Field Verification of Superpave Dynamic Modulus

Daba S. Gedafa, Ph.D., EIT, Aff.ASCE[1]; Mustaque Hossain, Ph.D., P.E., F.ASCE[2]; Stefan Romanoschi, Ph.D., P.E., M.ASCE[3]; and Andrew J. Gisi, P.E., M.ASCE[4]

Abstract: In the mechanistic-empirical pavement design guide, prediction of flexible pavement response and performance needs an input of dynamic modulus of hot-mix asphalt at all three levels of hierarchical inputs. This study was intended to find the best way to predict/derive this input. Nine Superpave pavement sections were selected as test sections in this study. Deflection data on all test sections was collected with a Dynatest 8000 falling weight deflectometer shortly after construction. The deflection data, normalized with respect to 40-kN load, were used to back-calculate asphalt layer moduli using three back-calculation algorithms. Laboratory dynamic modulus tests were conducted on asphalt concrete (AC) cores and laboratory-compacted samples. Dynamic modulus was also estimated with the Witczak model, new Witczak model, and Hirsch model. The results show that the AC moduli obtained from various back-calculation programs used in the study are generally comparable. Laboratory dynamic modulus is comparable at 4°C, but the variation increases as the test temperature increases. The Witczak model underestimates the dynamic modulus at low temperature and overestimates it at higher temperature. The parameter estimate when the laboratory dynamic modulus is used as a dependent variable and the moduli from other approaches as independent variables is close to 1. This is especially true for the AC moduli estimated by various prediction methods. The Hirsch model appears to be the best for estimation and is closely followed by the new Witczak model.

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Introduction

The design methods adopted in the NCHRP 1-37A guide for mechanistic-empirical design of new and rehabilitated pavement Structures (National Cooperative Highway Research Program 2004) are based on mechanistic-empirical principles. This guide is popularly known as mechanistic-empirical pavement design guide (MEPDG). In this guide, prediction of pavement response and performance must take into account fundamental properties of layer materials. Among these, the most important property of hot-mix asphalt (HMA), a relatively new concept to the state highway agencies, is the dynamic modulus of asphalt concrete. This property represents the temperature- and frequency-dependent (and therefore, time-dependent) stiffness characteristics of the HMA material. Extensive research effort has resulted in a standard test protocol that can be used for the simple performance test for superpave mix design (NCHRP 2002). The protocol calls for use of axial compression testing for measuring dynamic modulus. One of the issues related to the dynamic modulus is its use in forensic studies and pavement rehabilitation design.

In the hierarchical design approach proposed in MEPDG for new HMA pavements, direct measurements of dynamic modulus are required for the highest design reliability (Level 1), which is intended for pavements with very high traffic volumes. However, dynamic modulus is used as the primary stiffness property for HMA at all three levels of hierarchical inputs in MEPDG.

In the overlay analysis of existing HMA pavements, the modulus of the existing HMA pavements is characterized by a damaged modulus that represents the condition at the time of overlay placement. However, according to MEPDG, the laboratory dynamic modulus tests are not needed for measuring the in-place modulus because the test must be performed on intact, but age-hardened specimens. In fact, MEPDG contends that the resulting modulus values will likely be higher than those for new HMA mixtures. Thus, MEPDG recommends that the modulus be determined from the deflection basin tests. However, no correlation between the laboratory dynamic modulus of asphalt concrete (AC) mixture and the back-calculated AC layer modulus has been established to date.

The dynamic modulus test is relatively difficult and expensive to perform. Therefore, numerous attempts have been made to develop regression equations to estimate the dynamic modulus from mixture volumetric properties. The predictive model developed by Witczak et al. (2002) is one of the most comprehensive mixture dynamic modulus models available to date that can predict the dynamic modulus of dense-graded HMA mixtures. A revised version of this model has been recommended in the design of

[1]Research Associate, Dept. of Civil Engineering, 2118 Fiedler Hall, Kansas State Univ., Manhattan, KS 66506 (corresponding author). E-mail: daba@ksu.edu

[2]Professor, Dept. of Civil Engineering, 2118 Fiedler Hall, Kansas State Univ., Manhattan, KS 66506. E-mail: mustak@ksu.edu

[3]Associate Professor, Department of Civil Engineering, 408 Nedderman Hall, The University of Texas at Arlington, Arlington, TX 76019. E-mail: romanoschi@uta.edu

[4]Geotechnical Engineer, Kansas Dept. of Transportation, Materials and Research Center, 2300 Van Buren, Topeka, KS 66611. E-mail: agisi@ksdot.org

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Table 1. Layer Type and Thickness

Layer number	Layer type	Material type	Thickness (mm)				
a. New projects							
			U.S.-54 Butler	U.S.-77 Butler	U.S.-283 Graham	K-7 Doniphan	K-99 Elk
1	Surface	SM-9.5A (PG 64–28)	40[a]	40	40	40	40
2	Binder	SM-19A (PG 64–28)	60	60	60	60	60
3	Base	SM-19A (PG 64–22)	220	200	180	120	180
4	Aggregate Base	AB-3	N.A.	N.A.	N.A.	280	N.A.
5	Subgrade	Modified Subgrade	150[b]	150[b]	150[b]	150[c]	150[b]
b. U.S.-75 test sections							
			S-1	S-2	S-3	S-4	
1	Surface	SM-9.5A (PG 70–28)	40	40	40	40	
2	Binder	SM-19A (PG 70–28)	60	60	60	60	
3	Base	SM-19A (PG 64–22)	N.A.	187.5	225	300	
		SM-19A (PG70-22)	225	N.A.	N.A.	N.A.	
4	Subgrade	Lime Treated Subgrade	150[b]	150[b]	150[b]	150[b]	

Note: N.A. means not applicable.
[a]SM-9.5T PG 64–28.
[b]Lime treated subgrade.
[c]Fly ash modified subgrade.

intermediate- and low-volume roadways (design Levels 2 and 3) in MEPDG (AASHTO 2008).

Problem Statement

Adoption of MEPDG for new asphalt pavement design would require the dynamic modulus of HMA mixture as the basic input parameter. The dynamic modulus is measured in the laboratory during design phase using samples compacted by the superpave gyratory compactor (SGC). However, verification is needed whether this input parameter can be achieved in the as-constructed pavement. This can be done through in situ deflection tests using a falling weight deflectometer (FWD) and corresponding laboratory tests on the cores taken from the constructed pavements.

Objectives of the Study

The objectives of this study were as follows:
- Compare laboratory dynamic modulus with estimated dynamic modulus from various prediction models as well as those back-calculated from FWD data; and
- Develop a correction procedure for the input modulus of Superpave mixtures based on back-calculated, laboratory-derived, and estimated dynamic moduli.

Test Sections

Five newly built Superpave pavements, designed using 1993 AASHTO Design Guide, and four Superpave pavement test sections on the Kansas perpetual pavement project on U.S.-75 were selected as experimental sections in this study. Table 1 indicates the layer type and thicknesses of these sections.

All new pavement sections have a surface course of 40 mm thickness. The layer consists of 9.5-mm nominal maximum aggregate size Superpave mixture (known as SM-9.5A and SM-9.5T in Kansas) with PG 64-28 binder. Layers 2 and 3 are composed of fine graded 19-mm nominal maximum aggregate size Superpave mixture (SM-19A) with PG 64-28 and PG 64-22 binders, respectively. The base layer thickness varies from 120 to 220 mm. The K-7 project in Doniphan County has the thinnest asphalt base layer (120 mm) since it also has 280 mm crushed aggregate base designated as AB-3 in Kansas.

On the perpetual pavement project on U.S.-75, Section 1 (S-1), Section 2 (S-2), and Section 3 (S-3) were designed by the Kansas Asphalt Pavement Association (KAPA) whereas Section 4 (S-4), thickest section, was designed by the Kansas Department of Transportation (KDOT). Sections 1 and 3 have the same thickness, but Section 3 has a softer binder in the base layer. Section 2 has a predicted fatigue life of 30 million ESALs/lane, which corresponds to a reliability factor of about 5.2 (a reliability level of 85%). Thus it was named the high reliability section (Romanoschi et al. 2008). All projects have lime-treated subgrade except K-7 in Doniphan County where subgrade was modified with a Class C fly ash.

Data Collection

Deflection Data

Deflection data was collected with a Dynatest 8000 FWD approximately 8–10 weeks after construction. Multiple target loads were used on most projects to evaluate the stress sensitivity of the materials in the pavement structure. The load pulse duration was in between 25 and 30 ms. This frequency enabled us to compare back-calculated HMA moduli with the laboratory-measured and estimated dynamic moduli at 25 Hz.

The target loads used in FWD testing were 40, 53, and/or 67

J. Mater. Civ. Eng. 2010.22:485-494.

Table 2. Summary of Volumetric Properties for New Projects

	U.S.-54			U.S.-77			U.S.-283			K-7			K-99		
	Surface	Binder	Base	Surface	Binder	Base	Surface	Binder	Base	Surface	Binder	Base	Surface	Binder	Base
ρ_{200}	4.7	4.3	3.5	4.0	5.3	2.6	4.0	4.9	4.7	3.3	4.6	2.9	2.2	2.8	2.9
ρ_4	27.0	37.0	33.0	23.0	36.0	37.0	26.0	32.0	28.0	22.0	44.0	37.0	28.0	41.0	34.0
$\rho_{3/8}$	2.0	18.0	17.0	3.0	17.0	17.0	6.0	18.0	19.0	2.0	29.0	20.0	5.0	24.0	18.0
$\rho_{3/4}$	0.0	3.0	3.0	0.0	3.0	2.0	0.0	2.0	2.0	0.0	0.0	0.0	0.0	4.0	1.0
Gse	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Gsb	2.5	2.5	2.6	2.5	2.5	2.5	2.6	2.6	2.6	2.5	2.5	2.5	2.5	2.5	2.5
Gmb	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.2	2.2	2.2	2.3	2.3	2.3
Gmm	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Gb	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
%AC	6.0	5.6	5.2	6.1	5.5	5.2	5.8	4.9	4.8	6.4	5.7	5.7	6.8	5.5	5.5
VMA	16.9	16.2	16.5	15.6	14.8	14.1	16.2	15.6	15.2	17.6	15.9	16.3	17.3	15.7	16.1
VFA	72.6	64.3	60.7	74.4	69.2	65.5	72.2	62.4	64.1	64.2	59.9	58.1	74.3	61.3	58.1
*V*a	4.6	5.8	6.5	4.0	4.6	4.9	4.5	5.9	5.5	6.3	6.4	6.8	4.5	6.1	6.8
*V*eff	12.7	10.9	10.2	12.0	10.5	9.6	12.1	9.7	10.0	11.7	9.9	9.8	13.4	10.0	9.8

Note: ρ_{200}=percent passing sieve 0.075 mm; ρ_4, $\rho_{3/8}$, $\rho_{3/4}$=cumulative percent retained on 4.75-, 9.5-, and 19-mm sieves, respectively; Gse, Gsb =effective and bulk specific gravities of aggregate, respectively; Gmb and Gmm=bulk and theoretical maximum specific gravity of the mixture, respectively; %AC and Gb=percent asphalt content and asphalt specific gravity, respectively; VMA and VFA=voids in the mineral aggregates (%) and percent of VMA filled with binder (%), respectively; and *V*a and *V*eff=air voids (%) and effective asphalt content (%), respectively.

kN for all new projects and 40 kN for all U.S.-75 test sections. Deflection measurements were made in the outside wheel path of the travel lane at 11 stations at 30 m intervals on all new projects. FWD data at seven to nine stations were collected on the U.S.-75 test sections. The geophone spacing was 0, 200, 300, 450, 600, 900, and 1,200 mm for U.S.-54, U.S.-77, and U.S.-283. The last sensor was located at 1,500 mm for K-7 and K-99 projects and on all U.S.-75 test sections. The pavement surface temperature was measured at the time of testing. This temperature varied from 17 to 59°C for all new projects and 12 to 40°C for the U.S.-75 test sections. The variation in temperature for the U.S.-75 test sections was due to time difference, though testing was done on the same day.

Samples for Laboratory Dynamic Modulus Test

On all new projects, full depth, 100-mm-diameter cores were taken at the same locations where FWD deflections tests had been done. Later the samples were trimmed to the required height of 150 mm for dynamic modulus testing. Some thicker cores were cut into two 150-mm samples, whereas base layer (bottom) of thinner cores was cut to 150-mm sample. No cores were taken from the test sections on U.S.-75. Dynamic modulus test samples for these test sections were prepared from the mixtures mixed in the laboratory and compacted by the SGC. The 150-mm-diameter SGC-compacted samples were then cored in the laboratory to get 100-mm-diameter dynamic modulus test samples.

Volumetric Properties for Estimating Dynamic Modulus

Most data required for predicting dynamic modulus using the Witczak model, new Witczak model, and Hirsch model were obtained from the mixture design. Design information includes gradation of aggregates (cumulative percent retained on 4.75-, 9.5-, and 19-mm sieves and percent passing sieve of 0.075 mm), physical properties of the aggregates (bulk and effective specific gravities), asphalt content and asphalt specific gravity, and theoretical maximum specific gravity of the mixture. Bulk specific gravities of the compacted samples and the cores were determined in the laboratory based on the Kansas Standard Test Method KT-15, Procedure III. KT-15 closely follows AASHTO T 166 (AASHTO 2001a). From these pieces of information, the air void (%), effective bitumen content (% by volume), voids in the mineral aggregates (%), and percent of VMA filled with binder (%) were calculated. Table 2 shows summary of volumetric properties for the mixtures in the new projects.

Data Analysis

Back-Calculation of Layer Moduli

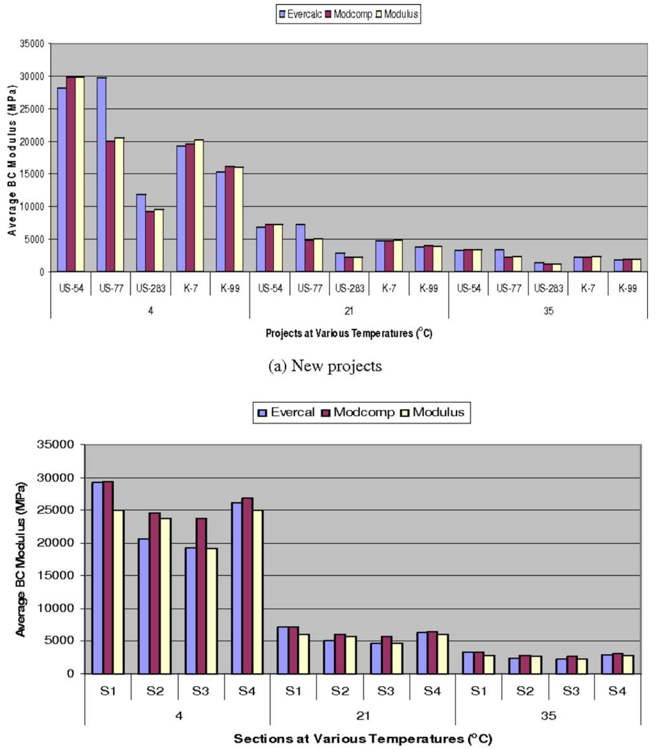
All deflections were normalized to 40-kN FWD load and were used to back-calculate the moduli of AC layers based on multilayered linear elastic theory. Pavement sections were modeled as three-layer systems by combining all AC layers into one. Comparison of solutions from different back-calculation algorithms gives an idea of the range of values that can be expected (Chou and Lytton 1991). Thus, three back-calculation computer programs, EVERCALC, MODCOMP 5, and MODULUS, were used in this study.

In the back-calculation of pavement layer moduli, the objective is to identify a set of pavement layer moduli that would produce a deflection basin matching the measured deflection basin. Since only a finite number of sensor data points are available from the deflection measurements, the objective function in back-calculation analysis typically involves minimization of the root-mean-square difference (D_{rms}) of the measured and computed deflections. A solution that has a smaller D_{rms}, derived from Eq. (1), is considered to be a better fit, and thus a better solution (Fwa et al. 1997)

$$\text{minimize } D_{\mathrm{rms}} = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(\frac{d_i - D_i}{D_i}\right)} \tag{1}$$

where m=number of deflection-measurement points; d_i=back-calculated deflection at point i; and D_i=measured deflection at point i.

J. Mater. Civ. Eng. 2010.22:485-494.



(a) New projects

(b) US-75 test sections

Fig. 1. Comparison of average back-calculated moduli at various temperatures: (a) new projects; (b) U.S.-75 test sections

Temperature Correction of Back-Calculated AC Modulus

The most important environmental factor affecting surface deflections and back-calculated AC moduli of flexible pavements is the temperature of the AC layer (Kim and Lee 1995; Park and Kim 1997; Shao et al. 1997; Park et al. 2002). Since FWD testing is performed at different temperatures, the back-calculated AC moduli need to be adjusted to a standard temperature to allow for a direct comparison between the back-calculated moduli and other moduli.

To determine corrected AC modulus, a two-step correction procedure is needed. Typically, the first step consists of predicting the effective temperature of the AC layer and the second step consists of adjusting the computed modulus to a reference temperature using a correction factor (Park et al. 2001). This two-step procedure was followed in this study.

AC layer temperature: using measured pavement temperatures at different depths from the long-term pavement performance database, Inge and Kim (1995) developed the BELLS equation for predicting AC layer temperature at the one-third depth. A third model, BELLS3, was subsequently developed for use during routine FWD testing when pavement surface is typically shaded for less than a minute. BELLS3 model [Eq. (2)] was used in this study to calculate mid-depth pavement temperature (Federal Highway Administration 2000).

$$T_d = 0.95 + 0.892T_s + (\log d - 1.25) \times \left[1.83 \sin\left(2\pi\frac{A}{18}\right) - 0.448T_s + 0.621T_{avg}\right] + 0.042T_s \sin\left(2\pi\frac{B}{18}\right) \quad (2)$$

where T_d=pavement temperature at layer mid-depth (°C); T_s =infrared surface temperature (°C); T_{avg}=average of high and low air temperatures on the day before testing (°C); and d =layer mid-depth (mm). A and B are computed as follows:

$$A = \begin{cases} t_d + 9.5 & \text{if } 0 \le t_d < 5 \\ -4.5 & \text{if } 5 \le t_d < 11 \\ t_d - 15.5 & \text{if } 11 \le t_d < 24 \end{cases} \quad \text{and}$$

$$B = \begin{cases} t_d + 9.5 & \text{if } 0 \le t_d < 3 \\ -4.5 & \text{if } 3 \le t_d < 9 \\ t_d - 13.5 & \text{if } 9 \le t_d < 24 \end{cases}$$

where t_d=time of day (in decimal hours).

The last two variables are used as arguments to a pair of sine functions with 18 h periods, and 15.5- and 13.5-h phase lags, respectively. One cycle per day is allowed. During the other six hours of the day, A and B are set equal to -4.5 so that the sine functions return a value of -1.

Temperature correction for AC modulus: Chen et al. (2000) developed Eq. (3) based on deflection data from intact locations. This equation was used in this study since it can be used to adjust AC modulus to any temperature. AC modulus was corrected to 4, 21, and 35°C temperature to compare with the laboratory and estimated moduli.

$$E_{T_w} = \frac{E_{T_c}}{[(1.8T_w + 32)^{2.4462} \times (1.8T_c + 32)^{-2.4462}]} \quad (3)$$

where E_{T_w}=adjusted modulus of elasticity at T_w (MPa); E_{T_c} =measured modulus of elasticity at T_c (MPa); T_w=temperature to which the modulus of elasticity is adjusted (°C); and T_c=mid-depth temperature at the time of FWD data collection (°C).

Laboratory Tests for Dynamic Modulus

Dynamic modulus tests were conducted using a universal testing machine (UTM-25). AASHTO TP: 62-03 (standard method of test for determining dynamic modulus of HMA concrete mixtures) (AASHTO 2001b) was followed except for some minor modifications in test temperature and frequencies. Modifications were made in order to match the temperatures and frequencies of back-calculated and estimated moduli from prediction models. Tests at low temperature also takes time and cause freezing of the UTM, whereas at high temperature, samples start softening and LVDTs could not be glued to the samples. In this study, three temperatures: 4, 21, and 35°C, and six frequencies: 0.1, 0.5, 1, 5, 10, and 25 Hz, were used.

Computation of Dynamic Modulus Using Prediction Models

The effect of aging was incorporated in dynamic modulus estimation using the global aging system (Mirza and Witczak 1995). The original, mix/lay-down, surface aging, and aging at different depths and corresponding viscosities were determined at different temperatures (4, 21, and 35°C) and frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz). Temperature data for different project locations was obtained from the weather data library at Kansas State University. Dynamic modulus of the asphalt pavement layer material was estimated using the Witczak model, new Witczak model, and Hirsch model.

Witczak model: the predictive model developed by Witczak et al. (2002) is one of the most comprehensive mixture dynamic

J. Mater. Civ. Eng. 2010.22:485-494.

Table 3. Summary Statistics of Back-Calculated AC Modulus at Various Temperatures

Temp. (°C)		EVERCALC Average mod. (MPa)	EVERCALC SD (MPa)	EVERCALC COV (%)	MODCOMP Average mod. (MPa)	MODCOMP SD (MPa)	MODCOMP COV (%)	MODULUS Average mod. (MPa)	MODULUS SD (MPa)	MODULUS COV (%)
(a) New projects										
4	U.S.-54	28,142	2,238.2	8.0	29,844	1,609	5.4	29,913	24,61.9	8.2
	U.S.-77	29,705	8,309.4	28.0	19,987	1,834	9.2	20,515	2,627.8	12.8
	U.S.-283	11,887	2,159.1	18.2	9,279	942.5	10.2	9,438	834.0	8.8
	K-7	19,244	972.2	5.1	19,633	1,271	6.5	20,233	2,000.2	9.9
	K-99	15,279	1,838.2	12.0	16,177	1,136	7.0	15,965	1,108.8	6.9
21	U.S.-54	6,861	545.7	8.0	7,276	392.4	5.4	7,293	600.2	8.2
	U.S.-77	7,243	2,026.0	28.0	4,873	447.1	9.2	5,002	640.7	12.8
	U.S.-283	2,898	526.4	18.2	2,262	229.8	10.2	2,301	203.3	8.8
	K-7	4,692	237.2	5.1	4,787	310.3	6.5	4,933	487.5	9.9
	K-99	3,725	448.2	12.0	3,944	277.1	7.0	3,893	270.3	6.9
35	U.S.-54	3,228	256.8	8.0	3,423	184.6	5.4	3,431	282.4	8.2
	U.S.-77	3,407	953.2	28.0	2,293	210.4	9.2	2,353	301.4	12.8
	U.S.-283	1,364	247.7	18.2	1,064	108.1	10.2	1,083	95.6	8.8
	K-7	2,207	111.7	5.1	2,252	145.5	6.5	2,321	487.5	9.9
	K-99	1,753	210.9	12.0	1,831	127.2	6.9	1,856	130.3	7.0
(b) U.S.-75 test sections										
4	S-1	29,282	1,577	5.4	29,344	2,231	7.6	25,029	839.7	3.4
	S-2	20,671	3,746	18.1	24,602	1,005	4.1	23,758	1,164.3	4.9
	S-3	19,273	2,145	11.1	23,713	860.3	3.6	19,111	1,322.3	6.9
	S-4	26,164	2,127	8.1	26,806	2,135	8.0	25,030	1,515.3	6.1
21	S-1	7,139	384.4	5.4	7,155	543.9	7.6	6,103	204.7	3.4
	S-2	5,040	913.2	18.1	5,998	244.9	4.1	5,792	283.9	4.9
	S-3	4,699	523.0	11.1	5,782	209.8	3.6	4,660	322.4	6.9
	S-4	6,379	518.6	8.1	6,536	520.6	8.0	6,103	369.5	6.1
35	S-1	3,359	180.8	5.4	3,366	255.9	7.6	2,871	96.3	3.4
	S-2	2,371	429.6	18.1	2,822	115.2	4.1	2,725	133.6	4.9
	S-3	2,211	246.1	11.1	2,720	98.7	3.6	2,192	151.7	6.9
	S-4	3,001	244.0	8.1	3,075	244.9	8.0	2,871	173.8	6.1

modulus models available today. It is capable of estimating dynamic modulus of dense-graded HMA mixtures over a range of temperature, rates of loading, and aging conditions from information that is usually available from the conventional binder tests and the volumetric properties of the HMA mixture. The Witczak predictive model is based on bitumen viscosity, loading frequency, air void content, effective bitumen content, cumulative percent retained on 19-, 9.5-, and 4.75-mm sieves, and percent passing 0.075 mm sieve.

Hirsch model: Hirsch (1962) developed a variation of the law of mixtures for modeling the mechanical behavior of asphalt concrete. During 1999–2001, Pellinen (2001) conducted dynamic modulus testing of 18 HMA mixtures. Christensen et al. (2003) developed a new dynamic modulus prediction model based on the Hirsch model. The database generated by Pellinen (2001) was used. The model combines the series and parallel elements of phases. In applying the Hirsch model to the asphalt concrete, the relative portion of material in parallel arrangement, called contact volume, is not constant but varies with time and temperature. This model, based on shear modulus of the binder, voids in the mineral aggregates, and percent of VMA filled with binder and contact volume, has been used in this study. Dynamic shear modulus was estimated using Bari's model (Bari 2005).

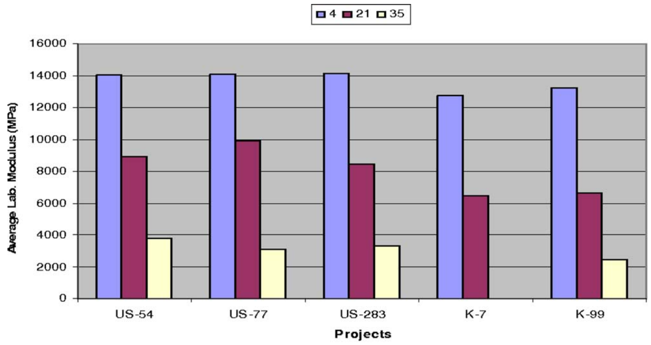
New Witczak model: Bari (2005) developed a comprehensive new Witczak model which uses air void content, effective bitumen content, percent retained on 19-, 9.5-, and 4.75-mm sieves, and percent passing the 0.075 mm sieve, dynamic shear modulus, and phase angle of binder as inputs. Bari (2005) also developed prediction models for dynamic shear modulus and phase angle of the binders. Dynamic shear modulus is estimated based on dynamic shear loading frequency, viscosity of asphalt binder as a function of loading frequency, temperature, and phase angle.

Results and Discussions

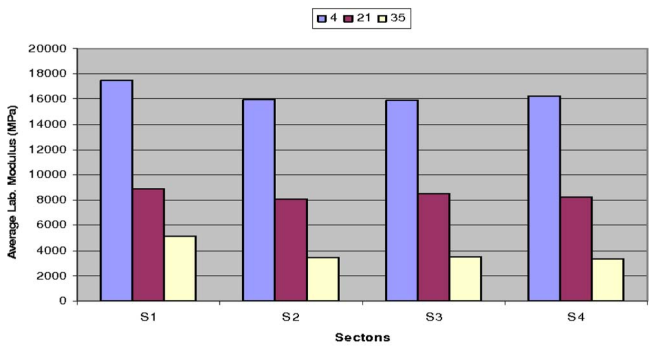
Comparison of Back-Calculated AC Modulus

Fig. 1 shows the comparison of back-calculated AC moduli obtained from different back-calculation programs at various temperatures. The AC moduli from different programs are comparable for all new projects except U.S.-77, where the back-calculated AC modulus using EVERCALC is very high. U.S.-54, which was tested at the lowest temperature, has the highest AC modulus and U.S.-283, which was tested at the highest temperature, has the lowest AC modulus. U.S.-77 and K-7 were tested at comparable temperature and their AC moduli are also comparable. This implies that the test temperature affects the back-calculated AC modulus significantly.

J. Mater. Civ. Eng. 2010.22:485-494.

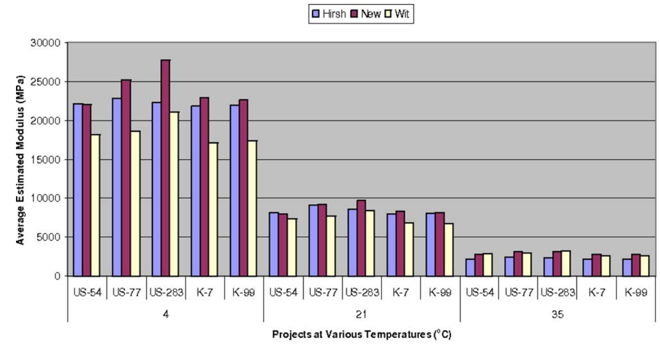


(a) New projects

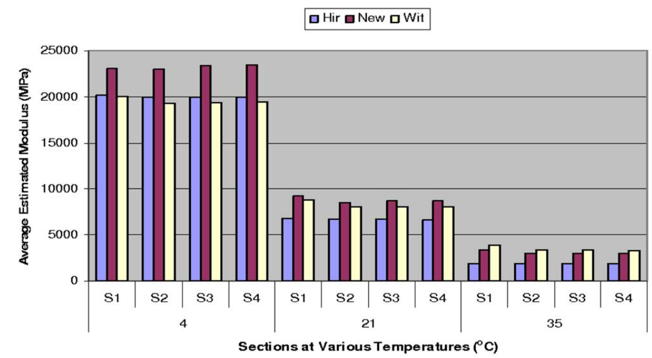


(b) US-75 test sections

Fig. 2. Laboratory dynamic modulus at various temperatures (°C): (a) new projects; (b) U.S.-75 test sections



(a) New projects



(b) US-75 test sections

Fig. 3. Dynamic modulus using prediction models at various temperatures: (a) new projects; (b) U.S.-75 test sections

The back-calculated AC moduli obtained from different back-calculation programs are also comparable for the U.S.-75 test sections. Sections 1–4 have modulus in a descending order. Section 1 was tested at a cooler temperature. Sections 2 and 4 were tested at comparable temperature. Section 4 has a very high back-calculated AC modulus since it is a very thick section. Section 3 was tested at a temperature cooler than 2 and thicker than 2, but the back-calculated AC modulus of this section is the lowest.

Table 3 lists the average back-calculated modulus, standard deviation (SD), and coefficient of variation (COV) for all new projects and U.S.-75 test sections. The standard deviation varies with the temperature whereas the COV remains about the same at all temperature levels. U.S.-77 has the highest average modulus, standard deviation, and COV for the EVERCALC results. U.S.-54 has the highest average AC modulus for MODCOMP and MODULUS. U.S.-77 has the highest standard deviation for the MODCOMP results and the highest standard deviation and COV for MODULUS results. K-7 has the lowest standard deviation and COV for the EVERCALC results. Overall there is no definite trend in the point statistics of the back-calculated moduli results. This is true for the new projects as well as for the U.S.-75 test sections.

Table 4. Comparison of Laboratory Dynamic Modulus at Various Temperatures

	4°C			21°C			35°C		
	Average mod. (MPa)	SD (MPa)	COV (%)	Average mod. (MPa)	SD (MPa)	COV (%)	Average mod. (MPa)	SD (MPa)	COV (%)
(a) New projects									
U.S.-54	14,045	2,098.1	14.9	8,929.0	1,172.2	13.1	3,772	49.0	1.3
U.S.-77	14,059	777.1	5.5	9,894.3	1,794.8	18.1	3,110	136.5	4.4
U.S.-283	14,107	1,003.2	7.1	8,453.3	1,069.4	12.7	3,296	59.3	1.8
K-7	12,721	2,331.9	18.3	6,446.8	1,228.0	19.1	—	—	—
K-99	13,202	309.5	2.3	6,622.4	698.9	10.6	2,473	210.3	8.5
(b) U.S.-75 test sections									
S-1	17,487			8,924.3			5,108		
S-2	15,939			8,068.5			3,432		
S-3	15,909			8,502.7			3,493		
S-4	16,250			8,212.8			3,373		

Table 5. Dynamic Modulus Using Predictive Models at Various Temperatures

Temp (°C)		Hirsch model Average mod. (MPa)	Hirsch model SD (MPa)	Hirsch model COV (%)	New Witczak model Average mod. (MPa)	New Witczak model SD (MPa)	New Witczak model COV (%)	Witczak model Average mod. (MPa)	Witczak model SD (MPa)	Witczak model COV (%)
(a) New projects										
4	U.S.-54	22,070	156.2	0.7	21,996	397.6	1.8	18,080	365.3	2.0
	U.S.-77	22,862	294.2	1.3	25,154	808.3	3.2	18,647	512.0	2.7
	U.S.-283	22,349	267.2	1.2	27,781	840.3	3.0	21,102	601.5	2.9
	K-7	21,807	154.0	0.7	22,926	410.4	1.8	17,107	347.8	2.0
	K-99	21,953	249.6	1.1	22,585	651.0	2.9	17,421	549.7	3.2
21	U.S.-54	8,237	157.2	1.9	8,024	152.9	1.9	7,376	148.9	2.0
	U.S.-77	9,073	342.4	3.8	9,218	296.0	3.2	7,662	210.4	2.7
	U.S.-283	8,564	290.0	3.4	9,686	298.6	3.1	8,389	238.8	2.8
	K-7	7,977	150.9	1.9	8,270	156.3	1.9	6,817	138.7	2.0
	K-99	8,107	250.0	3.1	8,180	247.1	3.0	6,752	213.3	3.2
35	U.S.-54	2,197	53.7	2.4	2,749	54.5	2.0	2,858	57.9	2.0
	U.S.-77	2,496	125.4	5.0	3,166	101.0	3.2	2,957	81.2	2.7
	U.S.-283	2,324	103.4	4.5	3,181	99.2	3.1	3,278	93.4	2.8
	K-7	2,119	51.1	2.4	2,809	55.5	2.0	2,673	54.4	2.0
	K-99	2,163	85.5	4.0	2,801	87.8	3.1	2,700	85.3	3.2
(b) U.S.-75 test sections										
4	S-1	20,151			23,132			20,068		
	S-2	19,972			22,948			19,262		
	S-3	20,005			23,374			19,405		
	S-4	19,941			23,513			19,478		
21	S-1	6,825			9,218			8,879		
	S-2	6,687			8,569			8,024		
	S-3	6,712			8,716			8,056		
	S-4	6,663			8,766			8,049		
35	S-1	1,918			3,436			3,931		
	S-2	1,872			3,007			3,378		
	S-3	1,880			3,040			3,375		
	S-4	1,864			3,039			3,349		

Comparison of Laboratory Dynamic Modulus

All new projects except K-7 and K-99 have comparable average dynamic modulus at 4°C as indicated in Fig. 2. Some variations are observed at 21 and 35°C. K-7 cores were not tested at 35°C since the sample started softening at this temperature and consequently, LVDTs could not be attached (glued) to the specimens. This was not observed for samples from the other projects.

For the test sections on U.S.-75, samples of six different mixes from different layers were tested. The dynamic modulus was then calculated using Eq. (4) for all sections based on the respective thickness of each mix in each section. As a result, only one modulus was calculated for each section as shown in Fig. 2(b)

$$E_{eq} = \frac{\Sigma E_i d_i}{\Sigma d_i} \tag{4}$$

where E_{eq}=equivalent dynamic modulus (MPa); E_i=dynamic modulus of mix in layer i (MPa); and d_i=thickness of mix in layer i (mm).

Sections 2–4 have comparable modulus at all temperatures. Section 1 has the highest dynamic modulus at all temperatures. This section has modified binder in the base layer.

Table 4 tabulates the summary statistics of the dynamic modulus test results of cored samples for the new projects and SGC-compacted specimens for the U.S.-75 test sections. All core samples were tested at 21°C, and three samples were tested at 4 and 35°C for all new projects except K-7. K-7 has the highest standard deviation and coefficient of variation. K-99 has the lowest standard deviation and coefficient of variation. U.S.-54 has the highest average modulus, lowest standard deviation, and COV at 35°C. Obviously dynamic modulus changes as the temperature changes but the degree of change depends upon mixture characteristics.

Dynamic modulus for Sections 1–4 are 8,924, 3,069, 8,503, and 8,213 MPa at 21°C, respectively. The test was done only at 21°C and Eq. (3) was used to convert to other temperatures. As a result, the trend is the same at all temperatures except change in magnitude.

Estimated Dynamic Modulus Using Predicton Models

Dynamic modulus was also estimated for each mix in each layer using aged viscosities at various depths from the prediction models. The equivalent AC modulus was computed using Eq. (4) based on individual thickness of each mixture. Fig. 3 illustrates the estimated AC dynamic moduli. The new Witczak model gave the highest average dynamic modulus for all new projects and

J. Mater. Civ. Eng. 2010.22:485-494.

Table 6. Comparison of Various Methods of Dynamic Modulus Estimation for New Projects at 21°C

Dependent variable	Independent variable	U.S.-54		U.S.-77		U.S.-283		K-7		K-99	
		p value	Similar	p value	Similar	p value	Similar	p value	Similar	p value	Similar
Hirsch	New	0.4078	Yes	0.7515	Yes	<.0001	Yes	0.2366	Yes	0.6378	Yes
	Wit	0.0017	No	0.0015	No	0.4157	Yes	<.0001	No	<0.0001	No
	Lab	0.0203	No	0.0784	Yes	0.6065	Yes	<.0001	No	<0.0001	No
	MODCOMP	0.0002	No	<.0001	No	<.0001	No	<.0001	No	<0.0001	No
	MODULUS	0.0001	No	<.0001	No	<.0001	No	<.0001	No	<0.0001	No
	EVERCALC	<.0001	No	<.0001	No	<.0001	No	<.0001	No	<0.0001	No
New Witczak	Wit	0.0171	No	0.0005	No	<.0001	No	<.0001	No	<0.0001	No
	Lab	0.0021	No	0.1468	Yes	<.0001	No	<.0001	No	<0.0001	No
	MODCOMP	0.0029	No	<.0001	No	<.0001	No	<.0001	No	<0.0001	No
	MODULUS	0.0019	No	<.0001	No	<.0001	No	<.0001	No	<0.0001	No
	EVERCALC	<.0001	No	<.0001	No	<.0001	No	<.0001	No	<0.0001	No
Witczak	Lab	<.0001	No	<.0001	No	0.7640	Yes	0.1889	Yes	0.4239	Yes
	MODCOMP	0.5118	Yes	<.0001	No	<.0001	No	<.0001	No	<0.0001	No
	MODULUS	0.4253	Yes	<.0001	No	<.0001	No	<.0001	No	<0.0001	No
	EVERCALC	0.0098	No	0.2101	Yes	<.0001	No	<.0001	No	<0.0001	No
Lab	MODCOMP	<.0001	No	<.0001	No	<.0001	No	<.0001	No	<0.0001	No
	MODULUS	<.0001	No	<.0001	No	<.0001	No	<.0001	No	<0.0001	No
	EVERCALC	<.0001	No	<.0001	No	<.0001	No	<.0001	No	<0.0001	No
MODCOMP	MODULUS	0.8868	Yes	0.7576	Yes	0.8552	Yes	0.5518	Yes	0.7586	Yes
	EVERCALC	0.0486	No	<.0001	No	0.0039	No	0.7006	Yes	0.1827	Yes
MODULUS	EVERCALC	0.0663	Yes	<.0001	No	0.0065	No	0.3286	Yes	0.3032	Yes

U.S.-75 test sections except on U.S.-54 at 4°C. However, at that temperature, the AC dynamic modulus from the new Witczak model is comparable with that from the Hirch model. The Witczak model gave the lowest average modulus at 4°C. The trend changes with temperature. At higher temperature, dynamic modulus from the Witczak model decreases significantly. The change in trend is very significant. Dynamic moduli using the Witczak model are lowest at 4°C and highest at 35°C for all test sections. Table 5 shows the summary statistics of the estimated dynamic moduli that were calculated based on volumetric data for all new projects and U.S.-75 test sections. The new Witczak model, Hirsch model, and Witczak model show highest to lowest average modulus for all new projects at all temperatures except on U.S.-54. Hirsch model gave the highest modulus for U.S.-54. The COV increases as the temperature increases for all new projects. The standard deviation of AC moduli values, estimated from the Witczak model, for all new projects decreases as the temperature increases but no specific trend is evident for the Hirsch model. The COV and standard deviation were not computed for the U.S.-75 test sections since only one sample was prepared in the laboratory per mix from which air voids was determined to estimate dynamic modulus. Results in Table 5 shows that the Witczak model underestimates the dynamic modulus at low temperature and overestimates at high temperature.

Table 7. Moduli Correction Factors for New Projects at 21°C

Dependent variable	Independent variable	Parameter estimate					
		U.S.-54	U.S.-77	U.S.-283	K-7	K-99	Overall
Lab	Hirsch	1.08	1.09	0.99	0.81	0.82	0.97
	New	1.10	1.07	0.87	0.79	0.81	0.93
	Witczak	1.20	1.29	1.01	0.95	0.98	1.09
	MODCOMP	1.23	2.01	3.70	1.34	1.68	1.61
	MODULUS	1.23	1.95	3.64	1.29	1.70	1.59
	EVERCALC	1.32	1.29	2.82	1.37	1.76	1.45
MODCOMP	Hirsch	0.87	0.53	0.26	0.60	0.49	0.53
	New	0.89	0.52	0.23	0.58	0.48	0.51
	Witczak	0.97	0.63	0.27	0.71	0.58	0.60
MODULUS	Hirsch	0.88	0.54	0.27	0.62	0.48	0.54
	New	0.90	0.53	0.24	0.60	0.48	0.51
	Witczak	0.98	0.64	0.27	0.73	0.58	0.60
EVERCALC	Hirsch	0.82	0.73	0.34	0.59	0.46	0.60
	New	0.84	0.72	0.30	0.57	0.45	0.57
	Witczak	0.92	0.87	0.35	0.69	0.55	0.67

J. Mater. Civ. Eng. 2010.22:485-494.

Statistical Analysis

Statistical analysis for comparing dynamic moduli obtained from various approaches was done by the statistical analysis system software and the significant difference method. All comparison was made at 5% level of significance. Dynamic moduli obtained at a temperature of 21°C and at a frequency of 25 Hz were used for comparison. It is to be noted that conservative comparison can be made between the back-calculated moduli (obtained from deflections measured by FWD at a frequency of between 33 and 40 Hz) and laboratory measured, and estimated dynamic moduli at 25 Hz. Statistical analysis was done at 25 Hz only since comparison between back-calculated and other moduli at other frequencies was not reasonable.

Significant difference test: significant differences among the average AC moduli from various approaches were only investigated for the new projects because of lack of replicate values for the test sections on U.S.-75 test sections. The p value was used to test the significance of the difference among the average dynamic moduli at 21°C.

The analysis results have been tabulated in Table 6. The results are spotty at best i.e., some approaches tend to give similar moduli for a certain project but not for all projects. There are two very consistent trends. Laboratory-determined and the back-calculated moduli are significantly different. MODCOMP and MODULUS give statistically similar results for all projects.

Correction factors: correction factor (parameter estimate) has been developed with SAS. The correction factor may help in getting the right dynamic modulus input into MEPDG. In this part of analysis, laboratory dynamic modulus, estimated modulus, and back-calculated modulus were taken as dependent variables and the other as independent variable. Table 7 tabulates the numerical values of the correction factor.

When the laboratory dynamic modulus is used as the dependent variable, the correction factor varies from 1.08 to 1.32 for U.S.-54, 1.07 to 2.01 for U.S.-77, 0.87 to 3.70 for U.S.-283, 0.79 to 1.37 for K-,7 and 0.81 to 1.76 for K-99. On average, the correction factor varies from 0.93 to 1.61. The largest discrepancy was observed for U.S.-283 for back-calculated moduli where FWD testing was done at a very high temperature. The correction factors for the laboratory modulus and the estimated modulus are consistently close to 1.00 for all projects, with the Hirsch model being the best and that is closely followed by the new Witczak model. This is also evident from the results obtained for the U.S.-75 test sections where laboratory dynamic modulus tests were conducted on reconstituted samples. The correction factors will be used to obtain laboratory dynamic modulus that is required as input in MEPDG based on estimated and/or back-calculated moduli. The overall correction factors may be used for other sites since the new projects were selected from different parts of the state.

Conclusions

Based on this study, the following conclusions can be made:

- The back-calculated moduli from various back-calculation programs used in the study were generally comparable;
- Laboratory dynamic modulus was comparable for all new projects and U.S.-75 test sections at 4°C. The variation increased as the test temperature increased;
- The new Witczak model gave the highest predicted dynamic modulus at 4°C;
- The Witczak model underestimated the dynamic modulus at low temperature and overestimated at high temperature when compared with the laboratory modulus;
- The laboratory and back-calculated moduli were statistically different. The back-calculated moduli from MODCOMP and MODULUS are statistically similar for all projects; and
- The parameter estimate when the laboratory dynamic modulus was used as a dependent variable was close to 1.0 especially for the moduli estimated by various prediction models. This may indicate that the prediction models can be used for estimating dynamic modulus of superpave mixtures. The Hirsch model appears to be the best for estimation and is closely followed by the new Witczak model.

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J. Mater. Civ. Eng. 2010.22:485-494.