 52–28, PG 58–34
G2	Florida	Fine-graded	6	PG 67–22 (AC- 30)
G3	Florida	Coarse-graded	7	PG 67–22 (AC- 30)
G4	MnRoad, Minnesota	Fine-graded	5	AC- 30, Pen 120–150

Table 1(*b*). Gradation parameters, volumetric properties and measured $|E^*|$ at 40 °C, 1 Hz of the mixtures

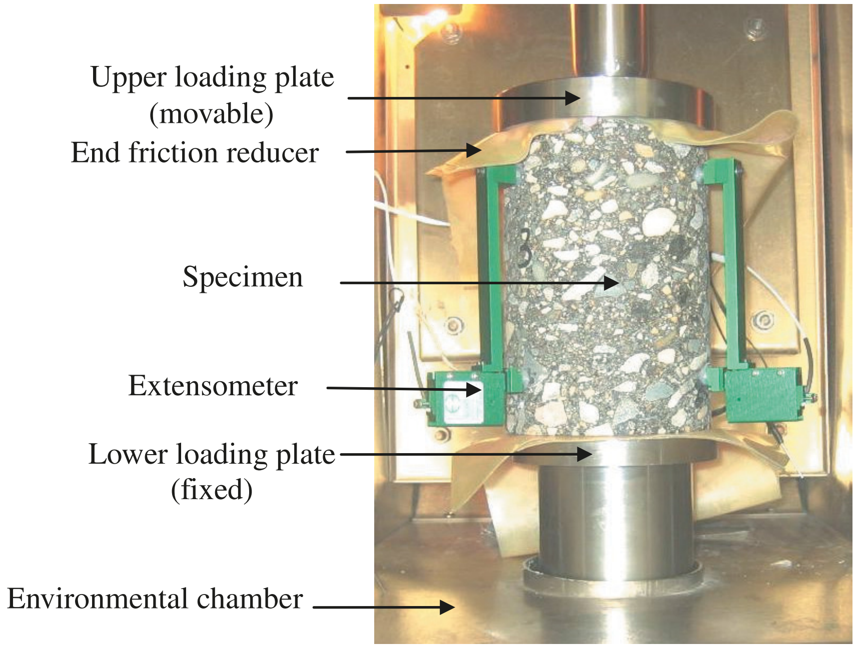
	Gradation							
	Percent passing (%)					Mix properties		
Mix	0.075 mm sieve	4.75 mm sieve	9.5 mm sieve	GR	Levels of compaction	Air voids (%)	Effective binder content (%), by volume	Measured $\|E^*_{40}\|$ at 1 Hz, 40 °C (MPa)
G1								
S1	3.5	61.8	79.3	17.7	75 gyrations	4.5	4.68	363
S2	3.6	61.9	79.0	17.2	75 gyrations	4.9	4.19	460
S3	5.2	63.5	80.0	12.3	100 gyrations	4.7	4.33	1257
S4	3.7	61.8	77.3	16.6	75 gyrations	5.7	5.07	407
B3	5.0	77.5	88.3	15.5	100 gyrations	9.7	4.74	504
B4	4.2	69.9	85.6	16.5	75 gyrations	9.3	4.28	401
G2								
F1	4.8	69.3	85.1	14.4	109 gyrations	4.0	5.09	850
F2	6.3	61.3	78.0	9.7	109 gyrations	3.9	4.12	1076
F4	6.3	69.3	85.1	11.0	109 gyrations	4.0	4.41	1044
F5	4.8	61.3	85.1	12.8	109 gyrations	4.0	5.39	727
F6	6.3	69.3	85.1	11.0	109 gyrations	4.2	4.99	880
P7	4.2	70.0	88.0	16.7	84 gyrations	4.5	4.35	550
G3								
C1	4.8	60.2	90.0	12.5	109 gyrations	4.0	5.12	526
C2	4.8	47.1	73.5	9.8	109 gyrations	3.9	4.44	759
C3	6.3	57.4	89.3	9.1	109 gyrations	4.0	4.35	801
P1	5.1	64.0	99.0	12.5	96 gyrations	4.1	4.73	524
P2	4.9	45.0	89.0	9.2	96 gyrations	4.4	4.35	607
P3	4.4	67.0	90.0	15.2	96 gyrations	4.2	5.50	459
P5	3.9	64.0	94.0	16.4	96 gyrations	4.4	4.40	638
G4								
Cell 16	4.6	68.3	84.5	14.8	N.A. gyrations	8.2	9.60	794[a]
Cell 17	4.2	68.8	85.0	16.4	75 blows	7.7	10.30	751[a]
Cell 18	4.4	68.8	84.5	15.6	50 blows	5.6	11.40	641[a]
Cell 20	4.8	69.3	85.0	14.4	35 blows	6.3	11.80	350[a]
Cell 22	4.3	69.5	85.0	16.2	75 blows	6.5	10.20	421[a]

[a]Interpolated value using measured dynamic moduli at 37.8 °C and 54.4 °C.

Table 1(*c*). G1 binder grades and vicosity (A) and temperature susceptibility (VTS) values estimated from dynamic shear rheometer (DSR) test results.

Mixture	Binder grade (PG)	A	VTS
S1	58–28	10.985	–3.693
S2	58–28	10.985	–3.693
S3	52–28	11.520	–3.890
S4	58–34	11.040	–3.715
B3	52–28	11.520	–3.890
B4	58–34	11.040	–3.715

Fig. 1. Specimen and instrumentation of the |*E**| test.



Dynamic modulus testing

The |*E**| test was conducted according to AASHTO TP 62-03 (AASHTO 2003). Figure 1 shows the specimen instrumentation used for testing G1 mixtures. The load was transmitted via two hardened steel circular plates with nominal 100 mm (4 inch) diameter. End friction reducers, consisting of two latex sheets filled with silicone grease, were used between the specimen and the loading plates. Three extensometers were used to capture the axial deformation of the specimen. The specimens were tested inside an environmental chamber at the following temperatures: –10, 5, 25, and 40 °C. The test was carried out from low to high temperature and, at each temperature, the test was carried out at frequencies from high to low: 25, 10, 5, 1, 0.5 and 0.1 Hz. The load level was selected such that the resilient strain was less than 150 microstrains and the permanent strain was not to exceed 1500 microstrains.

Witczak |*E**| predictive model

The MEPDG software provides three input levels for pavement design and analysis (NCHRP 2004). Level 1 provides the highest reliability and requires that |*E**| and the properties of paving materials be measured directly in the laboratory. Level 2 requires predicting |*E**| from aggregate gradation, mixture volumetric properties, and the viscosity testing of the binder. Level 3 uses aggregate gradation, mixture volumetric properties, and default values for binder properties eliminating the need for any testing and as such has the lowest level of reliability. The MEPDG allows the Witczak model to predict |*E**| asphalt concrete, whereas eq. [1] can be used with level 2 and 3.

$$[1]\quad \begin{aligned} \log|E^*| &= 3.750063 + 0.02932p_{200} - 0.001767(p_{200})^2 - 0.002841p_4 \\ &- 0.058097V_{\mathrm{a}} - 0.802208\left(\frac{V_{\mathrm{beff}}}{V_{\mathrm{beff}} + V_{\mathrm{a}}}\right) \\ &+ \frac{3.871977 - 0.0021p_4 + 0.003958p_{38} - 0.000017(p_{38})^2 + 0.00547p_{34}}{1 + e^{-0.603313-0.31335\log\,(f)-0.393532\log\,(\eta)}} \end{aligned}$$

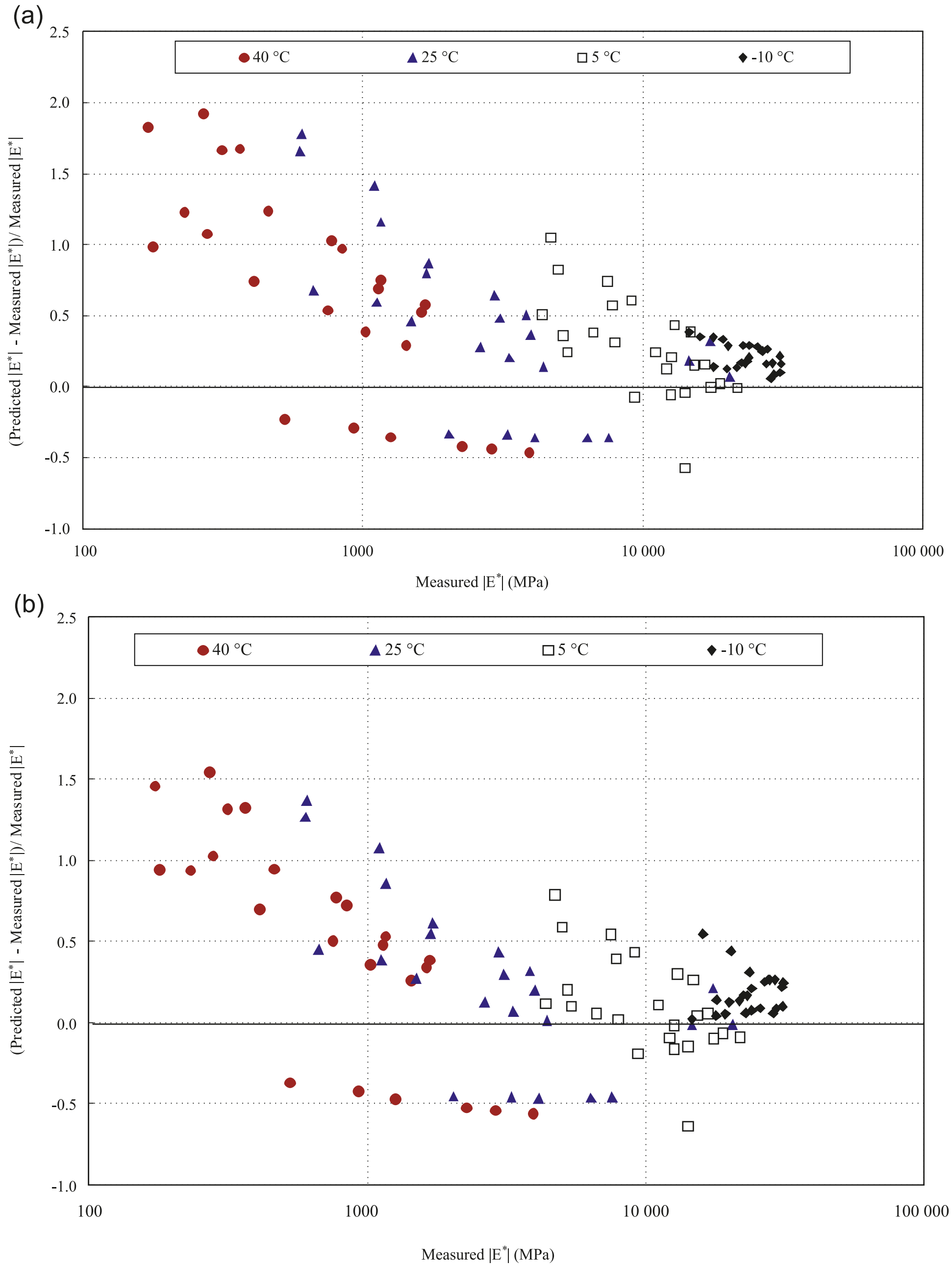
where |*E**| is the dynamic modulus, psi, p_{200} is the percentage passing from a 0.075 mm (No. 200) sieve, p_4 is the cumulative percentage retained on a 4.75 mm (No. 4) sieve, p_{38} is the cumulative percentage retained on a 9.5 mm (No. 3/8) sieve, p_{34} is the cumulative percentage retained on a 19 mm (No. 3/4) sieve, V_{beff} is the percentage effective binder content by volume, V_{a} is the percentage air content, f is the frequency (Hz), and η is the binder viscosity in 10^6 Poise.

The effect of temperature on |*E**| is incorporated in the binder viscosity and is defined by:

$$[2]\quad \log\,[\log\,(\eta)] = A + \mathrm{VTS}\,\log\,(T_{\mathrm{R}})$$

where *A* and VTS are regression constants determined according to level 2 and level 3. In level 3, where no laboratory data is available, typical values for a binder grade are available in the MEPDG (NCHRP 2004). In level 2, the

Fig. 2. Comparison of the predicted and the measured |*E**| values of S1–S4 mixtures grouped by temperature: (*a*) design level 2 (*b*) design level 3.



viscosity of the binder at any temperature is either measured directly or estimated from the dynamic shear rheometer (DSR), test parameters, the complex shear modulus (G^*), and the phase angle (δ) of the binder.

$$[3] \qquad \eta = \frac{G^*}{10}\left(\frac{1}{\sin\delta}\right)^{4.8628}$$

The G^* and δ for the binder used in G1 mixtures are available in the published literature (Shalaby 2002). Figure 2 shows a comparison of the predicted and measured |*E**| for the B1–B4 mixtures at the reliability levels 2 and 3. The predicted |*E**| values are comparable to those measured in the laboratory at low temperatures (–10 and 5 °C) at both reliability levels. On the contrary, the predicted values range from 0.65 to 2.5 times those measured in the laboratory at intermediate and high temperatures (25 and 40 °C). It should be noted that |*E**| at high temperature correlates significantly to permanent deformation and rutting (Witczak et al. 2002*a*).

Dynamic modulus – gradation relationship

In this paper, gradation parameters are used to study the relationship between the dynamic modulus at high temperature and aggregate gradations of AC mixtures. These param-

Table 2(*a*). Correlation coefficients (r) between $|E^*_{40}|$ at high temperature and aggregate gradation parameters.

	Mixture groups				
Gradation parameters	G1	G2	G1 and G2	G3	G2 and G3
Passing 4.75 mm sieve	–0.101	–0.231	–0.085	–0.546	0.120
Passing 0.075 mm sieve	0.721	0.888[a]	0.805[a]	0.520	0.762[a]
Gradation ratio (GR)	–0.957[a]	–0.883[a]	–0.887[a]	–0.598	–0.504

[a]Significance level (ρ) < 0.05.

Table 2(*b*). Significance of the relationship between $|E^*_{40}|$ and GR in the mixture groups.

	Mixture groups				
Statistical criteria	G1	G2	G1 and G2	G3	G2 and G3
Sample size (N)	6	6	12	7	13
Critical coefficient (r_{crt}) at (N-2) and $\rho \leq 0.05$	0.811	0.811	0.576	0.754	0.553
Correlation ($r \geq r_{crt}$)	Yes	Yes	Yes	No	No
Level ρ	0.003	0.020	0.0001	0.156	0.079
Significant ($\rho \leq 0.05$)	Yes	Yes	Yes	No	No

eters are the percent passing the 0.075 mm sieve, the percent passing the 4.75 mm sieve and a gradation ratio (GR). The gradation ratio is defined by:

$$[4] \qquad \mathrm{GR} = \frac{\%\ \text{passing 4.75 mm sieve}}{\%\ \text{passing 0.075 mm sieve}}$$

The 4.75 mm sieve and the 0.075 mm sieve were selected since they are typically used to split the aggregate into three portions, coarse aggregate (CA), fine aggregate (FA), and mineral filler. The GR value measures the ratio of the FA portion to the mineral filler portion. The dynamic modulus at 40 °C and 1 Hz, $|E^*_{40}|$, was selected to capture the influence of the aggregate gradation (Birgisson and Roque 2005). A statistical analysis was carried out to test the relationship between $|E^*_{40}|$ and the gradation parameters. The relationship between the gradation parameters and $|E^*_{40}|$ was tested at a threshold significance level (ρ = 0.05).

The dynamic modulus – gradation relationship was tested within five dataset groups, G1, G2, (G1 and G2), G3, and (G2 and G3). The first three datasets are fine-graded mixtures. G1 and (G1 and G2) contain various binder grades to test the relation in mixtures that include different binder grades. G2, G3, and (G2 and G3) contain a single binder grade, PG 76–22, as such the effect of the binder rheology on the relationship is neutralized. The fourth dataset, G3, contains coarse-graded mixtures and the fifth dataset, (G2 and G3), contains combined fine- and coarse-graded mixtures. The relationship was tested at two sample size levels of the fine-graded mixtures that include various binder grades. The G1 dataset has a sample size of 6 and a GR range of 12.3–17.7 and the (G1 and G2) has a sample size of 12 and a GR range of 9.7–17.7. The relationship is considered significant if the correlation coefficient (r) is higher than or equals the critical correlation coefficient (r_{crt}) at a significance level of 0.05 or less.

Table 2*a* lists the correlation coefficients between $|E^*_{40}|$ and the gradation parameters, the passing 0.075 mm sieve, the passing 4.75 mm sieve and the GR. The data shows that the GR has the potential to describe the relationship between $|E^*_{40}|$ and aggregate gradation. Table 2*b* summarizes the relationship between the GR and $|E^*_{40}|$ in the various datasets, G1, G2, (G1 and G2), G3, and (G2 and G3). The following observations can be made:

- In fine-graded mixtures, the relationship is significant regardless of the binder grade.
- The relationship is insignificant in coarse-graded mixtures.
- The relationship is also insignificant in combination of coarse-graded and fine-graded mixtures.

Using G1 and G2 data, it was found that the correlation between $|E^*_{40}|$ and the following mixture properties, asphalt binder content, effective binder content by volume (V_{eff}), air voids (V_a) and voids in mineral aggregates is weak. The correlation coefficients were 0.25, –0.20, –0.29, and –0.54, respectively.

$|E^*_{40}|$ – GR regression model

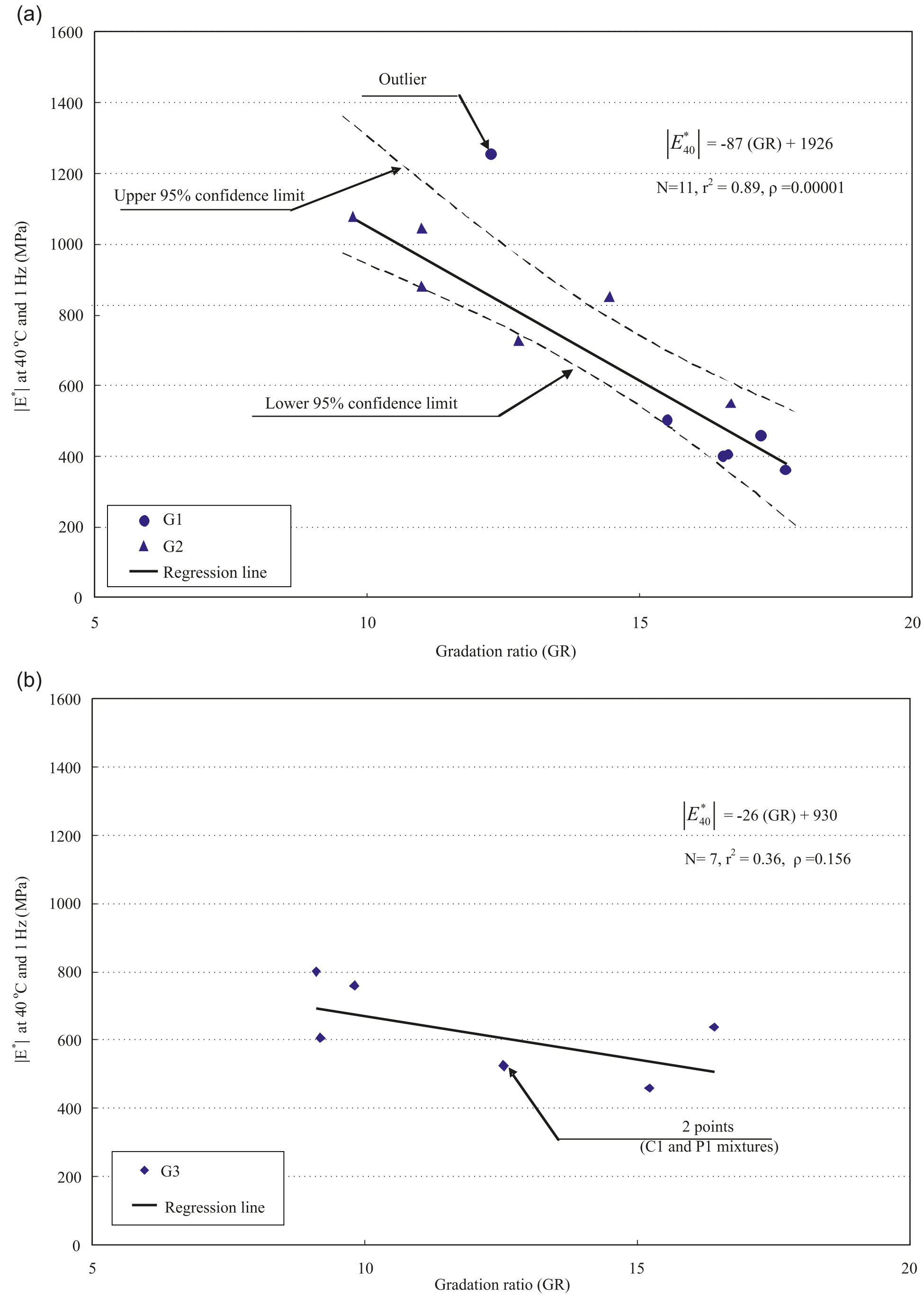
Figure 3 shows the relationship between $|E^*_{40}|$ and GR for both fine-graded and coarse-graded mixtures, respectively. Figure 3*a* shows the 95% confidence limits based on G1 and G2 datasets and suggests a linear relationship for fine-graded mixtures. The confidence limits suggest that S3 data point is an outlier. It can be noticed that $|E^*_{40}|$ of S3 is relatively high compared to $|E^*_{40}|$ of the G1 mixtures and it is also relatively high compared to $|E^*_{40}|$ of G2 mixtures that have similar GR values. Accordingly, S3 data was excluded from the regression model. The model, as shown in eq. [5], was found to be statistically significant for the range of GR values of 9.7 to 17.7.

$$[5] \qquad |E^*_{40}| = -87(\mathrm{GR}) + 1926$$

where $|E^*_{40}|$ is the dynamic modulus at 40 °C and 1 Hz, in MPa, GR is the gradation ratio.

The statistical summary: N = 11 (based on G1 and G2 mixtures, S3 excluded), r^2 = 0.89, adjusted r^2 = 0.87, S_e = standard error of estimate = 93.00 MPa, S_y = standard deviation = 265.00 MPa, S_e/S_y = 0.35 and ρ = 0.00001 < 0.05.

Fig. 3. $|E^*_{40}|$ –GR relationship in: (*a*) fine-graded mixtures. (*b*) coarse-graded mixtures.



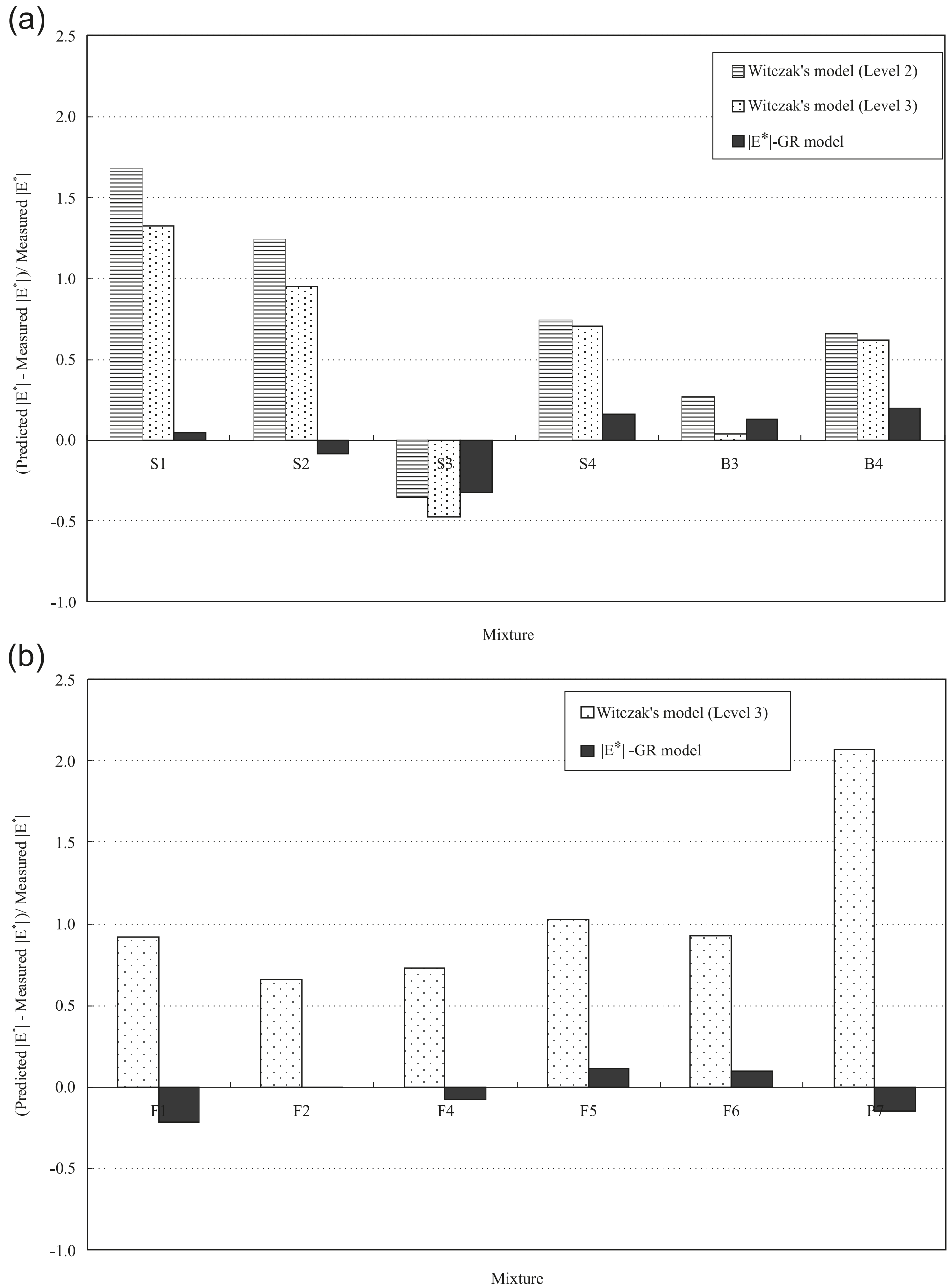
The statistics of the model confirm a significant relationship between $|E^*_{40}|$ and GR for fine-graded mixtures. The data consists of 11 fine-graded mixtures with different aggregate gradations, aggregate sources, and binder grades. The material passing both the 0.075 mm and the 4.75 mm sieves are in the range of 3.5%–6.3% and 61.3%–77.5%, respectively. The model is simple since it includes one independent variable (GR) and it is rational since dynamic modulus decreases as GR increases.

Figure 3*b* confirms that the relationship between $|E^*_{40}|$ and GR in coarse-graded mixtures is statistically insignificant.

Validation of the model

The model was validated with the datasets used for the calibration, G1 and G2, and with an independent dataset, G4. The validation with G1 and G2 illustrates the accuracy of the model when applied to its calibration data. Figure 4 shows the prediction errors of $|E^*_{40}|$ of G1 and G2 mixtures. The proposed model predicts $|E^*_{40}|$ of these mixtures reasonably well and the prediction errors range between –32% and +20%. The prediction errors are much lower than those of the Witczak model, which were in the range of –50%

Fig. 4. Validation of $|E^*_{40}|$-GR model and comparison of the prediction errors from the proposed model and Witczak model using: (*a*) G1 mixtures (*b*) G2 mixtures.



and +210%. The comparison demonstrates the potential for using GR to adjust the predicted |*E**| master curve generated by the Witczak model.

The predicted $|E^*_{40}|$ values of G1 with the Witczak model were obtained at two design levels, level 2 and level 3 and those of G2 at design level 3 only. The typical binder values, *A* and VTS, for design level 3 are provided by the MEPDG (NCHRP 2004). The Witczak model mostly tends to overpredict $|E^*_{40}|$ at the two reliability levels.

In addition, the model presented in eq. [5] was verified using the independent dataset, G4. The effective binder content by volume and air voids of G4 mixtures are higher than those of G1 and G2 mixtures used to calibrate the model. The $|E^*_{40}|$ values of G3 mixtures were interpolated using measured values at 37.8 °C and 54.4 °C (100°F and 130°F). Figure 5 shows the prediction errors of $|E^*_{40}|$ using the proposed model. The model predicted $|E^*_{40}|$ of four mixtures of G4 reasonably well with an error range of –34% to +21%, and overpredicted $|E^*_{40}|$ of cell 20 by almost 90%. Schwartz (2005) used G4 to validate the Witczak model and reported |*E**| prediction errors to be up to 300% at high temperatures.

Application of the model

The model is used for adjusting the predicted |*E**| master curve for fine-graded mixtures. The adjustment considers

Fig. 5. Verification of the $|E^*_{40}|$–GR model using G4 mixtures.

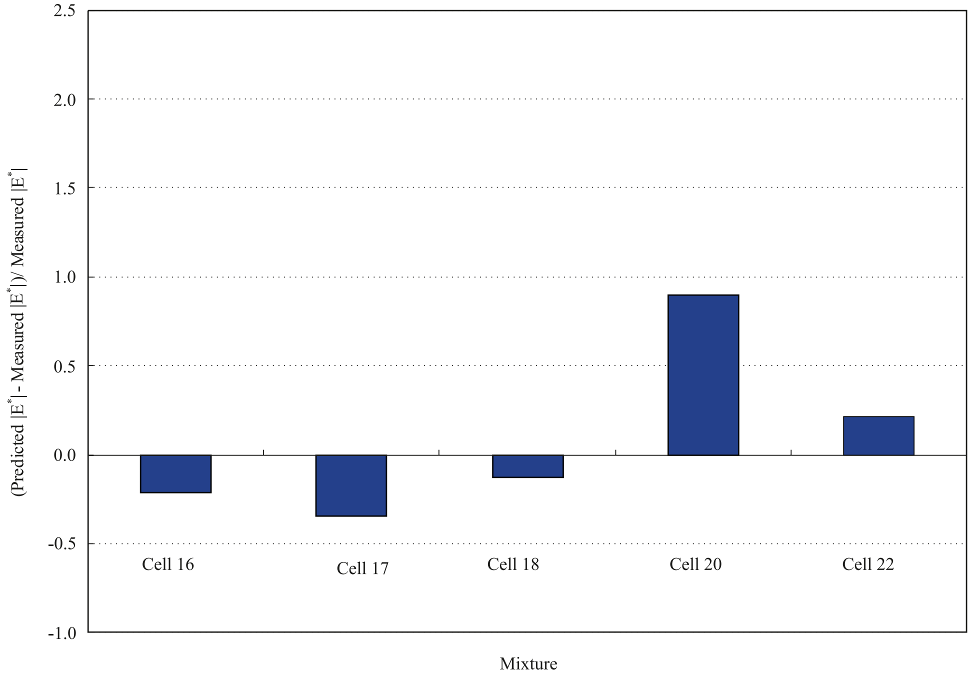
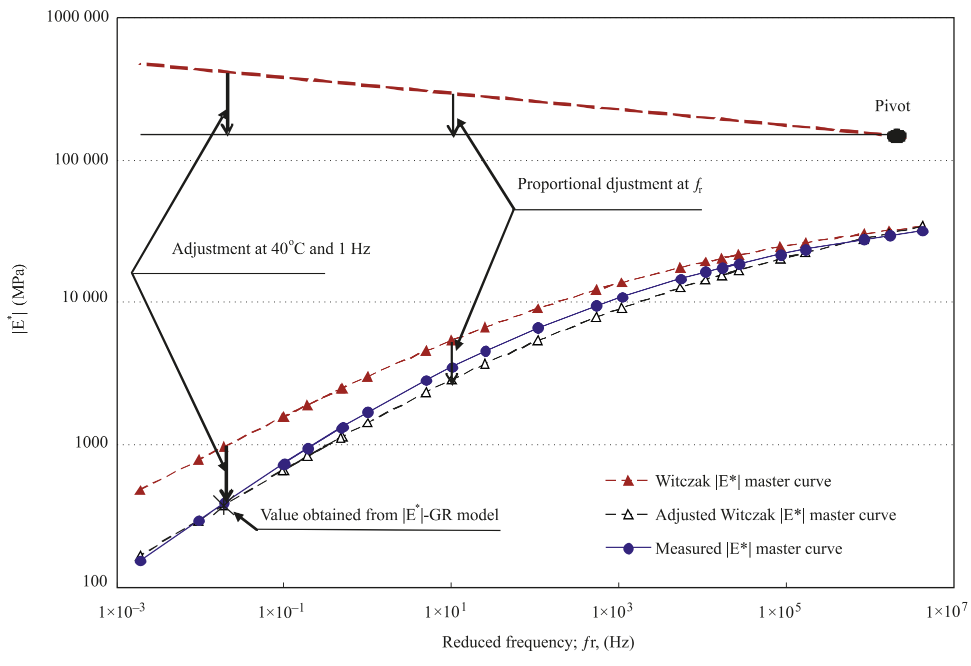


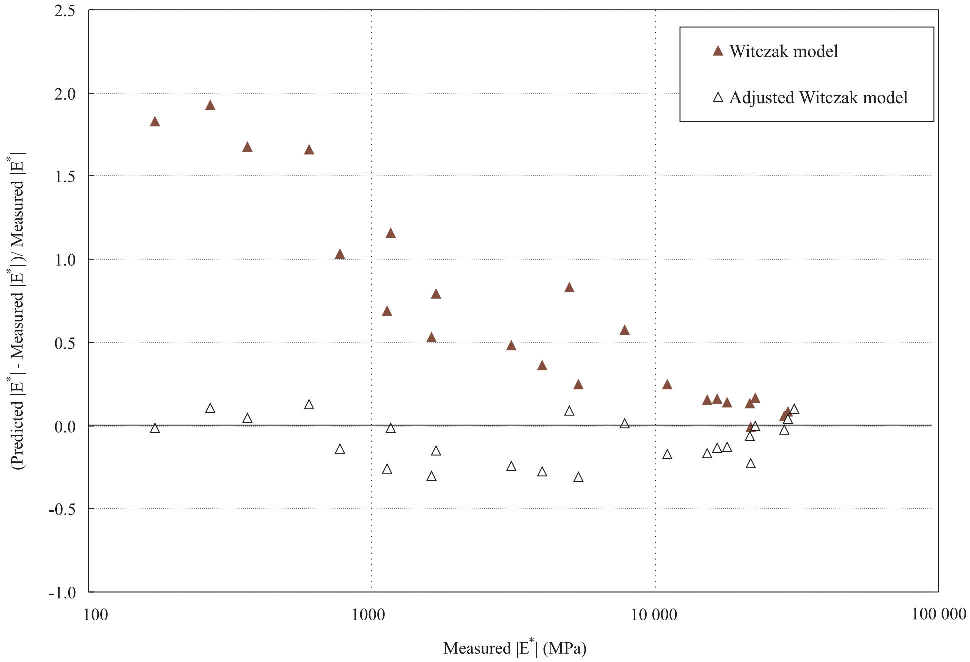
Fig. 6. Adjusting of the Witczak predicted |E*| master curve using the $|E^*_{40}|$–GR model.



that the effect of aggregate gradation dominates |E*| at high temperature and this effect reduces with decreasing temperature. The adjustment is performed in two steps. Firstly, the Witczak model is used to predict |E*| master curve using the volumetric properties of mixtures. Secondly, $|E^*_{40}|$ is predicted from the GR applying the proposed model shown by eq. [5]. Finally, the predicted |E*| master curve is pivoted at the highest reduced frequency ($f_r \approx 10^6$ Hz) and rotated to match the predicted $|E^*_{40}|$. Figure 6 illustrates the process of adjusting the predicted |E*| master curve of the S1 mixture and compares the predicted |E*| master curves, before and after the adjustment, with the measured |E*| master curve. As illustrated in Fig. 7, the predicted |E*| is improved at high and intermediate temperatures. Consequently, the prediction of rutting and fatigue cracking, which is relevant to high and intermediate temperatures is expected to be improved.

In addition, the model could be used as a preliminary mix design tool for optimizing stiffness of asphalt mixtures at high temperatures and accordingly reducing the potential of rutting. Higher stiffness mixtures can be achieved by lowering the GR.

Fig. 7. Predicted $|E^*|$ before and after adjustment with the $|E^*_{40}|$– GR mode.



Discussion

The statistical analysis confirmed that aggregate gradation has a significant effect on the dynamic modulus at high temperature and that the GR appears to capture this effect adequately for fine-graded mixtures. This finding was validated in a relatively wide range of mixtures and aggregate blends.

In mix design, a low GR should be desirable whenever possible, because it relates to a higher dynamic modulus. By definition, low gradation ratios are the result of larger coarse fraction and smaller fine fraction in the mix. A mixture with a low GR should have a higher percentage of inter-particle contacts and crush counts than a mixture with a high GR.

These findings are consistent with current mixture design practices which encourage stone-on-stone contact and better aggregate interlock with emphasis on aggregate shape and angularity. Excessive use of fines reduces the stiffness of the mixture and its ability to recover during unloading, thus leading to a more rapid rate of permanent deformations.

The Witczak model accounts for many aggregate, binder, and mixture properties and predicts performance reasonably well at low and intermediate temperatures; however at high temperature performance depends largely on the aggregate structure. Using Witczak's model alone reduces the reliability of the modulus data at high temperature because the effect of aggregate structure may not be adequately represented in the model. The GR model, being statistically based on the GR and on laboratory tests performed at high temperature only, can be used successfully to calibrate master curves produced by the more complex predictive models of dynamic modulus.

Summary and conclusions

Current methods for predicting dynamic modulus, $|E^*|$, are less reliable at high temperatures, which increases the uncertainty in the forecasted pavement performance and the estimated service life. Aggregate gradation has a dominant effect particularly at high temperature where the binder stiffness is low. The GR is the ratio of the percent passing the 4.75 mm sieve to the percent passing the 0.075 mm sieve. It was used to describe the relationship between aggregate gradation and $|E^*|$ at high temperature.

In addition, a linear regression model was developed to adjust the predicted $|E^*|$ master curves. The study used 24 mixtures prepared from various aggregate types and gradations, and various binder grades. The mixtures were divided into three groups: fine-graded containing three binder grades, and the other two groups were fine-graded and coarse-graded containing the same binder grade. It can be concluded that

- The relationship between $|E^*|$ at high temperatures and aggregate gradation represented by the GR should be studied independently in fine-graded and coarse-graded mixtures.
- The relationship between $|E^*|$ at high temperatures and aggregate gradation was tested for fine-graded mixtures prepared from a single binder grade and others prepared from several binder grades. The relationship was found statistically significant regardless of the binder grade.
- A model was developed to adjust the predicted $|E^*|$ at high temperature for fine-graded mixtures. The model was calibrated with data of 11 fine-graded mixtures and has goodness of fit of $r^2 = 0.89$ and $S_e/S_y = 0.35$.
- The proposed model predicted $|E^*|$ reasonably well at 40 °C and 1 Hz for several mixture groups including those independently tested by others.
- A method was presented to adjust the predicted $|E^*|$ master curve using the Witczak model. The adjustment improved the predicted moduli significantly, especially at high temperatures.

- The relationship between the dynamic modulus at high temperature and aggregate gradation was suggested as a guide to optimize the aggregate gradation of fine-graded mixtures for higher dynamic modulus.

Acknowledgements

This work was completed under a research project to characterize the paving materials in Manitoba. Funding and laboratory assistance received from Manitoba Infrastructure and Transportation, and the technical assistance of Dr. Gani Ganapathy, Manitoba Infrastructure and Transportation, are gratefully acknowledged.

References

AASHTO. 2003. Standard method of test for determining dynamic modulus of hot-mix asphalt concrete mixtures. AASHTO TP 62–03. American Association of State Highway and Transportation Officials, Washington, DC.

Birgisson, B., and Ruth, B. 2001. Development of tentative guidelines for the selection of aggregate gradation in hot-mix asphalt. *In* ASTM Aggregate Contribution to Hot Mix Asphalt (HMA) Performance, ASTM 1412(STP). Edited by T.D. White, S.R. Johnson, and J.J. Yzenas. American Society for Testing and Materials, West Conshohocken, Penn. pp. 110–127.

Birgisson, B., and Roque, R. 2005. Evaluation of the gradation effect on the dynamic modulus. Transportation Research Record, **1929**: 193–199. doi:10.3141/1929-23.

Dongré, R., Myers, L., D'Angelo, J., Paugh, C., Gudimettla, J., Christensen, D., et al. 2005. Field evaluation of Witczak and Hirsch models for predicting dynamic modulus of hot-mix asphalt. Journal of the Association of Asphalt Paving Technologists, **74**: 381–442.

Goodrich, J.L. 1991. Asphalt binder rheology, asphalt concrete rheology and asphalt concrete mix properties. Journal of the Association of Asphalt Paving Technologies, **57**: 81–121.

NCHRP. 2004. Mechanistic-empirical design of new and rehabilitated pavement structures. NCHRP Project 1–37A Final Report. Transportation Research Board, National Research Council, Washington, DC. Available from ww.trb.org/mepdg/guide.htm.

Pellinen, T. 2001. Investigation of the use of dynamic modulus as an indicator of hot-mix asphalt performance. Ph.D. thesis, Arizona State University.

Ruth, B.E., Roque, R., Nukunya, B., Davis, R., Marasteanu, M., Vavrik, W., et al. 2002. Aggregate gradation characterization factors and their relationship to fracture energy and failure strain of asphalt mixtures. Journal of Association of Asphalt Paving Technologists, **71**: 310–344.

Shalaby, A. 2002. Modeling short-term aging of asphalt binders using the rolling thin film oven test. Canadian Journal of Civil Engineering, **29**(1): 135–144. doi:10.1139/l01-086.

Schwartz, C. 2005. Evaluation of the Witczak dynamic modulus prediction model. *In* Proceedings of the 84th Annual Meeting of the Transportation Research Board, Washington, D.C., No. 05–2112.

Witczak, M., Kaloush, K., and Von Quintus, H. 2002*a*. Pursuit of the simple performance test for asphalt mixture rutting. Journal of the Association of Asphalt Paving Technologies, **71**: 671–691.

Witczak, M., Pellinen, T., and El-Basyouny, M. 2002*b*. Pursuit of the simple performance test for asphalt concrete fracture/cracking. Journal of the Association of Asphalt Paving Technologies, **71**: 767–778.