Jurnal Teknologi

Full paper

Dynamic Modulus of Western Australia Asphalt Wearing Course

Gunawan Wibisono1[a,b,*], Hamid Nikraz,[a]

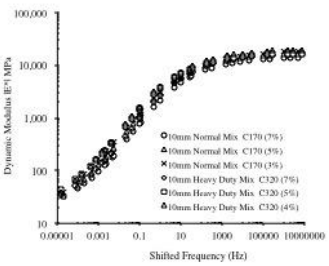
[a]Civil Engineering Department, School of Civil and Mechanical Engineering, Curtin University, WA6102, Western Australia, Australia
[b]Civil Engineering Department, Faculty of Engineering, Universitas Riau, Pekanbaru 28293, Riau, Indonesia

*Corresponding author: gunawan.wibisono@student.curtin.edu.au

Article history

Received :5 June 2014
Received in revised form :
25 September 2014
Accepted : 16 October 2014

Graphical abstract



Abstract

In the new AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG), the dynamic modulus |E*| test has been selected to assess the performance of asphalt concretes. The type of test, which relates asphalt mixtures modulus to temperature and time rate of loading, is never used in Western Australia. This paper presents a study on the dynamic modulus of typical Western Australia asphalt mixtures. Five mixtures with 10mm nominal sizes and two types of bitumen classes, i.e. C170 (Pen 60/80) and C320 (Pen 40/60) comply with Main Road Western Australia (MRWA) Specification were used in the research. Mixing and compacting process were carried out according to Austroads methods. The specimens were compacted using a gyratory compactor to achieve 5±0.5% target air void. Testing was performed at four temperatures (4, 20, 40 and 55^{O}C) and six frequencies (25, 10, 5, 1, 0.5, 0.1 and 0.05 Hz). Dynamic modulus and phase angle master curves were generated from the results. The master curves were compared to the curves from Witczak's predictive equation. From this preliminary study, it was found that the measured values correlated well with the predictive equation except at high temperatures or low frequencies.

Keywords: Asphalt mixtures; dynamic modulus; master curve; MEPDG; Witczak model

■1.0 INTRODUCTION

The dynamic modulus |E*| is a principal parameter to characterize stiffness for hot mix asphalt in Mechanistic-Empirical Pavement Design Guide (MEPDG). The dynamic modulus test is considered more accurate on determining stiffness. This method is measuring stress-strain of asphalt mixtures by applying various loading frequencies and temperatures to simulate the actual traffic and weather condition [1]. The specimen geometry, nominal aggregate size, loading time and test temperature are some factors that determined the dynamic modulus. Kim et al.[2] found the asphalt sources, grades and contents were more influential on |E*| than aggregate sources and gradation. Further, a high dynamic modulus |E*| or stiffness was shown by mixtures with large size aggregates due to a strong aggregate interlock in the system [3]. Inclusion of additives such ash styrene butadiene styrene (SBS) produced high |E*| mixes with regards to a decrease of energy loss at high temperature [4].

The MEPDG software runs three hierarchical levels of input for pavement design and analysis. Level 1 provide the dynamic modulus |E*| from the laboratory test. Level 2 involves |E*| estimation based on aggregate properties, mixture volumetric properties and the viscosity testing of the binder. Level 3 uses 'best estimated' or 'default values' from regional areas to predict |E*|. Witczak predictive model can be used to estimate |E*| in Level 2 and 3. A comparison between predictive and measured dynamic modulus could be used to validate the laboratory results [5].

The hot mix asphalt stiffness is also characterized by beam fatigue, creep, relaxation modulus and resilient modulus tests [5]. The flexural fatigue test is mostly used in Australian Pavement Design Guide [6]. There were few studies done in this area, with regard to utilizing the flexural fatigue test to characterize asphalt stiffness and to correlate it with the indirect tensile test in Australia [7, 8]. There is lack of report about dynamic modulus of Australian asphalt mixtures until now. In this preliminary study, the dynamic modulus |E*| of hot mix asphalt wearing course was investigated. In addition, a dynamic modulus prediction model, i.e. Witczak was evaluated. The predicted |E*| values were compared with the measured |E*| values to validate the Western Australia asphalt mixtures.

2.0 MATERIALS AND METHODS

2.1 Materials

Two types of bitumen classes meeting Austroads (AP-T62/06) [9] specification, Class 170 (Pen 60/80) and C320 (Pen 40/60), were used as primary binders. Both mixtures contained granite aggregates from Gosnells Quarry with maximum grain size of 10mm. The coarse aggregates had specific gravities of 2.62 and water absorption of 0.74%. The asphalt mixture gradation is presented in Table 1. Swan hydrated lime used has Calcium Hydroxide more than 65%, in complies with Australian Standard (AS) 1672.1-1997 [10]. Mineral filler was bag house dust that passing a 75 micron sieve.

Table 1 Asphalt mixture gradation

Sieve Size, mm (AS1152)	Percent Passing, %			
	10 mm	WQS*	BHD**	Hydrated lime
26.5	100	100	100	100
19	100	100	100	100
13.2	100	100	100	100
9.5	89.7	100	100	100
6.7	8.5	100	100	100
4.75	1.4	99.5	100	100
2.36	0.6	84.5	100	100
1.18	0.4	54.0	100	100
0.6	0.4	32.1	100	100
0.3	0.3	16.5	100	100
0.15	0.3	6.3	98	98
0.075	0.1	2.6	95	95

*: washed quarry sand, **: baghouse dust.

2.2 Specimen Preparation

Specimens were prepared according to Austroads AP-T132 [12] mixing procedure. This is to ensure that the specimens were produced such in field condition and oxidation of binder can be controlled. Raw materials were mixed at 150°C and conditioned at 150°C for one hour prior to compaction. All samples were compacted directly at gyratory using 100mm diameter molds. After being compacted by the IPC Servopac gyratory compactor the specimens were allowed to cold at room temperature for several hours. Then the samples were cut as cylinder with 150mm height. The density and air void were measured according to Main Road Western Australia (MRWA) WA-732.2 [13] and WA-733.1 [14]. The methods are similar to ASTM 2041 [15] and ASTM D2726 [16], respectively. The target air void for all specimens was 5.0±0.5%. In this research, a trial compaction was required to determine gyration cycles for the target air void. Figure 1 shows the trial compaction curves for 10mm mixtures.

2.3 Test Equipment and Procedures

The dynamic modulus tests were carried out using an IPC UTM-25 testing machine. The machine comprises of a loading frame, which is integrally mounted with a 25kN servo hydraulic actuator system, a load cell and a displacement transducer. An IMACS (Integrated Multi-Axis Control System) and a personal computer were used to provide force or displacement waveform generation, to control and enable automatic sequencing of test procedures. The test rig, as shown in Figure 2, uses a set of three LVDTs to measure deformations.

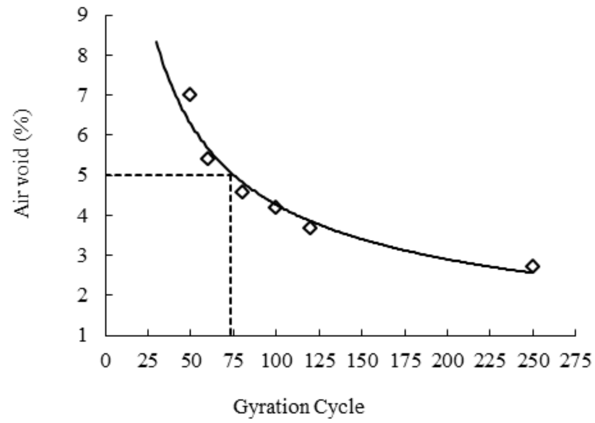


Figure 1 The variation of air void with gyration cycles

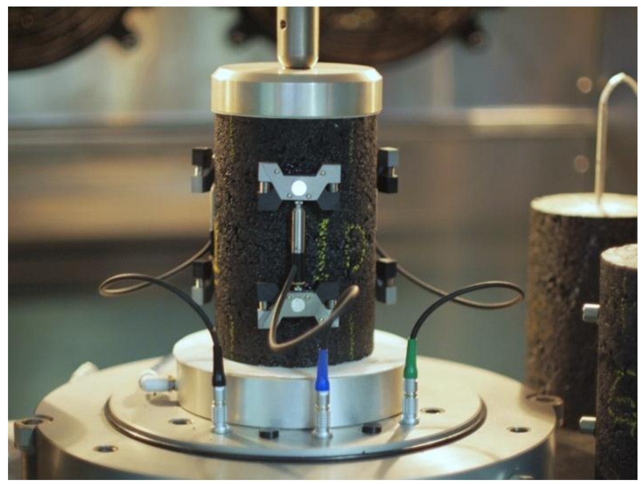


Figure 2 The dynamic modulus test set up

In order to simulate climatic condition, an environmental chamber rated -15°C to 60°C was used. The experiment starts with placing the specimen in the environmental chamber overnight at 4°C to ensure temperature equilibrium. A dummy sample with a temperature probe to check the target temperature was located close to the sample being tested. A friction reduction system consists of two Teflon sheets were placed on the top and the bottom of the specimen. The specimen was tested for 24 combinations of temperature and frequency, comprises of four different of temperatures (4, 20, 40, 55°C) and six loading frequencies (25, 10, 5, 1, 0.1 and 0.05 Hz). The tests were carried out from the lowest to the highest temperature, and in reverse, from the highest to the lowest frequency. Although the protocol test (AASHTO PP 62) [10] requires testing at -10°C, this temperature was not adopted considering such temperature is too low for Western Australia condition. After the entire cycle of testing was complete at 4°C, the environmental chamber was set to the next temperature. About several hours of conditioning, the steps were repeated until the entire sequence of temperatures and frequencies has completed. The required temperature-conditioning time before testing is presented in Table 2. The strain level was kept within the range between 50 to 150 microstrain. The specimens underwent unrecoverable axial strains exceeded 1500 micro strain were discarded.

Table 2 Temperature equilibrium time based from AASHTO PP 62 [10]

Testing temperature (°C)	Time from previous test temperature (hours)
4	4 hours or overnight
20	3
40	3
55	3

3.0 RESULTS AND DISCUSSION

3.1 Dynamic Modulus Analysis

The dynamic modulus of Western Australia asphalt mixtures was calculated at each of the frequencies and temperatures stated above. Each dynamic modulus test provides two responses, namely |E*| and phase angle. Phase angle indicates the elastic and viscous properties of the mix. A total of 48 responses (|E*| and phase angle) values were calculated for each combination of five test temperatures and six frequencies.

Table 3 shows the dynamic modulus and phase angle for both normal mix 10mm + C170 and heavy duty mix 10mm + C320. The effect of air voids and binder grade are quite significant. For example, mixes with an air void content of 3% showed higher dynamic modulus than mixes with an air void content of 4% and 7%. The AC10-320 mix with a higher grade binder yielded better dynamic modulus values than the mix with a lower grade asphalt. The phase angle showed a different trend to the dynamic modulus. Initially the phase angle decreased as the loading frequency increased from 4°C to 20°C. At 40°C and 55°C, the behavior of the phase angle as a function of frequency seemed more complex. At higher temperatures, the phase angle increased with an increase in frequency to 10Hz, after which the values decreased at the highest loading frequency. The complex behavior of the phase angle at higher temperatures or at lower frequencies may be attributed to the predominant effect of the aggregate interlock. Other studies have confirmed that similar elastic behavior of aggregate at high temperature and low frequency determines the response of the specimen. It can be observed from the tables that the phase angle values for the mix AC10-320 were considerably lower than those for mix AC10-170. This is attributed to the better quality asphalt grade used in mix AC10-320 which contributed to the low phase angle.

3.2 Master Curve

Master curves were generated from three samples at each target air voids. Figure 3 shows the master curves with a reference temperature of 20°C for two types of asphalt classes (Class 170 and Class 320) at various air voids (3-7%). The results of the fitted curves followed a general trend, increasing with an increase in loading frequency and decreasing as the temperature increased. The dynamic modulus |E*| decreases as the percentage of air void is increased in the mix. Furthermore, the asphalt mixture with a combination of bitumen class C320 and 4% air voids had the greatest dynamic moduli. As expected, the |E*| values, in general, decreases as the temperature increases, and increases as the loading frequency increases. Similar findings were confirmed in many studies [3, 17].

Figure 4 displays Black Space diagram for all mixtures. This diagram is plotted from average values of the |E*| and phase angle for each laboratory data. The Black Space plot is used to identify testing variability, nonlinearity or both in the material behavior [18]. The diagram indicate that either non-linearity or measurement error was occurring at the intermediate-to-higher test temperatures for the 9.5mm mix. Intermediate and higher test temperatures are represented toward the middle and left side of the curves, respectively. In this study, variability in phase angle was slightly greater at lower frequencies.

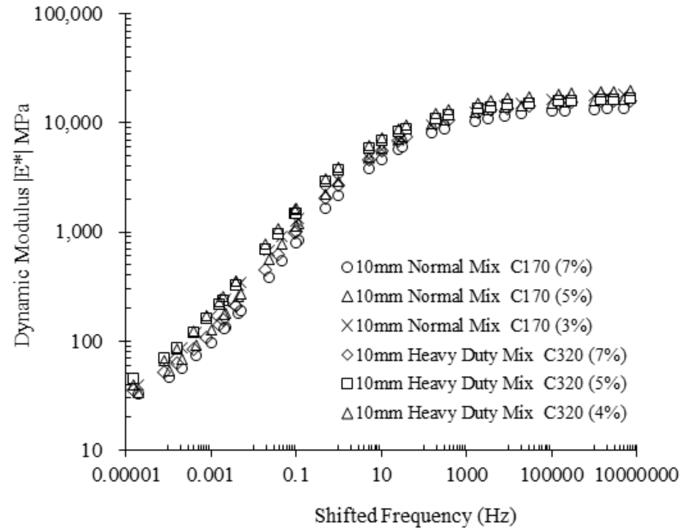


Figure 3 Dynamic modulus of asphalt mixtures at various air voids and bitumen type

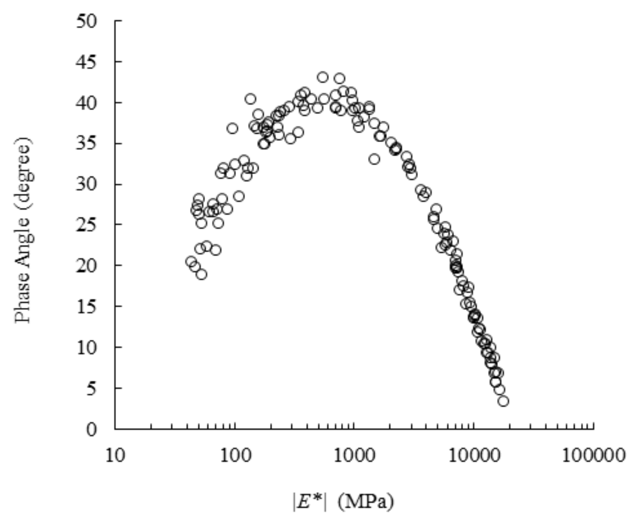


Figure 4 Black Space diagrams for all mixtures

3.3 Comparison With MEPDG Witczak's Predictive Model

Witczak model is an example that was established empirically from 149 different mixtures to predict the dynamic modulus various range of temperature, rates of loading, and aging conditions. The dynamic modulus model is [19]:

Table 3 Dynamic modulus |E*| and phase angle (ϕ) for each mixture

Temp	Freq	10mm Normal Mix C170						10mm Heavy Duty Mix C320					
		3%		5%		7%		4%		5%		7%	
(^{o}C)	(Hz)	|E*| MPa	ϕ (deg)	|E*| MPa	ϕ (deg)	|E*| MPa	ϕ (deg)	|E*| MPa	ϕ (deg)	|E*| MPa	ϕ (deg)	|E*| MPa	ϕ (deg)
4	0.1	7070	20.7	6986	20.1	5419	22.2	8255	17.6	7488	19.2	6384	22.0
4	0.5	9477	15.1	9365	15.5	7564	17.1	11180	12.3	10141	14.1	8911	16.8
4	1	10627	13.6	10347	14.0	8504	15.3	12288	10.5	11146	12.3	10019	13.7
4	5	13043	9.4	12700	11.0	10720	12.0	15122	7.0	13716	8.2	12629	10.6
4	10	14043	8.0	13674	10.0	11622	10.8	16304	4.8	14788	6.8	13691	8.8
4	25	15410	5.8	15004	8.7	12790	9.4	17829	3.5	16171	6.9	15067	5.8
20	0.1	1096	39.3	1078	37.8	777	39.0	1455	33.0	1332	39.2	955	39.0
20	0.5	2260	34.4	2221	34.5	1666	35.9	3055	31.3	2797	32.2	2047	35.0
20	1	2950	31.9	2901	32.5	2208	34.1	3981	29.0	3646	29.3	2713	33.4
20	5	4924	24.6	4840	27.0	3801	28.5	6643	23.0	6083	23.8	4669	25.7
20	10	5897	22.9	5797	24.7	4582	26.1	7951	18.2	7281	19.7	5630	24.1
20	25	7306	19.9	7182	21.5	5732	22.6	9871	13.6	9039	17.4	7042	19.7
40	0.1	110	28.5	79	28.3	50	28.2	126	31.0	101	32.5	90	31.3
40	0.5	196	35.7	147	37.2	95	36.8	232	36.0	187	37.3	120	32.8
40	1	258	39.0	223	38.4	135	40.4	343	40.1	284	39.5	172	36.9
40	5	697	39.5	555	40.5	381	41.2	753	43.0	703	39.3	487	39.4
40	15	965	40.3	802	41.4	544	43.1	1094	37.0	1021	39.3	696	40.8
40	25	1476	37.5	1328	39.5	951	41.2	1738	37.0	1623	35.9	1216	38.2
55	0.1	48	26.8	46	20.0	52	25.2	53	19.0	51	26.4	43	20.5
55	0.5	73	25.3	58	22.5	51	22.2	70	22.0	66	27.6	61	26.7
55	1	88	27.0	66	26.6	49	27.4	81	32.0	77	31.4	71	26.9
55	5	175	35.0	142	31.9	127	32.0	179	35.0	184	36.3	155	36.8
55	15	232	38.5	186	36.5	157	38.6	229	37.0	242	38.9	191	37.6
55	25	379	39.7	342	36.3	296	35.6	387	39.0	441	40.4	360	40.9

$$\log E = 3.7530063 + 0.002932 p_{200} - 0.001767 (p_{200})^2 - 0.002841 p_4 - 0.05809 V_a - 0.802208 \left(\frac{V_{beff}}{V_{beff} + V_a} \right) - \left(\frac{3.871977 - 0.0021 p_4 + 0.003958 p_{38} - 0.000017 (p_{38})^2 + 0.00547 p_{34}}{1 + e^{-0.603313 - 0.31335 \log f - 0.393532 \log \eta}} \right) \quad (1)$$

where
$|E^*|$ = asphalt mix dynamic modulus,
η = bitumen viscosity in 10^6 poise,
f = load frequency (Hz),
V_a = percentage air voids in the mix,
V_{eff} = percent effective bitumen content by volume,
p_{34} = cumulative percentage retained on 19 mm sieve,
p_{38} = cumulative percentage retained on 9.5 mm sieve,
p_4 = cumulative percentage retained on 4.75 mm sieve,
p_{200} = percentage passing from 0.075 mm sieve.

The master curve of Western Australia asphalt mixtures was generated and compared with Witczak's predicted |E*| master curve. The curve based on time temperature superposition principle which describes viscoelastic behavior of asphalt binders and mixtures. The effect of temperature on |E*| is included in binder viscosity (η) based on [20]:

$$\log \eta = A + VTS \log T \quad (2)$$

Where A and VTS are regression constants determined according to Level 2 and Level 3. Table 4 shows the correlation between viscosity at temperature, A and VTS for bitumen used in this research.

It can be seen from Figure 5, the Witczak predicted |E*| values were comparatively higher at high-test temperature and slightly lower values at low temperature. Witczak predicted model had |E*| master curve higher than those of Western Australia asphalt mixtures at the intermediate and higher test temperatures (i.e. loading frequencies less than 1 Hz). This trend was highlighted in the previous studies since Witczak's model tend to overemphasize the influence of high and very low temperatures [5, 21]. It also might be due to differences of microstrain level [22]. To solve this problem, Bennert and Williams [23] suggested to reduce of the upper limit (150 microstrains) in the |E*| test to improve laboratory measurement precision. A tighter allowable range in microstrain level may be required to promote better precision among different laboratories and limit potential for nonlinearity effects.

Table 4 Asphalt bitumen properties at various temperatures

t (^{o}C)	Viscosity at Temperature - Pa.s				A	VTS
	25	45	60	135		
C 170	184077	2831	175	0.390	10.95	-3.68
C 320	349945	5957	301	0.519	10.89	-3.65

Figure 6 represents the comparison of predicted dynamic modulus using the Witczak equation and measured dynamic modulus at each test temperature. The reliability of test data is 89%. Judging from the results, the predicted dynamic modulus is a little higher than the measured values at high temperature and slightly lower than the values at low temperature. Instead of differences on the applied microstrain level in |E*| test, the discrepancies was mostly due to different aggregate gradation, aggregate type and asphalt source than the specification of the United States. Few studies highlighted this issue and tried to modify the predictive equation to match the local material condition. For example in Korea, the predictive equation for |E*| was constructed using a nonlinear regression analysis for 540 dynamic modulus data [24]. This is certainly a challenge to modify the dynamic modulus predictive equation for use in Western Australia asphalt mixture.

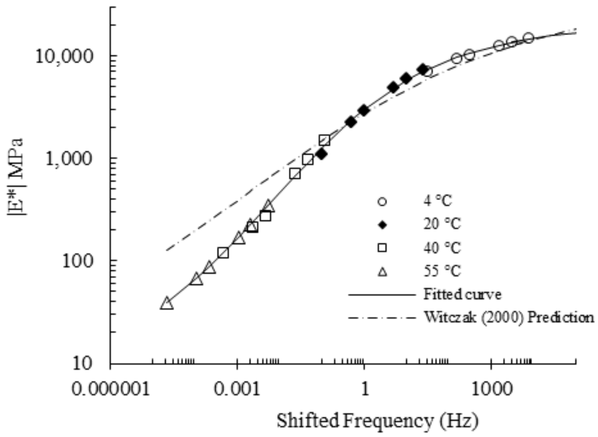


Figure 5 Comparison of developed |E*| master curve with Witczak's predicted |E*| master curve

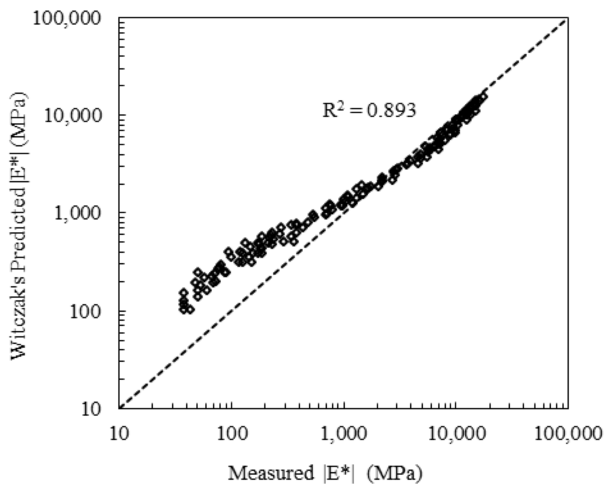


Figure 6 Comparison of measured and predicted dynamic modulus by Witczak

■4.0 CONCLUSION

This research was taken to investigate the dynamic modulus |E*| of Western Australia asphalt mixtures. Asphalt mixtures were tested at different temperatures and loading rates. From the limited study results, the dynamic modulus of WA asphalt mixtures is increased as loading frequency increases, temperature decreases and air void decreases. The effect of air voids on dynamic modulus was slightly significant. Mixtures with better asphalt grade (C320) performed higher dynamic modulus than grade C170. It is indicated that the stiffness of Western Australia asphalt mixtures follows general trend, which is sensitive to loading frequency, temperature, air voids and asphalt grade. In this preliminary study, the correlation (R^2 = 89%) between measured |E*| and Witczak predicted |E*| showed the measured values correlated well with the predictive equation except at high temperatures or low frequencies. This supports the use of dynamic modulus determination based on MEDPG as a tool to predict asphalt stiffness in Australia.

Acknowledgement

The authors would like to acknowledge Darren Isaac, Mark Whittaker and the Pavement Research Group at Curtin University for their kind assistance for the laboratory work. PhD Scholarships from the DIKTI (Directorate General of Higher Education Indonesia) for the first author is acknowledged.

References

[1] Pelinen, T.K. 2009. Complex Modulus Characterization of Asphalt Concrete. in YR Kim (ed.) Modeling of Asphalt Concrete. Sydney: ASCE Press- McGraw-Hill Construction.

[2] Kim, Y.R., M. King, and M. Momen. 2005. *Typical dynamic moduli for North Carolina asphalt concrete mixtures.* FWHA Report NC/2005-03. Raleigh: North Carolina State University.

[3] Mohammad, L.N., S. Saadeh, S. Obulareddy, and S. Cooper. 2007. Characterization of Louisiana asphalt mixtures using simple performance tests. *Journal of Testing and Evaluation*. 36(1): 1–12.

[4] Kumar, S.A., and A. Veeraragavan. 2011. Dynamic mechanical characterization of asphalt concrete mixes with modified asphalt binders. *Materials Science and Engineering: A*. 528(21): 6445–6454.

[5] Ceyland, H., C.W. Schwartz, K. Sunghwan, and G. Kasthurirangan. 2009. Accuracy of predictive models for dynamic modulus of hot-mix asphalt. *Journal of Materials in Civil Engineering*. 21(6): 286–293.

[6] Austroads 2004. *Pavement design – a guide to the structural design of road pavements*. AP-G17/04. Sydney: Austroads.

[7] Fakhri, M. 1997. *Characterisation of asphalt pavement materials.* PhD Dissertation. University of New South Wales.

[8] Pronk, A. and S. Erkens. 2002. A Note on Fatigue Bending Tests Using a Haversine Loading. *Road Materials and Pavement Design*. 3(1): 95–106.

[9] Austroads. 2006. *Introduction to Asphalt Mix Design.* No. AP-T62/06. Sydney: Austroads Incorporated.

[10] AASHTO 2010. *Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA).* AASHTO PP 62. Washington D.C.: American Association of State Highway Transportation Officials.

[11] Standards Australia. 1997. Limes and Limestones: for Building. AS. 1672.1-1997. Standards Australia Online: http://www.saiglobal.com (accessed September 02, 1999).

[12] Austroads. 2009. *Austroads Technical Report: Preparation of Asphalt Samples for Testing*. No. AP-T132/09. Sydney: Austroads Incorporated.

[13] Main Roads Western Australia. 2007. *Maximum Density of Asphalt: Rice Method.* Document No. 71/04/732.2. Perth: Main Roads Western Australia.

[14] Main Roads Western Australia. 2006. *Bulk Density and Void Content of Asphalt.* Document No. 71/09/733.1. Perth: Main Roads Western Australia.

[15] ASTM. 2003. *Theoritical Maximum Specific Gravity and Density of Bituminous Paving Mixtures*. No. D2041-03a. Philadelphia: ASTM International.

[16] ASTM. 2008. *Bulk Specific Gravity and Density of Non-absorptive Compacted Bituminous Mixtures*. No. D2726. Philadelphia: ASTM International.

[17] Singh, D., F.N. Beainy, A.T Mai, S. Commuri, and M. Zaman. 2011. In-situ assessment of stiffness during the construction of HMA pavements. *Journal of Pavement Research and Technology*. 4(3): 131–139.

[18] Pellinen, T. 2001. *Investigation of the use of dynamic modulus as an indicator of hot-mix-asphalt performance*. PhD Dissertation. Arizona State University.

[19] Witczak, M.W., K. Kaloush, T. Pellinen, M. El-Basyouny and H. Von Quintus. 2002. *Simple Performance Test for Superpave Mix Design.* NCHRP Report 465. Transportation Research Board-National Research Council. Washington DC: National Academy Press.

[20] Harran, G. and A. Shalaby. 2009. Improving the prediction of the dynamic modulus of fine-graded asphalt concrete mixtures at high temperatures. *Canadian Journal of Civil Engineering*. 36: 180–190.

[21] Apeagyei, A.K., B.K. Diefenderfer, and S.D. Diefenderfer. 2011. Development of dynamic modulus master curves for hot-mix asphalt with abbreviated testing temperatures. *International Journal of Pavement Engineering*. 13(2): 98–109.

[22] Tran, N.H. and K.D. Hall. 2006. Evaluation of testing protocols for dynamic modulus of hot-mix asphalt. *Journal of the Transportation Research* Board 1970: 126–132.

[23] Bennert, T., and S.G. Williams. 2009. Precision of AASHTO TP62-07 for use in Mechanistic-Empirical Pavement Design Guide for flexible pavements. *Journal of the Transportation Research Board* 2127: 115–126.

[24] Cho, Y-H, D-W Park, and S-D Hwang. 2010. A predictive equation for dynamic modulus of asphalt mixtures used in Korea. *Construction and Building Materials*. 24: 513–519.