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Evaluation of the Dynamic Modulus for Asphalt Mixtures with Varying Volumetric Properties

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Abstract: The dynamic modulus $|E^*|$ of asphalt mixtures with varying volumetric properties was evaluated in this study. The dynamic modulus test, repeated load permanent deformation test, and beam fatigue test were performed in laboratory to evaluate the stiffness, rutting, and fatigue performance for three types of mixtures, respectively. The Falling Weight Deflectometer (FWD) test was conducted to evaluate field pavement conditions of four sections from two highways in Jiangsu. It is observed from the $|E^*|$ master curves that for a specific type of mixture, $|E^*|$ decreases with the increase in binder content at the lower reduced frequency, while at the higher reduced frequency a peak $|E^*|$ value exists at the approximate optimum binder content obtained from volumetric mix design criteria. It is also found from the tests results that dynamic modulus indicators $|E^*|$ and $|E^*|/\sin\varphi$ do not show good agreements with fatigue and rutting performance of different mixtures. In addition, it is shown that the Witczak model strongly underestimates $|E^*|$ of the mixtures used in this study and should be corrected by a shift factor of 1.8621. Finally, a dynamic modulus prediction model for asphalt mixtures with varying volumetric properties was developed in laboratory and successfully verified using in-situ FWD backcalculation.

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Key words: *Asphalt mixture; Dynamic modulus; Falling weight deflectometer; Master curve.*

Introduction

The dynamic modulus $|E^*|$ is an important parameter that determines the ability of the material to resist compressive deformation as it is subjected to cyclic compressive loading and unloading [1]. It is a linear viscoelastic property to define the stiffness characteristics of asphalt mixtures and generally illustrated by the master curve generated according to the time-temperature superposition principle under different temperatures and loading frequencies [2-3]. It is usually used as a main material parameter to calculate the stress and strain responses in asphalt pavements based on layered system theory. Then these responses are correlated to field performance in various pavement models, such as the Mechanistic-Empirical Pavement Design Guide (MEPDG) [4]. Therefore, it is important to make an accurate estimation of $|E^*|$ for designing a sound pavement structure [5].

Also, the dynamic modulus test has been recommended by the National Cooperative Highway Research Program (NCHRP) projects 9-19 and 9-29 as one of the Superpave simple performance tests (SPT) to complement the volumetric mix design process [6-7]. Witczak et al. [6] proposed that the dynamic modulus term $|E^*|/\sin\varphi$ (φ is the phase angle) correlated well with observed rutting and fatigue cracking in pavements. Therefore, it could be used as the potential quality control-quality assurance (QC/QA) parameter in field [8]. Recently, a few further studies have been done by other researchers [9-11]. However, there are disagreements as to the correlations of dynamic modulus indicators and pavement distresses. On one hand, Goh et al. [9] proposed that $|E^*|$ was a suitable parameter in comparing field and laboratory rutting performance for asphalt pavements in Michigan. On the other hand, Mohammad et al. [10] proposed that $|E^*|$ at high temperatures could not differentiate laboratory permanent deformation characteristics of six different asphalt mixtures. In addition, Shenoy and Romero [11] investigated the pavement distresses in WesTrack sections and found that $|E^*|$ in the intermediate temperature range might relate to fatigue cracking based on a limited database. Therefore, further research is required to validate the above findings.

Volumetric properties play an important role in determining the performance of asphalt mixtures. However, little research has considered the effects of volumetric properties on dynamic properties of asphalt mixtures in mix design process. That may be one reason why the existing mix design method could not accurately take care of the field pavement performance. Therefore, the goal of this study is to evaluate the dynamic modulus $|E^*|$ of asphalt mixtures with varying volumetric properties. A dynamic modulus prediction model based on the master curve was developed using laboratory tests and verified using modulus backcalculation from Falling Weight Deflectometer (FWD) data. The correlations between the dynamic modulus indicators with permanent deformation and fatigue performance were also examined. In addition, the Witczak dynamic modulus model was corrected using the measured data in laboratory.

Experimental Program

Materials and Mix Design

Three different types of asphalt mixtures were used in this study [12-14]. Two of them (AC-19C and AC-19M) were dense graded mixtures with 19 mm nominal maximum aggregate size (NMAS) and two different asphalt binders, PG 64-22 and

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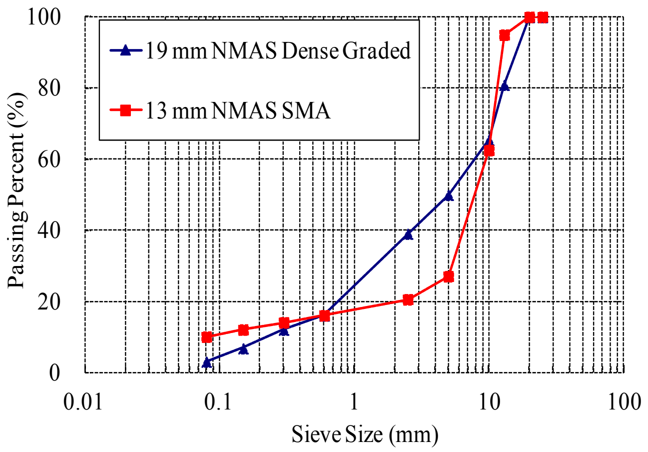


Fig. 1. Aggregate Gradations.

styrene–butadiene–styrene (SBS) modified PG 76-22, respectively. The other one (SMA-13C) was a 13 mm NMAS stone mastic asphalt (SMA) mixture with PG 64-22 binder. The specimens with varying volumetric properties were produced according to mix design procedure. The aggregate gradations are shown in Fig. 1. The details on the mix design are provided in Table 1.

Specimen Preparation

Three different types of laboratory tests including unconfined dynamic modulus test, repeated load permanent deformation (RLPD) test, and 4-Point bending (4PB) beam fatigue test were conducted in this study. The specimens for the dynamic modulus test and RLPD test were compacted using a Superpave gyratory compactor. The cylindrical specimens of 150 mm in diameter and 175 mm in height were cored from the center and sawed from each end. The testing specimens of 100 mm in diameter and 150 mm in height were obtained. The beam slabs used in 4PB beam fatigue tests were produced using a roller compactor. The dimensions were approximately 50.8 mm in height, 63.5 mm in width, and 406.4 mm in length.

Tests Setup

Dynamic Modulus Test

The stiffness characterization for asphalt mixtures was accomplished using the unconfined dynamic modulus test. A haversine compressive stress was applied on the specimen with frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz at temperatures of -10°C, 5°C, 20°C, 35°C, and 50°C, respectively. The target vertical strain level in the tests was about 100 με. Because the dynamic modulus test is non-destructive, the specimens were reused in the RLPD test. Two replicates were used for each test. The dynamic modulus $|E^*|$ and phase angle φ could be calculated as follows [6]:

$$\left|E^*\right| = \frac{\sigma_0}{\varepsilon_0} \tag{1}$$

$$\varphi = \frac{t_i}{t_p} \times 360 \tag{2}$$

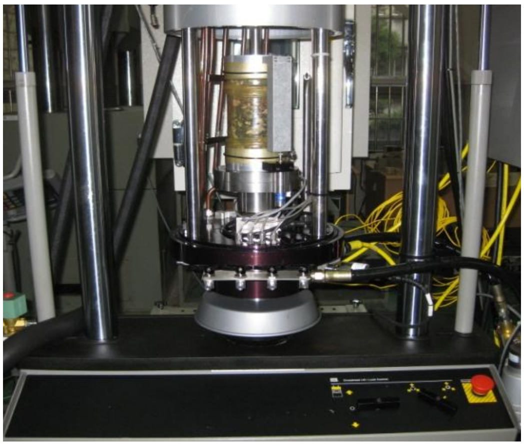
where σ_0 is the applied stress amplitude; ε_0 is the measured strain amplitude; t_i is the average time lag between a cycle of stress and strain; and t_p is the average time for a stress cycle.

RLPD Test

The triaxial RLPD test was performed to capture rutting characteristics for asphalt mixtures. It was conducted under a deviatoric stress of 690 kPa and a confining pressure of 69 kPa at a temperature of 50°C [12]. A specimen was subjected to a repeated haversine axial compressive load pulse, a 0.1 second of loading, followed by a 0.9 second of unloading. The axial displacement ε_{pf} at the loading cycle of 40,000 of two replicates was averaged for analysis. Both dynamic modulus test and RLPD test were conducted on a MTS servo-hydraulic testing system. The test setup is shown in Fig. 2(a).

Table 1. Mix Design Results.

Mix Type	Mix ID	Aggregate Gradation	Binder Type	Binder Content (% by Weight) P_b	Air Void (% by Volume) V_a	Effective Binder Content (% by Volume) V_{beff}
AC-19C	C-4.0	Dense Graded	PG 64-22	4.0	7.2	8.7
AC-19C	C-4.5	Dense Graded	PG 64-22	4.5	4.8	9.9
AC-19C	C-5.0	Dense Graded	PG 64-22	5.0	2.8	11.1
AC-19C	C-5.5	Dense Graded	PG 64-22	5.5	1.7	12.3
AC-19C	C-6.0	Dense Graded	PG 64-22	6.0	1.3	13.5
AC-19M	M-4.0	Dense Graded	PG 76-22	4.0	7.7	8.7
AC-19M	M-4.5	Dense Graded	PG 76-22	4.5	5.7	9.9
AC-19M	M-5.0	Dense Graded	PG 76-22	5.0	3.2	11.2
AC-19M	M-5.5	Dense Graded	PG 76-22	5.5	2.1	12.4
AC-19M	M-6.0	Dense Graded	PG 76-22	6.0	1.8	13.5
SMA-13C	S-5.0	SMA	PG 64-22	5.0	7.2	11.3
SMA-13C	S-5.5	SMA	PG 64-22	5.5	5.5	12.6
SMA-13C	S-6.0	SMA	PG 64-22	6.0	4.2	13.7
SMA-13C	S-6.5	SMA	PG 64-22	6.5	2.8	14.8
SMA-13C	S-7.0	SMA	PG 64-22	7.0	2.1	15.9



(a)

(b)

Fig. 2. Tests Setup for (a) Dynamic Modulus and RLPD Tests and (b) 4PB Beam Fatigue Test.

Table 2. Laboratory Tests Results.

Mix ID	Dynamic Modulus Test						RLPD Test		4PB Beam Fatigue Test	
	$\|E^*\|$-20℃		$\|E^*\|$-50℃		$\|E^*\|/\sin\varphi$-50℃		ε_{pf}-50℃		N_f-20℃	
	Average (MPa)	COV	Average (MPa)	COV	Average (MPa)	COV	Average	COV	Average	COV
C-4.0	11,647	6.6%	1,870	5.1%	6,184	5.6%	0.0464	15.8%	29,555	31.3%
C-4.5	14,786	4.5%	1,436	4.1%	5,242	3.2%	0.0591	9.7%	40,150	22.5%
C-5.0	10,389	6.8%	1,186	4.4%	4,438	4.7%	0.0706	11.4%	67,405	8.7%
C-5.5	8,941	4.6%	950	2.2%	3,385	2.6%	0.0974	21.2%	96,590	17.0%
C-6.0	7,258	3.3%	776	4.4%	2,595	4.1%	0.1514	9.7%	123,790	14.1%
M-4.0	9,048	1.2%	1,803	3.7%	7,105	4.0%	0.0148	22.3%	54,670	29.7%
M-4.5	9,279	1.4%	1,000	0.7%	4,379	1.2%	0.0160	9.8%	128,700	20.1%
M-5.0	7,820	8.6%	940	4.3%	3,859	4.2%	0.0167	10.7%	954,660	11.4%
M-5.5	7,088	2.7%	753	0.2%	2,967	0.7%	0.0173	5.8%	1,587,510	14.2%
M-6.0	6,814	5.0%	616	4.7%	2,320	5.2%	0.0244	14.7%	—	
S-5.0	8,069	2.1%	1,732	1.0%	6,208	0.7%	0.0388	19.8%	—	
S-5.5	8,800	4.7%	1,426	0.8%	5,582	0.4%	0.0456	7.4%	—	
S-6.0	8,598	1.0%	1,288	5.3%	4,820	5.2%	0.0463	9.7%	—	
S-6.5	7,219	3.8%	929	7.7%	3,252	6.0%	0.0571	16.7%	—	
S-7.0	7,152	2.1%	750	0.4%	2,508	0.5%	0.0738	22.4%	—	

4PB Beam Fatigue Test

The beam fatigue test was performed to characterize fatigue behavior of asphalt mixtures. It was conducted under the strain-controlled mode with a strain of 500 με at a temperature of 20°C [14]. A repeated haversine load was applied at a frequency of 10 Hz without rest periods. The average load cycle N_f corresponding to the 50% of initial stiffness of two replicates was used as a fatigue life of asphalt mixtures. The test setup is shown in Fig. 2(b).

Tests Results and Data Analysis

A brief summary of the results including average values and coefficient of variation (COV) from various tests is provided in Table 2.

Dynamic Modulus Prediction Model

Generally, a log sigmoidal model [4] is used to construct the dynamic modulus master curves of asphalt mixtures, as expressed in Eq. (3).

$$log\left(\left|E^*\right|\right) = \delta + \frac{\alpha}{1+e^{\beta+\gamma(log\, f_r)}} \tag{3}$$

where f_r is the reduced frequency for the reference temperature (20℃ in this study); δ, α, β, and γ are the regression coefficients.

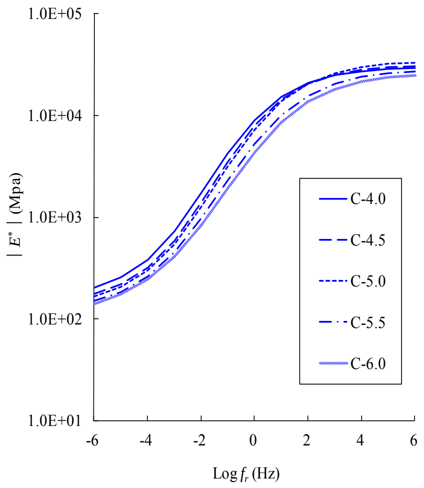
Based on the time-temperature superposition principle, f_r is expressed as follows:

$$log\, f_r = log\, f + log\, a_T \tag{4}$$

where f is the actual frequency at a given temperature T; and a_T is the shift factor. The relationship between log a_T and T is expressed in Eq. (5):

$$log\, a_T = aT^2 + bT + c \tag{5}$$

where a, b, and c are regression coefficients.



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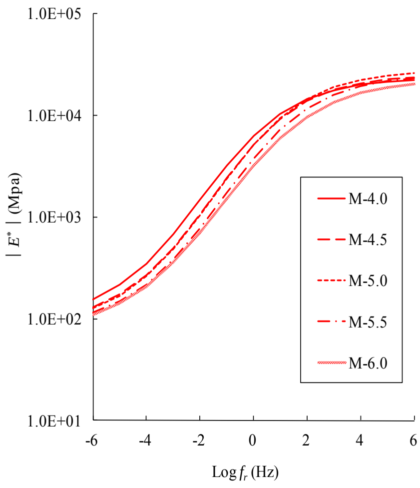

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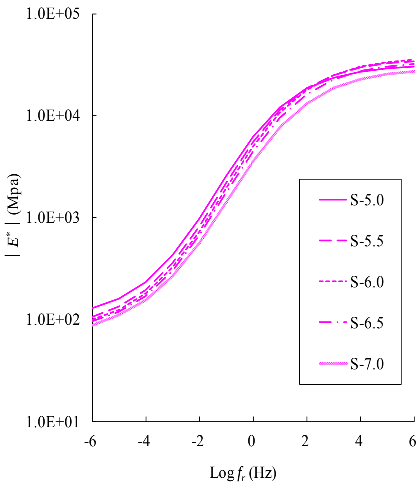

(c)

Fig. 3. Dynamic Modulus Master Curves for (a) AC-19C, (b) AC-19M, and (c) SMA-13C.

Table 3. Regression Coefficients δ, α, β, and γ in Eq. (3).

Mix ID	Regression Coefficient				R^2
	δ	α	β	γ	
C-4.0	2.1984	2.2773	-1.2150	-0.7017	0.9879
C-4.5	2.1449	2.3545	-1.0717	-0.6948	0.9921
C-5.0	2.1064	2.4333	-0.9516	-0.6694	0.9821
C-5.5	2.0671	2.3886	-0.8184	-0.6451	0.9981
C-6.0	2.0479	2.3763	-0.7111	-0.6284	0.9882
M-4.0	1.9863	2.3859	-1.1606	-0.5864	0.9905
M-4.5	1.9397	2.4680	-0.9395	-0.5834	0.9887
M-5.0	1.9198	2.5321	-0.8871	-0.5719	0.9898
M-5.5	1.8995	2.5090	-0.7113	-0.5654	0.9942
M-6.0	1.8714	2.4922	-0.6370	-0.5404	0.9885
S-5.0	2.0045	2.4913	-0.9221	-0.6748	0.9921
S-5.5	1.9094	2.6489	-0.7995	-0.6465	0.9918
S-6.0	1.8864	2.6915	-0.7124	-0.6376	0.9964
S-6.5	1.8696	2.6653	-0.6903	-0.6350	0.9987
S-7.0	1.8396	2.6261	-0.6207	-0.6259	0.9879

Table 4. Regression Coefficients *a*, *b*, and *c* in Eq. (5).

Regression Coefficient	Mix Type		
	AC-19C	AC-19M	SMA-13C
a	8.2540×10^{-4}	5.0794×10^{-4}	7.3016×10^{-4}
b	-0.1543	-0.1283	-0.1259
c	2.8854	2.4746	2.2168
R^2	0.9985	0.9974	0.9955

The dynamic modulus master curve for each mixture as shown in Fig. 3 was constructed using Eqs. (3) – (5) with the aid of an Excel solver function. The regression coefficients δ, α, β, and γ in Eq. (3) are listed in Table 3. The regression coefficients *a*, *b*, and *c* in Eq. (5) are provided in Table 4. These tables show that the goodness of fit is nice since the coefficient of determination R^2 values are greater than 0.98 for all the cases.

It is found in Fig. 3 that for a specific type of mixture, $|E^*|$ decreases with the increase in binder content at the lower reduced frequency, especially when it is lower than about 10,000 MPa. It indicates that an asphalt mixture with lower binder content is more resistant to permanent deformation at a high temperature or a low frequency. However, at the higher reduced frequency there is a peak $|E^*|$ value appearing at the approximate optimum binder content obtained from volumetric mix design criteria (i.e., air voids of 4% for AC-19C/M mixtures and 3% for SMA mixtures). It signifies that only using the volumetric criteria to control the mix design is not adequate to guarantee the mixture performance, because at the low temperature, the higher $|E^*|$ at optimum binder content may generally cause more pavement cracks. The above findings are valid for all three types of mixtures.

Seo et al. [15] found that the dynamic modulus of asphalt mixtures had a good correlation with air void content. In this study, it is also observed that there are nice multiple linear relationships between the regression coefficients of master curve δ, α, β, and γ listed in Table 3 and the volumetric properties listed in Table 1, as expressed in Eq. (6).

$$\delta,\alpha,\beta,\gamma = mP_b + nV_a + l \tag{6}$$

where P_b is the binder content (% by weight); V_a is the air void (% by volume); *m*, *n*, and *l* are the regression coefficients, as presented in Table 5.

Finally, the following dynamic modulus model for asphalt mixtures with varying volumetric properties shown in Eq. (7) has been developed in combination of Eqs. (3) – (6). The basic form of the model is based on Eqs. (3) – (5) for constructing the master curve of dynamic modulus. The regression function shown in Eq. (6) is also incorporated into the model to take care of the effects of volumetric properties of mixtures. All the model coefficients could be obtained by regression analysis on testing results. In this model, the dynamic modulus $|E^*|$ is a function of frequency, temperature, binder content, and air void. Therefore, if the volumetric properties, temperature, and traffic speed are known, the dynamic modulus of asphalt concrete at a given pavement depth could be predicted.

Table 5. Regression Coefficients *m*, *n*, and *l* in Eq. (6).

Regression Coefficient	Mix Type								
	AC-19C			AC-19M			SMA-13C		
	m	*n*	*l*	*m*	*n*	*L*	*m*	*n*	*l*
δ	-0.0353	0.0136	2.2410	-0.0421	0.0039	2.1180	0.0752	0.0578	1.1989
α	-0.1391	-0.0623	3.2831	-0.1116	-0.0623	3.2831	-0.4705	-0.2045	6.3391
β	0.2179	-0.0115	-2.0020	0.1649	-0.0303	-1.5839	0.0412	-0.0340	-0.8342
γ	0.0488	0.0032	-0.9235	0.0436	0.0070	-0.8162	-0.0251	-0.0182	-0.4141

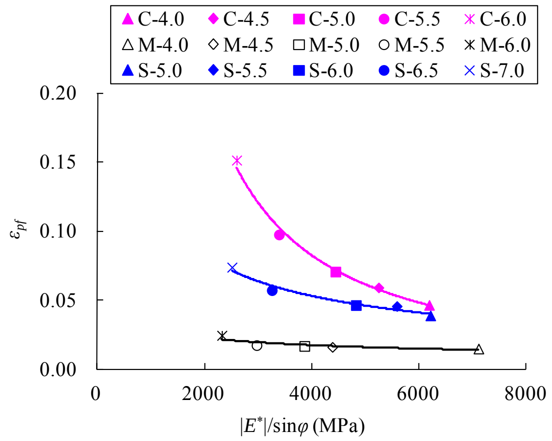

Fig. 4. Relation of ε_{pf} and $|E^*|/\sin\varphi$ at a Temperature of 50℃.

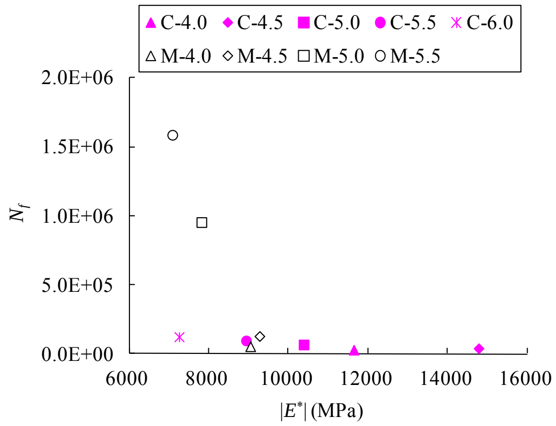

Fig. 5. Relation of N_f and $|E^*|$ at a Temperature of 20℃.

$$log\left(\left|E^*\right|\right) = \delta(P_b, V_a) + \frac{\alpha(P_b, V_a)}{1 + e^{\beta(P_b, V_a) + \gamma(P_b, V_a)(log\, f \times a_T(T))}} \tag{7}$$

Evaluation of Permanent Deformation Using |*E**|/sinφ

Obviously, it is found in Table 2 that the ranking order of the mixture resistance to permanent deformation from high to low is AC-19M, SMA-13C and AC-19C, since the improvement of the binder or aggregate gradation in AC-19M and SMA-13C mixtures is quite beneficial to resist load-induced deformation. Moreover, rutting potential increases with binder content for a specific type of mixture.

The dynamic modulus term |*E**|/sinφ measured at a frequency of 5 Hz and a temperature of 50°C was recommended as a SPT indicator to rutting by Witczak et al. [4]. In this study, |*E**|/sinφ values for all mixtures were correlated with the permanent strains ε_{pf} at the loading cycle of 40,000 measured in the RLPD test, as shown in Fig. 4. It is discovered in Table 2 and Fig. 4 that ε_{pf} decreases with increase in |*E**|/sinφ for the same type of mixture with varying volumetric properties. An excellent power law relationship exists between them. Stiffer mixtures generally show better deformation resistance. Thus, |*E**|/sinφ can distinguish rutting susceptibility for a specific type of mixture.

However, it cannot take care of mixture type dependency. For example, the AC-19M mixtures with SBS modified binder show much better resistance to permanent deformation than the AC-19C mixtures with conventional binder. However, at the same binder content, the |*E**|/sinφ value of the AC-19M mixture is even a little lower than that of the AC-19C mixture for all cases except for the pair of M-4.0 and C-4.0. Also, the S-6.5 and S-7.0 mixtures have better resistance to permanent deformation but lower |*E**|/sinφ values compared to the AC-19C mixtures. The above observations confirm that using the dynamic modulus indicator alone is not accurate enough to evaluate permanent deformation for different mixtures. One possible reason might be because the dynamic modulus obtained within linear viscoelastic range was incapable of capturing rutting characteristics which comprised large strain and displacement phenomena [16].

Evaluation of Fatigue Performance Using |*E**|

Due to lack of materials, the beam fatigue test was only performed for the AC-19C and AC-19M mixtures. It is also observed in Table 2 that at the same binder content, the AC-19M mixture always shows a much better fatigue performance than the AC-19C mixture, and the improvement becomes much greater when higher binder content is used. Thus, it is proved that the SBS modified binder can also improve the mixture resistance to fatigue cracking. For a specific type of mixture, fatigue life significantly increases with binder content, as expected.

The dynamic modulus |*E**| was recommended as a SPT indicator to fatigue cracking by Witczak et al. [6]. In this study, the plot of |*E**| values measured at a frequency of 5 Hz and a temperature of 20°C versus fatigue lives N_f measured in the 4PB beam fatigue test for all mixtures is presented in Fig. 5. Table 2 and Fig. 5 show that |*E**| does not have a good agreement with N_f. The lower modulus does not always correspond to the better fatigue performance. |*E**| even cannot identify fatigue performance for the same type of mixture with varying volumetric properties, not to mention taking care of mixture type dependency. For example, the M-4.5 mixture shows a more than two times fatigue life compared to the M-4.0

mixture at the same testing condition, however, the |*E**| value of the former is even a little higher than that of the latter. Similarly, although the C-6.0 mixture has a lower |*E**|, it shows a much shorter fatigue life than most of the AC-19M mixtures (M-4.0, M-4.5, and M-5.0). Thus, it can be concluded that the dynamic modulus is not a good measure of fatigue performance for asphalt mixtures.

Evaluation of the Witczak Model

Many attempts have been made to develop prediction models of dynamic modulus |*E**| for asphalt mixtures. The Witczak model [17] is one of the most widely used models until now. It is also used in the MEPDG for the calculation of materials parameters in Levels 2 and 3 [4]. It can predict the dynamic modulus |*E**| of asphalt mixtures over a range of temperatures and loading frequencies according to the information of aggregate gradation, binder properties, and volumetric properties of mixtures, as expressed in Eq. (8):

$$\begin{aligned} log\left|E^*\right| &= -1.25 + 0.029\rho_{200} - 0.0018(\rho_{200})^2 - 0.0028\rho_4 \\ &- 0.058V_a - 0.822\frac{V_{beff}}{V_{beff}+V_a} \\ &+ \frac{3.872 - 0.0021\rho_4}{1+e^{(-0.603313-0.313351log(f)-0.393532log(\eta))}} \\ &+ \frac{0.004\rho_{3/8} - 0.000017(\rho_{3/8})^2 + 0.0055\rho_{3/4}}{1+e^{(-0.603313-0.313351log(f)-0.393532log(\eta))}} \end{aligned} \tag{8}$$

where |*E**| is the dynamic modulus, 105 psi; ρ_{200} is % passing #200 (0.075 mm) sieve; ρ_4 is cumulative % retained on #4 (4.75 mm) sieve; $\rho_{3/8}$ is cumulative % retained on 3/8 in (9.5 mm) sieve; $\rho_{3/4}$ is cumulative % retained on 3/4 in (19 mm) sieve; V_{beff} is the effective binder content, % by volume; and η is viscosity of binder, 106 Poise.

The comparison of the measured dynamic modulus |*E**| in laboratory with the predicted ones using the Witczak model is shown in Fig. 6. The mixture parameters ρ_{200}, ρ_4, $\rho_{3/8}$, and $\rho_{3/4}$ related to aggregate gradations were obtained from Fig. 1. The volumetric properties V_{beff} and V_a of each mixture were provided in Table 1. The viscosity of each binder could be found in literature [18].

Fig. 6 shows that the Witczak model seriously underestimates the dynamic modulus of asphalt mixtures for most cases in this study. Moreover, the underestimation is generally more significant for higher modulus values. In other words, at a low temperature in winter and/or a high frequency, the actual stiffness of a mixture will be much higher than that predicted using the Witczak model. Therefore, using this model may be inclined to cause more pavement cracks. In addition, the higher prediction errors could be found in the SMA mixtures compared to the other two dense graded mixtures. It indicates that the application range of the Witczak model is still limited although it has been revised several times and greatly improved. It should be used with more caution for a new type of mixture. In this study, a shift factor of 1.8621 should be recommended for the Witczak model to correct the prediction results.

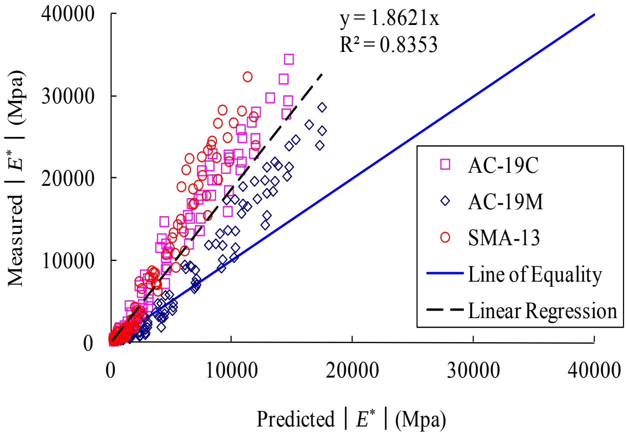

Fig. 6. Comparison of the Measured and Predicted |*E**| Using the Witczak Model.

Field Verification

To verify the proposed dynamic modulus model using field data, four sections from two pavements (Yanhai and Yanjiang Highways) built in the Jiangsu Province of China were selected in this study. All the sections have almost the same pavement structure typically used in this region. Only a slight difference exists in the thickness of the cement stabilized macadam base. Pavement condition evaluations have been conducted once for the three sections (YH-1, YH-2, and YH-3) in Yanhai Highway and four times for the other YJ section in Yanjiang Highway. Deflection data was measured using a non-destructive FWD test device. Deflection measurements were made in the outside wheel path of the travel lane by 9 sensors at 50 m intervals. The target load used in FWD testing was 50 kN. The load pulse duration was between 27 and 30 ms. The detailed pavement information is provided in Table 6.

A numerical backcalculation program MODULUS 6.0 was used to determine the in-situ pavement modulus from FWD data. Its reliability was verified elsewhere [19]. In this program, all pavement sections, as shown in Table 6, were modeled as four layer systems by combining all asphalt concrete sublayers into one layer. The average backcalculated modulus of the asphalt concrete layer from all measuring points was used in each section.

As shown in Table 6, all the investigated pavement sections in this study have the same combination of asphalt concrete layers. According to the field conditions, the dynamic modulus |*E**| of the top and intermediate asphalt concrete layers were predicted using the proposed model as shown in Eq. (7). The mixture types corresponded to the SMA-13C/S-6.5 (the top layer) and AC-19M/M-5.0 (the intermediate layer) used in laboratory, respectively. It should be mentioned that different binders were used in the SMA mixtures between laboratory and field. However, the prediction errors were negligible since the binder type did not significantly effect the dynamic modulus of asphalt mixtures as observed before. Various regression coefficients of the proposed model could be found in Tables 3-5. The volumetric properties of the two mixtures are listed in Table 1. The dynamic modulus |*E**| of the AC-25 mixture used in the bottom layer was directly measured in laboratory and could be found elsewhere [20].

Table 6. Pavement Structure and General Information.

Property	Section			
	Yanhai Highway			Yanjiang Highway
	YH-1	YH-2	YH-3	YJ
Surface	Top: 4 cm SMA-13+SBS Modified PG 76-22 Binder Intermediate: 6 cm AC-19+SBS Modified PG 76-22 Binder Bottom: 8 cm AC-25+Conventional PG 64-22 Binder			
Base	38 cm Cement Stabilized Macadam			40 cm Cement Stabilized Macadam
Subbase	Lime-fly Ash Soil			
Open to Traffic	2006.10	2005.11	2005.11	2004.11
Field Investigation	2007.12			1st: 2005.07; 2nd: 2006.04; 3rd: 2007.09; 4th: 2008.03

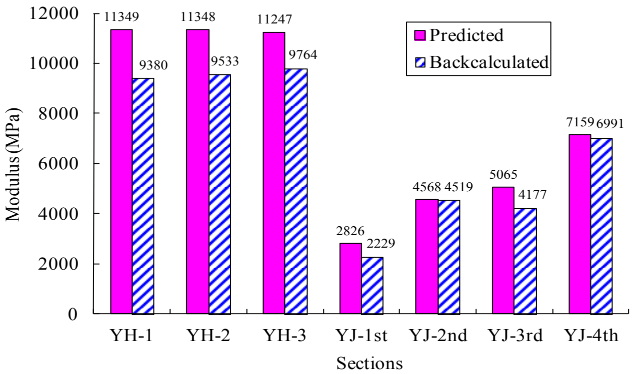

Fig. 7. Comparison of the Backcalculated Modulus and the Predicted Modulus $|E^*|_{equ}$.

The loading frequency and temperature are the two main parameters to determine the dynamic modulus. In this study, the loading frequencies at different depths of the sections were calculated based on the empirical relationship between surface load pulse duration and pavement depth obtained by Loulizi et al. [21]. The pavement temperature distribution with depth was predicted using an empirical function proposed by Zheng et al. [22]. The pavement surface temperature and load pulse duration were automatically recorded at the time of the FWD testing.

In the backcalculation using the MODULUS 6.0 program, only one in-situ pavement modulus was obtained to synthetically represent the three different asphalt concrete layers; however, three different $|E^*|$ values were obtained for different asphalt concrete layers from the proposed prediction model and the master curve. To conveniently compare the laboratory and field results, the concept of equivalent dynamic modulus $|E^*|_{equ}$ was established for converting the different modulus in three sublayers to an equivalent value in the entire layer, as expressed in Eq. (8). It could be easily derived from the Odemark's transformation [4].

$$|E^*|_{equ} = \left(\frac{h_1 + h_2 \sqrt[3]{\frac{|E^*|_2}{|E^*|_1}} + h_3 \sqrt[3]{\frac{|E^*|_3}{|E^*|_1}}}{h_1 + h_2 + h_3} \right) \bullet |E^*|_1 \quad (9)$$

where $|E^*|_{equ}$ is the equivalent dynamic modulus; $|E^*|_1$, $|E^*|_2$, and $|E^*|_3$ are respectively the dynamic modulus of the top, intermediate, and bottom asphalt concrete layer; h_1, h_2, and h_3 are respectively the thickness of the top, intermediate, and bottom asphalt concrete layer.

The comparison of the backcalculated in-situ pavement modulus with the equivalent dynamic modulus $|E^*|_{equ}$ predicted using the proposed model is shown in Fig. 7, which shows that the proposed model slightly overestimates the dynamic modulus of asphalt concrete layers in field for all cases. The prediction errors may be due to some aforementioned assumptions and simplified methods used in this study. The highest relative error is less than 30% among all the cases. Therefore, it can satisfy the accuracy requirement of actual engineering. Conducting Analysis of Variance (ANOVA) procedure at a 0.05 level of significance it was found that there was no statistical significant difference in the variances of the two data sets (F_{stat} = 1.43 and a p-value = 0.34). Finally, it can be concluded that the proposed model is able to reasonably predict the dynamic modulus of asphalt mixtures with varying volumetric properties at different loading frequencies and temperatures in field. Since field measured data is limited, a further study is required to validate the proposed dynamic modulus model in a wide range of pavement structure and material. Additionally, before using this model for a new type of mixture, some laboratory tests are required to determine the specific regression coefficients at this stage. Therefore, the practicality of the model should also be improved in future.

Conclusions

The following important observations and conclusions are made in this study:

(1) For a specific type of mixture, $|E^*|$ decreases with the increase in binder content at the lower reduced frequency, while at the higher reduced frequency, there is a peak $|E^*|$ value appearing at the approximate optimum binder content obtained from volumetric mix design criteria.

(2) $|E^*|/\sin\varphi$ can only distinguish rutting susceptibility measured from the RLPD test for a specific type of mixture; however, it cannot take care of mixture type dependency. Therefore, it is not a rational indicator to permanent deformation for different mixtures.

(3) $|E^*|$ is not a good measure of fatigue performance for asphalt mixtures since it is not well correlated to fatigue life measured from 4PB beam fatigue test.

(4) The Witczak model seriously underestimates $|E^*|$ of the

mixtures used in this study. A shift factor of 1.8621 is recommended to correct the prediction results.

(5) A dynamic modulus prediction model for asphalt mixtures with varying volumetric properties was developed in laboratory and successfully verified using FWD backcalculation.

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