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Research Article

Characterization of Various Plant-Produced Asphalt Concrete Mixtures Using Dynamic Modulus Test

Muhammad Irfan,[1] Asad S. Waraich,[2] Sarfraz Ahmed,[1] and Yasir Ali[3]

[1] *Military College of Engineering, National University of Sciences & Technology (NUST), Risalpur Campus, Risalpur 24080, Pakistan*
[2] *Department of Civil, Environmental, and Construction Engineering, University of Central Florida (UCF), 12800 Pegasus Drive No. 211, Orlando, FL 32816-2450, USA*
[3] *National Institute of Transportation, School of Civil and Environment Engineering, National University of Sciences & Technology, Islamabad 44000, Pakistan*

Correspondence should be addressed to Muhammad Irfan; mirfan@mce.nust.edu.pk

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This research characterizes the performance of various plant-produced asphalt concrete mixtures by dynamic modulus $|E^*|$ test using asphalt mixture performance tester (AMPT). Marshall designed specimens of seven different mixtures were prepared using the Superpave gyratory compactor and subjected to sinusoidal compressive loading at various temperatures (4.4 to 54.4°C) and loading frequencies (0.1 to 25 Hz). A catalog of default dynamic modulus values for typical asphalt concrete mixtures of Pakistan was established by developing stress-dependent master curves separately, for wearing and base course mixtures. The sensitivity of temperature and loading frequency on determination of dynamic modulus value was observed by typical isothermal and isochronal curves, respectively. Also, the effects of various variables on dynamic modulus were investigated using statistical technique of two-level factorial design of experiment. Furthermore, two dynamic modulus prediction models, namely, Witczak and Hirsch, were evaluated for their regional applicability. Results indicated that both the Witczak and Hirsch models mostly underpredict the value of dynamic modulus for the selected conditions/mixtures. The findings of this study are envisaged to facilitate the implementation of relatively new performance based mechanistic-empirical structural design and analysis approach.

1. Introduction

Hot-mix asphalt (HMA) consists of the optimum combination of two basic ingredients: aggregate and asphalt binder. In order to meet the diverse and often conflicting performance parameters, for example, resistance to fatigue, deformation, cracking, and moisture damage; durability; skid resistance; and workability and economy, the mix designer generally manipulates three variables, namely, aggregates, asphalt binder, and the ratio of asphalt binder to aggregates, and thus seeks to achieve the aforementioned performance requirements. In Pakistan, the past few years have seen an increase in the premature failure due to fatigue cracking and rutting in both newly constructed and rehabilitated asphalt concrete pavements. The phenomenon of premature failure of pavement structures is attributed to the current design procedures based on 1993 AASHTO design guide which are inherently empirical and incapable of providing adequate and reliable designs for heavy axle loads and tyre pressures in diversity of climatic regions and necessitates a more comprehensive design approach which incorporates both mechanistic and empirical aspects of design. Mechanistic-empirical pavement design guide (AASHTO Pavement ME) encompasses two parts: mechanistic (determine pavement responses) and empirical (distress prediction models/transfer functions). The success of the mechanistic-empirical structural design approach or framework lies in the accurate material characterization for predicting realistic pavement responses and ultimate performance. However, the viscoelastic nature of HMA is a challenge to be considered for its accurate characterization by the material properties. Dynamic modulus $|E^*|$ of HMA is one such material property which reflects the loading time and temperature dependency of HMA. Dynamic modulus is considered as the stiffness property of HMA which can partially characterize its viscoelastic nature. It is the measure of the HMA's resistance to deformation under sinusoidal loading and is given by the absolute value of the complex modulus [1, 2]. Dynamic modulus of HMA has gained attention of the researchers during the past decade especially after its selection as a design input parameter for material characterization of asphalt concrete in the AASHTO Pavement ME pavement design guide and a candidate for a simple performance test to complement Superpave mix design methodology.

Several studies have been conducted in order to gain an insight into the factors affecting $|E^*|$. Bonnaure et al. [3] determined the modulus of asphalt mixtures by the application of a sinusoidal load to trapezoidal specimens and reported that the amount of aggregate and percent of air voids had a significant effect on the stiffness of the mix. Another study reported that the mixtures containing stiffer binders resulted in higher values of $|E^*|$. Furthermore, sample preparation techniques did not affect the dynamic modulus test results [4]. Kim et al. [5] reported that aggregate sources and gradation, within the North Carolina Department of Transportation, Superpave classification, did not seem to have a significant effect on dynamic modulus. This study also determined that the binder source, binder performance grade (PG), and asphalt content seemed to affect the dynamic modulus of asphalt mixtures. Flintsch et al. [6] concluded that mixes of the same type resulted in different measured $|E^*|$ values because of different constituents, that is, aggregate type, asphalt content, and percentage RAP which showed that $|E^*|$ was sensitive to mix constituents and properties. Cross et al. [7] evaluated the factors affecting $|E^*|$ and observed that the testing on lowest temperature of −10°C caused significant frost buildup on the test frame, samples, and LVDTs making it a difficult and time consuming task to determine $|E^*|$ below 0°C. Further, it was reported that the gyratory sample should be compacted to 6.0 ± 1.0% air voids in order to obtain a cored test specimen of required dimensions at 4.5 ± 1.0% air voids. PG grade in addition to test temperature and frequency was reported to have a significant effect on $|E^*|$. However, no significant effect of nominal maximum aggregate size (NMAS) or mix designation was observed. Tashman and Elangovan [8] developed a database of $|E^*|$ values of seven different job mix formulae (JMF) mixes with aggregates of different types and sources typically used in Washington state. Statistical analysis of the results revealed that use of different JMF mixes affected the dynamic modulus. However, it was also observed that the difference in $|E^*|$ due to different JMF was more significant at high temperatures and low frequencies. It was also observed that variation in the aggregate percent passing number 200 sieve did not have any effect on the dynamic modulus. Mohammad et al. [9] documented the effect of aggregate size on $|E^*|$ as a result of the study conducted for characterization of Louisiana asphalt mixtures. It was observed that NMAS had a significant effect on $|E^*|$, as the larger aggregate size combined with recycled asphalt (RAP) yielded higher values of $|E^*|$ at high temperatures. Another study developed a dynamic modulus catalog for NJDOT for implementation of AASHTO Pavement ME structural design approach which was achieved by characterizing twenty-one different typical plant-produced HMA mixes [10]. Bonaquist [11] conducted dynamic modulus testing and reported that, for the same aggregate source mixes, dynamic modulus values were not much different from one another. Further, the aggregate sources with higher dynamic modulus values had the higher limiting minimum modulus values also when compared to other aggregate sources. Limiting minimum modulus values represents the stiffness of aggregate. A study compared the dynamic modulus of field extracted core with laboratory fabricated specimens and concluded that at 4°C dynamic modulus can be compared [12]. Laboratory evaluated dynamic modulus was related to field response and results indicated that laboratory obtained dynamic modulus was inversely proportional to the field measured pavement response of the asphalt longitudinal strains [13]. A number of recent comparative research studies characterized different HMA mixes based upon dynamic modulus test and constructed master curves in order to meet the practitioner needs [14–16].

Kim et al. [16] investigated the effect of additive (LEADCAP) on warm-mix asphalt using dynamic modulus, resilient modulus, and in-door accelerated pavement test (APT). The results suggested that additive is capable of producing mixture at relatively low temperature up to 30°C in comparison to conventional mixture and can be compared reasonably well with controlled hot-mix asphalt. Various researches determined the dynamic modulus of plant-produced or laboratory prepared mixes and validated the predictive ability of Witczak 1-37A model to a reasonable conformity [17–19]. El-Badawy et al. [20] in ensuing research study also calibrated the predictive equations for Idaho state mixtures. Cho et al. [21] evaluated the dynamic modulus of mixtures used in Korea and developed the $|E^*|$ predictive equation for Korean AASHTO Pavement ME and concluded that developed predictive equations were well correlated with measured values. A study was carried out in Saudi Arabia for implementation of AASHTOWare Pavement design and evaluated two models, namely, NCHRP 1-37A and 1-40D, and concluded that NCHRP 1-37A $|E^*|$ model showed accurate and unbiased results [22]. A recent study evaluated the viscoelastic properties of a performance grade binder modified with different percentages of a wax-based warm-mix asphalt (WMA) using dynamic modulus test. This study concluded that the Hirsch model (2003) [23] provided better approximations of the $|E^*|$ values than the Witczak model [24]. In consequence of requisition of skilled personnel, time, and cost effect associated with the dynamic modulus test, researchers have been attempting for several years by using various modeling techniques to develop the prediction equations which can predict the $|E^*|$ values directly from the mix properties. The last few decades have seen the development of these predictive equations as listed in Table 1.

The most recent models listed in Table 1, that is, Andrei, Witczak, and Mirza's revised model (hereafter referred to as Witczak model) and Hirsch model of Christensen, Pellinen,

Table 1: List of dynamic modulus $|E^*|$ predictive models [25].

Model number	E^* predictive model	Year (published)
1	Van der Poel model	1954
2	Bonnaure model	1977
3	Shook and Kallas model	1969
4	Witczak's early model	1972
5	Witczak and Shook's model	1978
6	Witczak's model	1981
7	Witczak, Miller, and Uzan's model	1983
8	Witczak and Akhter's model	1984
9	Witczak, Leahy, Caves, and Uzan's model	1989
10	Witczak and Fonseca's model	1996
11	Andrei, Witczak, and Mirza's revised model	1999
12	Hirsch model of Christensen, Pellinen, and Bonaquist	2003

and Bonaquist (hereafter referred to as Hirsch model), have been reported to be reasonably accurate and were used to evaluate understudy HMA mixtures in this research.

The findings of studies mentioned in Table 1 indicate dynamic modulus, a key material property of HMA that better reflects the viscoelastic nature of asphalt concrete. Its significance has further been increased as a result of its selection as a material characterization design input parameter in the AASHTO Pavement ME and thus asphalt concrete mixtures need to be characterized in terms of $|E^*|$ at regional levels [20–22]. However, to the knowledge of authors, no such research study characterized locally used mixtures in Pakistan. Hence, this research study aimed to determine the dynamic modulus of plant-produced asphalt mixtures in laboratory and results obtained were employed to two-level factorial design for determination of factor affecting $|E^*|$. This research study characterizes and develops the master curves for different asphalt concrete mixes (for wearing and base course mixes), investigates the factors affecting dynamic modulus (stiffness parameter) in order to compare and rank selected asphalt concrete mixes, and validates the laboratory observed dynamic modulus values with the two dynamic modulus prediction models, namely, Witczak and Hirsch models.

2. Methodology

2.1. Objective and Scope. The objective of this study is to develop master curves for various plant-produced asphalt concrete mixtures and rank them based on dynamic modulus. The study incorporates four wearing mixes of nominal maximum aggregate size (NMAS) of 19 mm and three base mixes of NMAS of 37.5 mm procured from different highway construction sites of Pakistan. The binder and aggregate type used for testing were penetration grade 60/70 and limestone aggregate, each from two different sources. The study variables for different selected mixtures are presented in Table 2.

2.2. Selection of Material. Seven plant-produced asphalt concrete mixtures were procured from different highway construction projects keeping in view the desired variability and availability of the plant-produced HMA in Pakistan. Representative samples of all seven mixes were collected from dump trucks at plant site, following the proper sampling techniques [26]. The mixtures used in the study were designed using Marshall method (optimum bitumen content determination) by the contractors of the selected projects pursuant to specifications of National Highway Authority (NHA) [27]. Job mix formulae and gradations of the selected asphalt mixtures are presented in Table 3.

2.3. Specimens Preparation. Representative plant-produced asphalt mix samples were subjected to testing for maximum theoretical specific gravity, asphalt content, and gradation of the aggregate. Then these samples were reheated to compaction temperature of 135°C in the laboratory and triplicate specimens for each test temperature were fabricated in accordance with ASTM 3496-99 [28] using Superpave gyratory compactor with target voids in total mix (VTM) of 4% ± 1% (after coring and/or cutting). The binders on these plant-produced mixes underwent short-term aging during their production stage; however, these binders were extracted/tested. The variation among triplicates specimens was in specified range as specified in AASHTO TP62-07 [1]. Each gyratory compacted specimen was carefully sawed up to required dimension of 100 mm diameter and 150 mm height to comply with the dynamic modulus test specimen requirements as per AASHTO TP 62-07 [1].

2.4. Laboratory Testing. The $|E^*|$ test yields phase angle and $|E^*|$ value. The phase angle (φ) is the angle by which induced axial strain lags behind the applied compressive stress. Figure 1 illustrates the sinusoidal stress and the resulting strain defined by the angular velocity which in turn are related to the loading frequency and time which implies that the phase lag represents the time dependency of HMA. AASHTO Pavement ME has three levels of input: level 1 includes determination of $|E^*|$ in laboratory (material input), whereas levels 2 and 3 encompass determination of $|E^*|$ by the use of predictive equations. Dynamic modulus has also been adopted by AASHTO as a provisional standard in AASHTO designation TP62-07 [1]. The dynamic modulus test method is a widely used laboratory test that requires application of a compressive axial stress to a cylindrical specimen of HMA and the recoverable strain is calculated from axial deformations measured at two, three, or four locations (as

Table 2: Project and mixtures designation—wearing and base course mixtures.

Mix course	Abbreviated name	Project name	Aggregate source	NMAS (mm)	Mix type	Bitumen source and pen. grade
Wearing course mixtures	LNLP	Lakhi-Naudero-Larkana Road	Quetta	19	Marshall	NRL 60/70
	HMW-W	Head Muhammad Wala Bridge (N-70)	Sargodha	19	Marshall	NRL 60/70
	WUP-W	Wah Underpass (N-5)	Margalla	19	Marshall	ARL 60/70
	SWB-TP	Swabi-Topi Road	Margalla	19	Marshall	ARL 60/70
Base course mixtures	JPU	Jalalpur-Pirwala-Uch Sharif Road (N-115)	Sargodha	37.5	Marshall	NRL 60/70
	HMW-B	Head Muhammad Wala Bridge (N-70)	Sargodha	37.5	Marshall	NRL 60/70
	WUP -B	Wah Underpass (N-5)	Margalla	37.5	Marshall	ARL 60/70

Note. NRL: National Refinery Limited; ARL: Attock Refinery Limited.

Table 3: Job mix formulae for selected asphalt mixtures.

Mix type/	Wearing course mixtures				Base course mixtures		
name	LNLP	HMW-W	WUP-W	SWB-TP	JPU	HMW-B	WUP-B
Binder type	NRL 60/70	NRL 60/70	ARL 60/70	ARL 60/70	NRL 60/70	NRL 60/70	ARL 60/70
Binder content (%)	4.0	4.4	4.2	4.2	3.3	3.4	3.5
Air void (%)	4.0	4.0	4.0	4.0	4.0	4.0	4.0
VMA (%)	14.8	15.3	14.2	13.4	13.7	13.2	12.8
VFA (%)	66.9	63.5	66.5	59.5	58.1	59.2	58.0
Metric (US) sieve	Gradation (% passing)						
37.5 mm (1(1/2) in.)	100	100	100	100	100	100	98.8
25 mm (1 in.)	100	100	100	100	82.6	85.4	82.7
19 mm (3/4 in.)	100	99.9	99.7	100	69.7	71.0	67.4
12.5 mm (1/2 in.)	82.5	79.5	84.5	80	59.2	59.9	56.2
9.5 mm (3/8 in.)	68.7	69.4	63.4	67	52.2	53.4	43.5
4.75 mm (number 4)	49.3	48.7	46	48	41.6	35.5	35.0
2.36 mm (number 8)	30.8	35.3	30.5	33	24.5	26.4	25.1
0.3 mm (number 50)	10.5	11.8	10.3	11	9.4	10.8	7.6
0.075 mm (number 200)	5.2	5.2	5.0	4.7	5.0	4.7	4.2

required) by using linear variable differential transformers (LVDTs). Dynamic modulus is then calculated as the ratio of stress magnitude to average strain magnitude.

The dynamic modulus test was conducted at four temperatures and six frequencies for each mixture using asphalt mixture performance tester (AMPT). Specimens were conditioned for the required equilibrium in order to achieve the desired test temperatures before conducting the test. The test equipment consists of environmental chamber, which controls temperature ranging from 4 to 60°C, and confined pressure system which provides pressure up to 210 kPa. Three replicate specimens were tested at each test temperature with COV ranging from 4% to 21%. The tests were performed at the loading frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz and the temperatures used for the testing were 4.4°C, 21.1°C, 37.8°C, and 54.4°C. The laboratory results were further cast off to develop master curves and statistical analysis.

3. Results and Discussion

The dynamic modulus exhibits stress-strain relationship under compressive sinusoidal loading. As expected, for all the tested asphalt concrete mixtures, the dynamic modulus values decreased with an increase in temperature and decrease in the loading frequency. It was observed that LNLP and WUP wearing course mixtures have relatively higher dynamic modulus values at low and high temperature variations, respectively, whereas JPU base course mix has relatively highest dynamic modulus values at both low and

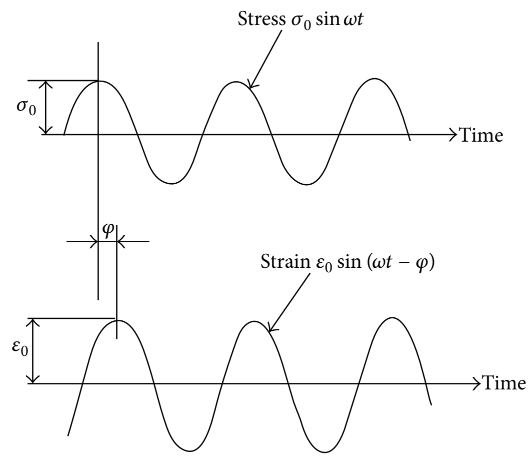


Figure 1: Phase lag between sinusoidal stress and recoverable strain [2].

high temperatures for the range of loading frequencies (Table 4).

The average test results/typical isothermal and isochronal curves for dynamic modulus at four different temperatures and six different loading frequencies for wearing and base mixtures tested in the study have been presented in Figures 2(a) and 2(b), respectively. It is evident from these plots that dynamic modulus decreases with increase in temperature and increases with increase in frequency. Also, sensitivity analysis reveals that, for a given loading frequency, an increase in temperature (from 21.1 to 37.8°C) translated into 57% and 55% drop in $|E^*|$ values on average for wearing and base course mixes, respectively, whereas, for a given temperature, an increase in loading frequency (from 0.1 to 25 Hz), 68% and 79% of variation in $|E^*|$ values on average, was attributed to wearing and base course mixes, respectively.

3.1. Master Curves for Dynamic Modulus. The test results obtained were used for development of master curve for subsequent use in pavement structural response and design process. The test results for the replicate specimens were averaged for each test temperature and master curves for the average values of $|E^*|$ at a reference temperature of 21°C for each mix were constructed using the time-temperature superposition principle using Microsoft® solver sheet. Also, keeping in view the testing limitation and inability of the asphalt mixture performance tester (AMPT) to conduct test at −10°C, an abbreviated approach developed in NCHRP Project 9-29 was used for construction of the stress-dependent master curves [29].

The general form of sigmoidal function used to develop a master curve is given as follows [30]:

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

where $\log(|E^*|)$ is log of dynamic modulus. δ is minimum modulus value. f_r is reduced frequency, that is, $f/a(T)$, where f is actual frequency and $a(T)$ is the required shift factor at reference temperature. α is span of modulus value (range of lowest and highest dynamic modulus values). β, γ are shape parameters of sigmoidal function.

The master curves wearing and base mixes are presented in Figure 3 which illustrates that they tend to converge at higher frequencies; however they have considerable degree of separation at lower frequencies. Higher frequency is analogous to lower temperature and vice versa in terms of temperature. It can be inferred that $|E^*|$ of LNLP wearing mix (Figure 3(a)) and JPU base mix (Figure 3(b)) are relatively better performing for given tested mixtures which is attributed to the mixtures packing arrangement with the relatively lower design asphalt content than other mixtures, thus exhibiting higher stiffness values (see Table 3).

3.2. Evaluation of Dynamic Modulus Prediction Equations. As part of this study two prediction equations were evaluated for regional applicability in Pakistan. As there was no information available with reference to the default dynamic modulus values for commonly used mixtures in Pakistan, it was necessary to characterize the commonly used mixtures accordingly. The inputs parameters for both the equations were primarily obtained from the JMF of the mixtures. However, certain other information like viscosity and shear modulus of binder were obtained by conducting laboratory tests on the extracted binders.

3.2.1. Witczak Model. The current Witczak model used in AASHTO Pavement ME is improved version of the previous Witczak and Fonseca model in order to use a wide range of AC mixtures. The Witczak model used 205 mixtures prepared with both modified and unmodified binders having a temperature range from 0 to 54.4°C and the loading frequency ranging from 0.1 to 25 Hz. A total of 39 different aggregate types were made part of this database and the mixtures tested included both kneading and gyratory compacted specimens [31]. Input parameters of Witczak 1-37A viscosity based model (2) include bitumen viscosity, effective asphalt content, aggregate gradations, air voids, and loading frequency:

Table 4: Measured dynamic modulus, $|E^*|$ (MPa), and phase angle, φ.

(a) Wearing course mixes

Temperature (°Celsius)	Freq. (Hz)	HMW-W $\|E^*\|$	HMW-W φ	WUP-W $\|E^*\|$	WUP-W φ	SWB-TP $\|E^*\|$	SWB-TP φ	LNLP $\|E^*\|$	LNLP φ
4.4	25	23077	7.90	17395	7.85	23821	5.93	29820	6.89
	10	21360	8.15	16258	8.21	22305	6.52	27572	7.62
	5	20346	9.12	15368	8.95	21229	6.91	26028	8.29
	1	16947	9.92	13293	11.27	18712	8.82	22829	10.56
	0.5	15865	11.58	12376	12.26	17382	9.58	20815	11.49
	0.1	13279	14.21	10259	14.87	14555	11.83	16623	14.66
21.1	25	17099	12.20	14141	11.12	17306	10.61	17547	13.91
	10	14769	13.36	12679	12.41	15610	11.51	15320	15.73
	5	13348	13.87	11811	13.10	14720	12.81	13803	16.80
	1	10639	16.65	9384	16.65	11342	16.52	10108	20.25
	0.5	9315	17.90	8246	17.81	9935	17.70	8770	21.75
	0.1	6750	22.07	5819	21.41	7281	21.52	5833	26.39
37.8	25	9942	17.09	8908	19.52	11238	16.86	6322	27.98
	10	7998	19.77	9754	21.17	9494	19.38	4695	29.91
	5	7040	21.35	8580	22.23	8370	20.65	3716	30.40
	1	5047	23.83	3284	24.62	5964	23.77	2075	31.24
	0.5	4337	24.61	2732	25.17	5033	24.69	1586	30.95
	0.1	2744	26.76	1575	27.16	3054	27.23	869	29.32
54.4	25	5268	25.62	6750	22.07	5619	27.50	3323	32.50
	10	4158	26.55	5502	24.11	4413	28.50	2351	32.60
	5	3475	26.05	4675	24.78	3372	28.45	1772	32.37
	1	2158	28.46	3103	27.18	1917	28.63	917	30.97
	0.5	1717	28.58	2517	27.52	1462	28.21	676	30.29
	0.1	889	26.56	1289	29.39	731	27.42	359	27.75

(b) Base course mixes

Temperature (°Celsius)	Freq. (Hz)	JPU $\|E^*\|$	JPU φ	HMW-B $\|E^*\|$	HMW-B φ	WUP-B $\|E^*\|$	WUP-B φ
4.4	25	31626	6.60	29068	6.72	23228	6.77
	10	30199	7.65	27379	7.71	21801	7.92
	5	28448	8.24	25973	8.62	20650	9.02
	1	24387	10.97	22229	11.79	17609	12.61
	0.5	22477	12.34	20415	13.22	16154	14.30
	0.1	17837	16.30	16092	17.67	12569	19.19
21.1	25	21167	11.68	19105	14.29	18699	12.41
	10	18940	14.37	16534	16.98	16603	14.76
	5	17037	16.15	14734	19.14	15141	16.62
	1	12886	21.30	10432	25.55	11307	22.40
	0.5	11156	23.33	8708	28.14	9694	24.66
	0.1	7212	29.02	4950	34.93	5909	30.80
37.8	25	11783	22.81	19580	22.68	12349	21.02
	10	9336	26.83	15789	26.57	9956	24.94
	5	7770	28.89	13190	29.11	8205	27.22
	1	4245	33.34	7663	35.27	4744	32.26
	0.5	2982	34.04	5669	36.78	3475	33.09
	0.1	1299	34.33	2243	38.53	1448	32.70

(b) Continued.

Temperature (°Celsius)	Freq. (Hz)	JPU		HMW-B		WUP-B	
		$\lvert E^*\rvert$	φ	$\lvert E^*\rvert$	φ	$\lvert E^*\rvert$	φ
54.4	25	7757	28.73	3399	42.17	5392	33.94
	10	5557	32.31	2082	43.91	3544	36.05
	5	4226	33.75	1351	44.68	2434	36.59
	1	1958	35.89	462	44.44	1069	35.77
	0.5	1317	35.33	276	44.40	689	34.92
	0.1	524	31.44	110	38.61	331	30.55

$$\begin{aligned}\operatorname{Log} E^* = {} & -1.249337 + 0.029232\left(p_{200}\right) - 0.001767\left(p_{200}\right)^2 - 0.00284\left(p_4\right) - 0.05809V_a - 0.802208\frac{V_{\text{beff}}}{V_{\text{beff}} + V_a} \\ & + \frac{3.871977 - 0.0021p_4 + 0.003958p_{38} - 0.000017p_{(38)^2} + 0.00547p_{34}}{1 + e^{[(-0.603313-0.313351\log(f)-0.393532\log\langle\eta\rangle)]}},\end{aligned} \tag{2}$$

where E^* is dynamic modulus of mix, 10^5 psi (1 psi = 0.00689 MPa). $\acute{\eta}$ is viscosity of binder, 10^6 Poise. f is loading frequency, Hz. p_{200} is % passing number 200 sieve. p_4 is cumulative % retained on number 4 sieve. p_{38} is cumulative % retained on 3/8 in. sieve. p_{34} is cumulative % retained on 3/4 in. sieve. V_a is air voids, % by volume. V_{beff} is effective binder content, % by volume.

For evaluation purposes, values of dynamic modulus were predicted using the Witczak model at the conditions corresponding to each measured value of $|E^*|$. $|E^*|$ values were predicted using the volumetric details and aggregate gradations obtained from the JMF of the mixtures tested: loading frequency (0.1 to 25 Hz); % passing number 200 sieve (4.2 to 5.2%); cumulative % retained on number 4 sieve (35 to 49%); cumulative % retained on 3/8 in. sieve (43 to 69%); cumulative % retained on 3/4 in. sieve (67 to 100%); and air voids % by volume (3.5 to 4.5%). Results indicated that the Witczak model mostly underpredicts the values for dynamic modulus for HMA mixes of Pakistan. Figure 4(a) illustrates the comparison of measured and predicted dynamic modulus values grouped on the basis of temperature. It can be inferred from the figure that the values are distributed along the line of equality for lower temperatures. However, with an increase in temperature, the model tends to underpredict the values for dynamic modulus of the mixtures selected for the study. This implies that the said model is more relevant and significant at lower test temperatures as compared to higher temperature conditions for the tested mixtures in the study.

3.2.2. Hirsch Model. Christensen et al. [23] developed Hirsch dynamic modulus prediction equation based on law of composite mixtures. The model was developed using database of various mixtures to determine dynamic modulus using binder shear modulus, that is, G^*, and the volumetric properties of the mix, that is, voids in mineral aggregate (VMA) and voids filled with asphalt (VFA). The Hirsch model used 18 different mixtures and five different binder types to fabricate both Marshall and Superpave designed specimens. The tests were conducted at temperature ranging from 4 to 38°C and loading frequencies of 0.1 and 5 Hz. The database used for the development of model had air voids ranging from 5.6 to 11.2%; VMA ranging from 13.7 to 21.65%; and VFA of 38.7 to 68%. However, the input parameters range used for validation purpose in this study is given in parentheses against each parameter below. Hirsch model is presented as follows:

$$\begin{aligned}|E^*| = {} & Pc\left[4200000\left(1 - \frac{\text{VMA}}{100}\right)\right. \\ & \left. + 3\left|G^*\right|_b\left(\frac{\text{VFA} \times \text{VMA}}{10000}\right)\right] \\ & + \frac{(1 - Pc)}{\left[(1 - \text{VMA}/100)/4200000 + \text{VMA}/3 \times \text{VFA}\left|G^*\right|_b\right]},\end{aligned} \tag{3}$$

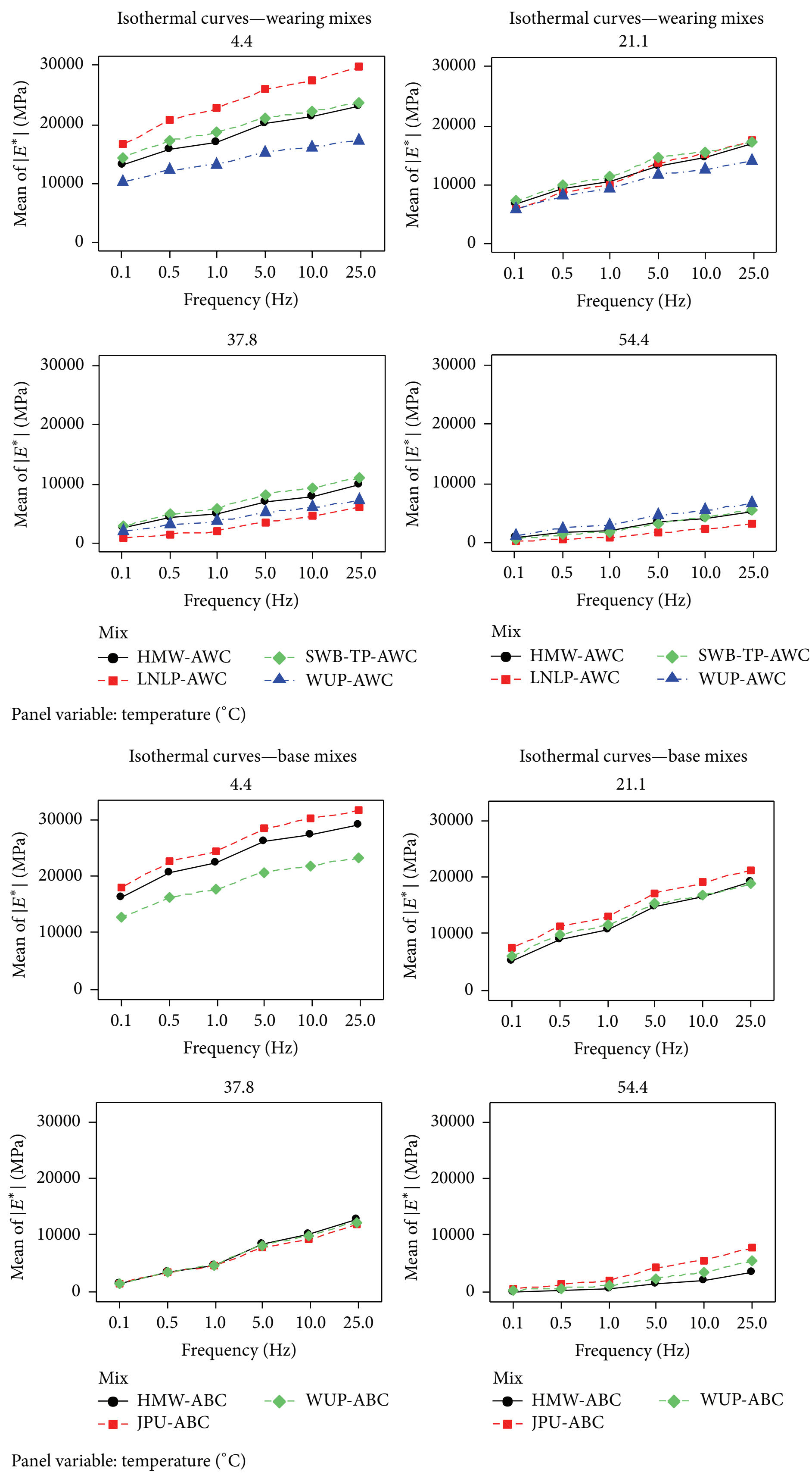
where

$$Pc = \frac{\left(20 + \text{VFA} \times 3\left|G^*\right|_b/\text{VMA}\right)^{0.58}}{650 + \left(\text{VFA} \times 3\left|G^*\right|_b/\text{VMA}\right)^{0.58}}. \tag{4}$$

$|E^*|$ is dynamic modulus, psi (1 psi = 0.00689 MPa). VMA is voids in mineral aggregate, % (12.8 to 15.3%). VFA is voids in aggregate filled with asphalt, % (58 to 67%). $|G^*|_b$ is dynamic shear modulus of binder, psi (0.12 to 0.55 psi) or (0.83 to 3.79 kPa).

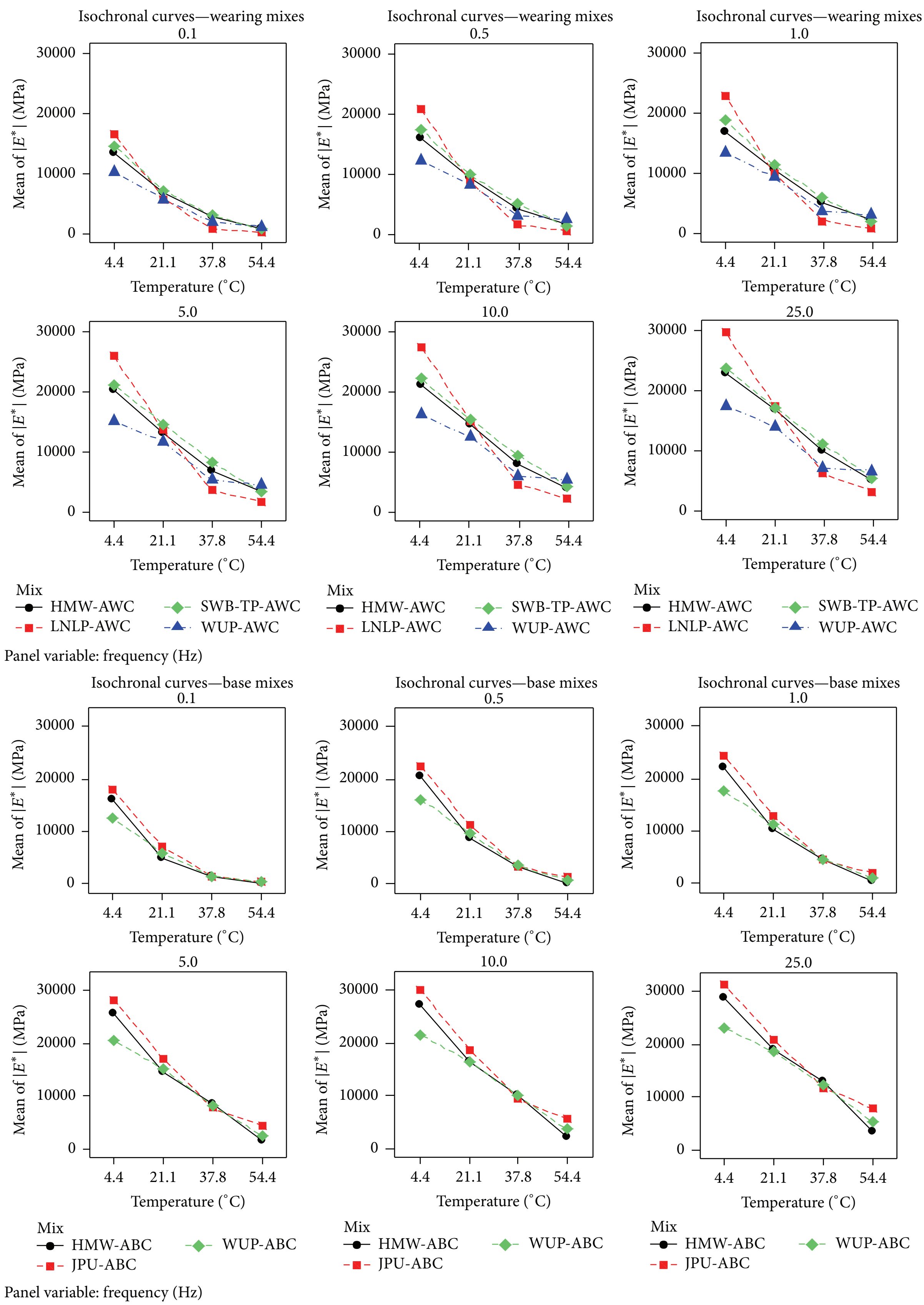
The test results obtained from laboratory testing were also used for evaluation of the Hirsch model by comparison of the measured $|E^*|$ and the predicted $|E^*|$ values. Hirsch model predictions were made using the input data, that is, VMA and VFA obtained from the JMF of each selected mix. Comparison of the results indicated that Hirsch model consistently underpredicts the dynamic modulus values for HMA mixes of Pakistan regardless of the test temperature, the frequency, or the mix selected as shown in Figure 4(b).

The underprediction of dynamic modulus values is attributed to the variation in binder and volumetric (JMF) properties used for preparation of plant-produced mixtures compared to that used for the development of Witczak



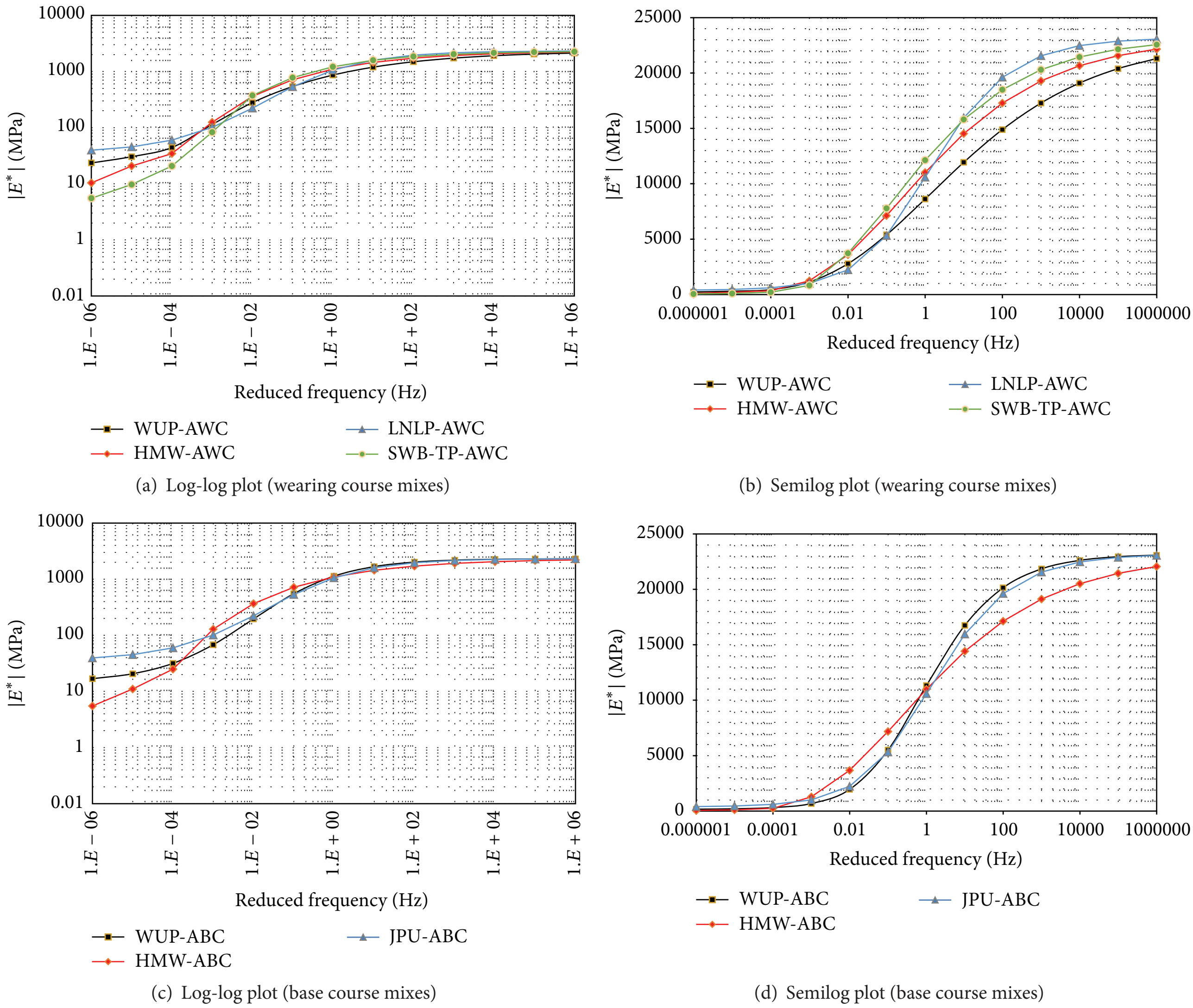
(a) Isothermal curves

Figure 2: Continued.



(b) Isochronal curves

FIGURE 2: Dynamic modulus test results.



(a) Log-log plot (wearing course mixes)

(b) Semilog plot (wearing course mixes)

(c) Log-log plot (base course mixes)

(d) Semilog plot (base course mixes)

FIGURE 3: Dynamic modulus master curves for plant-produced mixtures.

and Hirsch models. The parameter values obtained from the density-void analysis on the test sample could be more accurate than JMF parameters. Also, these models were calibrated using datasets of conditions quite different from Pakistan which are quarry dependent: variation in aggregate mineralogical composition (limestone, etc.) and gradation (percent passing different sieves) and variation in binder properties and its manufacturing process and industry. Also, the underprediction of dynamic modulus values is in agreement with similar past studies conducted on the local material for calibration of these models [32, 33].

4. Conclusions

Performance evaluation of seven plant-produced HMA mixtures was carried out using dynamic modulus testing and factors influencing the dynamic modulus of HMA were evaluated. It was observed that the test temperature and loading frequency are significant factors affecting dynamic modulus for both wearing and base course mixtures; however, VMA is marginally significant in case of base course mixtures, only. Furthermore, there was significant difference between the dynamic modulus of different mixtures based on different aggregate size, gradation, and aggregate source. At low (cold) temperatures, the parameter of viscous (or elastic) properties of the mixtures (phase angle) decreases which indicates more elastic behavior of material with high modulus values and is attributed to the dependency of binder on asphalt concrete response at lower temperatures. However, at high (warm) temperatures, the effect of aggregate skeleton/interlock starts to overpower the viscous binder effect causing the phase angle to decline. As part of this study the dynamic modulus prediction models, namely, Witczak and Hirsch, were also evaluated for their potential regional applicability. Results indicated that both models mostly underpredict the value of dynamic modulus for the selected conditions/mixtures. Nevertheless, these models could be used for evaluation purposes and for the design of low and medium traffic volumes pending future investigation of the revised prediction

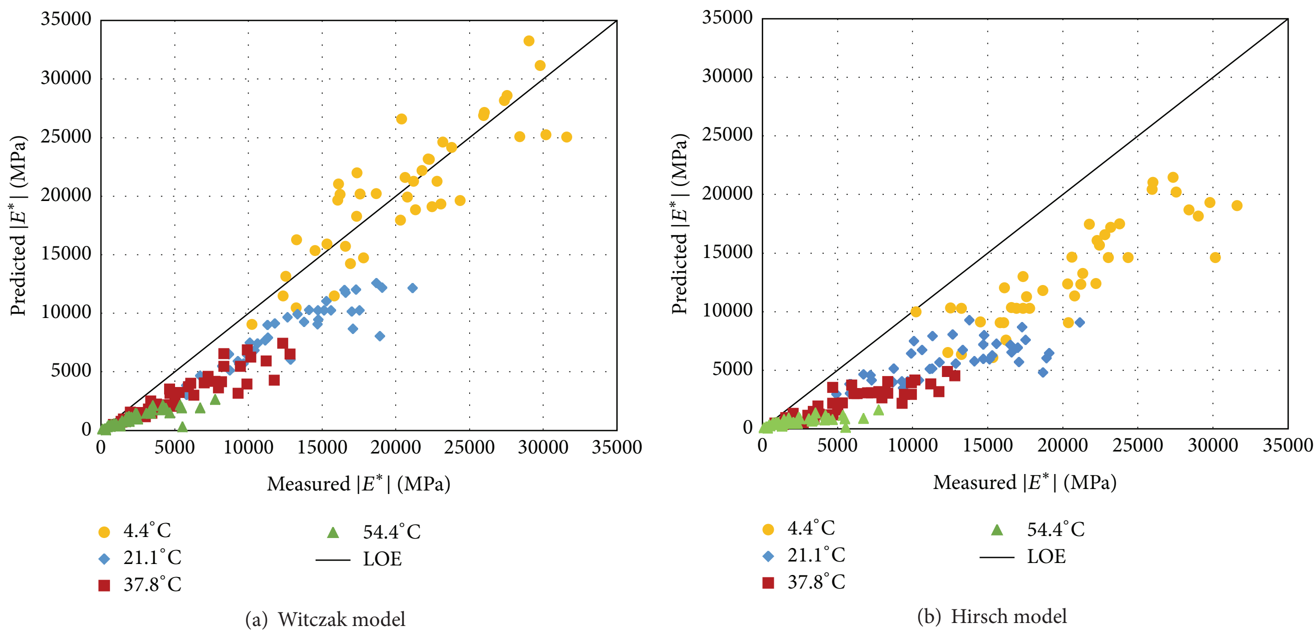


Figure 4: Measured versus predicted plot of dynamic modulus.

equation incorporated in the new AASHTO Pavement ME software/guide. The established default dynamic modulus values catalog for typical asphalt concrete mixtures of Pakistan at various temperatures and frequencies by developing the master curves of $|E^*|$ is the foremost effort in the country, thus facilitating the future implementation of performance based mechanistic-empirical structural design and analysis approach.

Disclosure

The content of this paper reflects the views of the authors who are responsible for the facts and the accuracy of the data and results presented herein. This is merely a technical paper for the experimental investigation of factors affecting the dynamic modulus of HMA using simple performance test. This research study does not constitute a standard, a specification, or a regulation.

Competing Interests

The authors declare that they have no competing interests.

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