Indian Journal of Engineering & Materials Sciences
Vol. 20, October 2013, pp. 376-384

Evaluation of the dynamic modulus of asphalt mixture incorporating reclaimed asphalt pavement

Zulkurnain Shahadan, Meor Othman Hamzah*, Ahmad Shukri Yahya & Ali Jamshidi
School of Civil Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia

Received 2 April 2012; accepted 7 May 2013

This paper presents the effects of temperature and loading frequency on the dynamic modulus and phase angle of asphalt mixtures incorporating reclaimed asphalt pavement (RAP) using the asphalt mixture performance tester. Milling waste from Damansara-Puchong Expressway is incorporated in asphalt mixtures in proportions of 0%, 10%, 20%, 30% and 40%. The asphalt mixtures are tested for dynamic modulus at three temperatures (20, 40, 50°C) and six loading frequencies (0.1, 0.5, 1, 5, 10 and 25 Hz). At constant temperature, the dynamic modulus increased as the loading frequency and RAP content increased. For a given frequency, the dynamic modulus decreased while the phase angle increased as the temperature increased. From statistical analysis, test temperature and frequency have significant effects with high effect size on the measured dynamic modulus and phase angle. The interaction effect of frequency and RAP give the highest effect size among the interaction effects in the dynamic modulus test. The results also indicated that the highest performance in terms of rutting and fatigue factors can be attained when the frequency of cumulative traffic loading was from 15 to 20 Hz.

Keywords: Reclaimed asphalt pavement, Asphalt mixture performance tester, Dynamic modulus, Phase angle, Interaction effect, Effect size

Incorporating reclaimed asphalt pavement (RAP) in asphalt mixtures has been a common practice in road construction and rehabilitation especially in North America and Europe. This is in line with sustainable road construction and green development concepts that have been championed for the last two decades. The advantages of utilizing reclaimed asphalt pavement include reduce waste, preservation of the existing pavement geometrics, preservation of natural resources, minimise life-cycle cost, and conservation energy[1]. Recycled asphalt pavement has been proven to perform equally or better than conventional asphalt pavement in the laboratory and field tests. From field tests, recycled asphalt pavement is able to withstand increasing number of vehicles and higher axle loads imposed by different axle configurations and severe climatic conditions. Addition of reclaimed asphalt pavement in asphalt mixture has improved permanent deformation and fatigue distress[2-4]. Currently, dynamic modulus (E^*) is one of the most important parameters required in flexible pavement design based on the Mechanistic Empirical Pavement Design Guide (MEPDG)[5]. According to Witczak *et al.*[6], the dynamic modulus is a crucial parameter used in evaluating rutting and fatigue cracking distress prediction in the MEPDG. Furthermore, the dynamic modulus represents asphalt mixture stiffness in response to the application of haversine compressive load on a cylindrical sample over several temperatures and loading frequencies[6,7]. The stiffness of an asphalt mixture reflects its load spreading ability. A master curve is developed to represent the stiffness relationship of asphalt mixture in relation to temperatures and loading frequencies.

There appears to be a gap in the knowledge on performance of asphalt mixtures incorporating different RAP contents at various test temperatures using the asphalt mixture performance tester (AMPT). Therefore, this paper focuses on the dynamic modulus and phase angle of asphalt mixtures incorporating reclaimed asphalt pavement (RAP) at five RAP proportions, three temperatures and six loading frequencies with in-depth statistical analysis particularly on the interaction effect and effect size. In addition, master curves are developed to evaluate rutting and fatigue factors at different test temperatures for asphalt mixtures incorporating different RAP contents.

Materials and Methods

Reclaimed asphalt pavement

Milling waste of aged and deteriorated pavements from the Damansara-Puchong Expressway (DPE),

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*Corresponding author (E-mail: cemeor@yahoo.com)

Malaysia was used in this study. The gradation of DPE RAP aggregate is shown in Table 1.

Asphalt binder

A conventional binder penetration grade 80/100 (PG64) supplied by PETRONAS, a Malaysian oil company, was used as the virgin binder. The RAP binder was recovered using the rotavapor method. Table 2 shows the physical and rheological properties of the virgin and DPE RAP recovered binders.

Aggregate

The crushed virgin granite aggregate was obtained from a local quarry. The virgin aggregate was washed, dried and sieved based on the Malaysian Public Works Department (PWD) aggregate gradation for asphaltic concrete ACW14 (JKR, 2008)[8] as shown in Table 3.

Sample preparation

Samples for dynamic modulus testing were prepared by mixing binder, virgin aggregates and processed reclaimed asphalt pavement at 160°C. An hour prior to the mixing, the processed reclaimed asphalt pavement was preheated in an oven at 135°C. The optimum binder content for each sample incorporating RAP was determined using Marshal mix design method according to ASTM D 6927 (2006) procedures[9]. The optimum binder content results are shown in Table 4. After mixing, the mixtures were poured onto a large flat pan and placed in an oven set at 135°C for 4 h for short term aging in accordance with AASHTO R30 (AASHTO)[10] procedures. The samples were compacted at 150°C in a 150 mm diameter mould to a height of 170 mm by using a gyratory compactor. After compaction, the sample was extruded from the compaction mould, labelled and allowed to cool to room temperature. The compacted samples were cored and trimmed to obtain a standard 150 mm height and 100 mm diameter test sample with targeted air voids 7±0.5%.

Table 1—Gradation of DPE RAP aggregate

Sieve size (mm)	20	14	10	5	3.35	1.18	0.425	0.150	0.075
Percent passing	99	93.8	87.4	73.2	63.5	38.2	21.7	10.9	6.3

Table 2—Physical and rheological properties of virgin and recovered binders

Binder	Penetration at 25°C (dmm)	Softening point (°C)	Viscosity at 135°C (Pa.s)	G*/Sinδ at 64°C (kPa)
Virgin	90	46.0	0.34	1.14
LDE	13	67.5	4.33	36.1

Methodology

Dynamic modulus test

The linear viscosity properties of asphalt mixtures were measured from the dynamic modulus test conducted in accordance with AASHTO TP 62-03(AASHTO)[11] procedures using the asphalt mixture performance tester (AMPT). The machine was equipped with a temperature chamber and a pressure cell. Compressive load was applied in the form of a continuous haversine wave without rest period. Six frequencies (0.1, 0.5, 1, 5, 10 and 25 Hz) and three temperatures (20, 40 and 50°C) were selected for the tests. For data measurement, three linear variable differential transducers (LVDTs) were used. The LVDTs were mounted on the sides of the specimen to measure axial deformation. The tests were conducted within the linear viscoelastic stress level where the strain was controlled between 85 to 115 micro-strains. Since the test was nondestructive test, the same specimen was used for a complete test at six frequencies and three temperatures. The tests were performed from the lowest temperature to the highest temperature and from the highest frequency to the lowest frequency.

The dynamic modulus $|E^*|$ was calculated using Eq. (1)[6].

$$|E^*| = \frac{\sigma o}{\varepsilon o} \qquad \dots (1)$$

where σ_o is applied stress amplitude (MPa) and ε_o is measured strain amplitude.

The phase angle can be obtained using Eq. (2).

$$\delta = \frac{t_i}{t_p} \qquad \dots (2)$$

Table 4—Optimum binder content

Percentage of RAP	0	10	20	30	40
Optimum binder content	4.6%	4.9%	5.2%	5.3%	5.4%

Table 3—PWD gradation limits for asphaltic concrete ACW14

Sieve size (mm)	20	14	10	5	3.35	1.18	0.425	0.150	0.075
Percent passing	100	90-100	67-86	50-62	40-54	18-34	12-24	6-14	4-8

where t_i is average time lag between a cycle of stress and strain (s) and t_p is average time for a stress cycle (s)

Statistical analysis

An analysis of variance (ANOVA) was adopted to analyze main and interaction effects of independent variables on the measured dynamic modulus and phase angle by using the statistical software SPSS. Further analysis was pursued to determine the effect sizes (the magnitude) of the main and interaction effects by using Eqs (3)-(7)[12]. This effect size analysis is limited to two main effects (two independent variables) and one interaction effect.

$$\hat{\sigma}\frac{2}{A} = \frac{(a-1)(MS_A - MS_R)}{nab} \quad \ldots (3)$$

$$\hat{\sigma}\frac{2}{B} = \frac{(a-1)(MS_B - MS_R)}{nab} \quad \ldots (4)$$

$$\hat{\sigma}\frac{2}{AxB} = \frac{(a-1)(b-1)(MS_{AxB} - MS_R)}{nab} \quad \ldots (5)$$

$$\hat{\sigma}\frac{2}{total} = \hat{\sigma}\frac{2}{A} + \hat{\sigma}\frac{2}{B} + \hat{\sigma}\frac{2}{AxB} + MS_R \quad \ldots (6)$$

$$\omega\frac{2}{effect} = \frac{\hat{\sigma}\frac{2}{effect}}{\hat{\sigma}\frac{2}{total}} \quad \ldots (7)$$

where, ω^2 is effect size, δ^2 is variance, MS is mean square, MS_R is mean square of residual, A is main effect of the first independent variable, *B* is main effect of the second independent variable, *A*x*B* is interaction effect, *a* is number of levels of the first independent variable and *b* is number of levels of the second independent variable

Results and Discussion

Dynamic modulus

Figure 1 shows the effects of RAP content, temperature and loading frequency on the dynamic modulus of asphalt mixtures. It can be seen that the dynamic modulus consistently increases as the RAP content increases, irrespective of loading frequency. For instance, at 20°C and 5 Hz, the dynamic modulus of control asphalt mixture (without RAP) is 8300 MPa, while the dynamic modulus of mixtures incorporating 30% RAP is 10000 MPa under the same condition. Furthermore, the average percentage increase ranges from 1% to 6% when up to 20% RAP is added. The dynamic modulus increases from 13% to 17% when incorporated with 30% to 40% RAP. When the temperature doubles to 40°C, the dynamic modulus dramatically reduces to 80% and 78% for asphalt mixtures incorporating 10% and 40% RAP, respectively. As the temperature increases from 40°C to 50°C, the dynamic modulus is significantly reduced to 70% and 64% for asphalt mixtures with 10% and 40% RAP, respectively. Similar decreasing trend in dynamic modulus between 71% to 87% and 61% to 68% is observed when loading frequency decreases as temperature increases from 20°C to 40°C and 40°C to 50°C, respectively.

For a given RAP content, the reduction in the dynamic modulus at 40°C is more evident compared to samples tested at 20°C. However, for samples tested at 40°C, the dynamic modulus increases from 47% to 50% and 53% to 59% when 20% and 40% RAP are added, respectively compared to control mixtures. This takes place because RAP materials contain aged asphalt binder where resins turn into asphaltenes which in turn affects the elastic solid behavior of the aged asphalt binder[13-15]. However, the higher amount of RAP incorporated in virgin mixtures implicates an increased amount of fuel requirement and green house gas emission during asphalt production in the mixing plants[16,17].

The dynamic modulus increases from 42% to 56% as the loading frequency increases from 0.1 Hz to 25 Hz. As the test temperature further increases to 50°C, the dynamic modulus reduces significantly to 94% and 92% for asphalt mixtures incorporating 10% and 40% RAP, respectively. For specimens tested at 50°C, in comparison with control mixtures, the dynamic

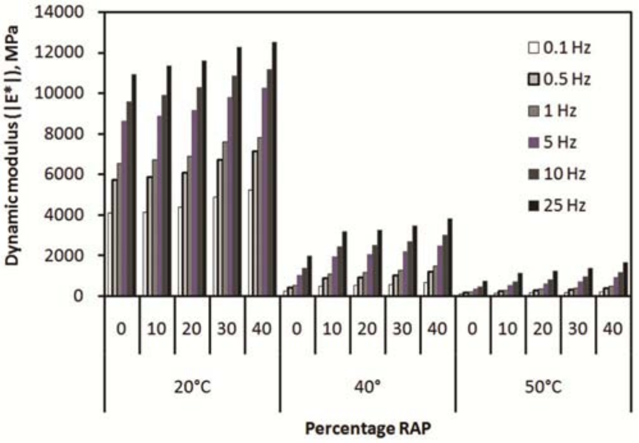


Fig. 1—Dynamic modulus at different RAP content, temperature and frequency

modulus increases from 32% to 40% and 47% to 57% when blended with 20% and 40% RAP, respectively. The increase of the dynamic modulus at that respective RAP content is less than 10% compared to those samples tested at 40°C. However, the dynamic modulus increases from 90% to 96% as the loading frequency increases from 0.1 Hz to 25 Hz. This increase in mixture stiffness is attributed to the viscoelastic property of the aged binder from the RAP. Higher RAP content incorporated in the asphalt mixtures results in increased mixture stiffness that enable the mixture to withstand the detrimental effects of high temperature and low loading frequency.

An analysis of variance (ANOVA) was performed to determine the effects of RAP content, temperature, frequency and interaction of the main effects on the measured dynamic modulus. Table 5 shows the results of ANOVA which indicate that all main effects as well as their interactions have significantly influenced the measured dynamic modulus at 5% significance level. It can be noticed that main effect of temperature has the highest F-ratio value which indicates that an increase in temperature would dramatically affects the dynamic modulus of the asphalt mixtures. The ANOVA results in Table 5 are also consistent with the results of dynamic modulus indicated in Fig. 1. It can be seen that dynamic modulus decreases significantly as temperature increases, irrespective of RAP content and loading frequencies.

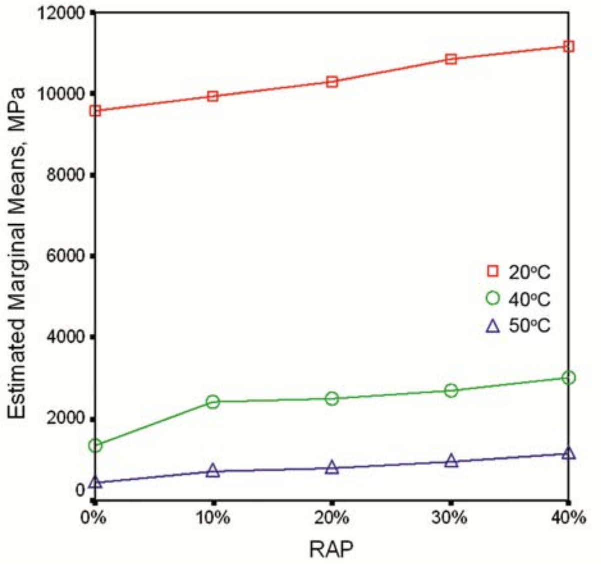


Fig. 2—Interaction plot of temperature and RAP against dynamic modulus at 10 Hz

Figure 2 shows the interaction plot of temperature and RAP against dynamic modulus at 10 Hz. The plot displays increasing trend of estimated marginal means of the dynamic modulus as RAP content increases. At 40°C, a sharp increase in estimated marginal mean of the dynamic modulus is observed for asphalt mixtures with 10% RAP. The effect of high temperature drastically reduces the stiffness of the asphalt mixtures regardless of RAP content. However, the addition of RAP in asphalt mixtures at a particular temperature has improved mixture stiffness compared to control mixtures.

Phase angle

Figure 3 shows the effects of RAP content, temperature and loading frequency on the phase angle of the asphalt mixtures tested. It can be seen that the phase angle decreases as the RAP content increases, irrespective of loading frequency. For instance, at 20°C and 5 Hz, the phase angle of control asphalt mixture (without RAP) is 18°, while the phase angle of mixtures incorporating 30% RAP is 12° under the same condition, indicating a decrease by 33% as 30% RAP is added.

Generally, at 20°C the phase angle decreases as the RAP content increases with average percentage

Table 5—ANOVA results on main and interaction effects on dynamic modulus

Source	Sum of squares	df	Mean square	F	p-value	Significant
Intercept	2194763907.200	1	2194763907.200	1159029.442	<0.001	Yes
RAP	22284799.244	4	5571199.811	2942.086	<0.001	Yes
Temperature	2059022431.433	2	1029511215.717	543672.969	<0.001	Yes
Frequency	278791124.267	5	55758224.853	29445.274	<0.001	Yes
RAP * Temperature	6156365.289	8	769545.661	406.388	<0.001	Yes
RAP * Frequency	2159036.622	20	107951.831	57.008	<0.001	Yes
Temperature * Frequency	145407902.300	10	14540790.230	7678.823	<0.001	Yes
RAP * Temperature * Frequency	501909.644	40	12547.741	6.626	<0.001	Yes
Error	170426.000	90	1893.622			
Total	4709257902.000	180				
Corrected total	2514493994.800	179				

decreases of 0.5% when up to 20% RAP is added and further decreases to between 8% to 14% when incorporating 20% to 40% RAP, compared to control mixtures. When the temperature doubles to 40°C, the phase angle for asphalt mixture incorporating up to 20% RAP, increases sharply between 12% to 52%, while for asphalt mixtures incorporating 30% to 40% RAP, the phase angle increases to between 23% to 54%. In addition, as the loading frequency increases, the phase angle consistently increases from 12% to 54%. When the test temperature increases from 40°C to 50°C, the phase angle initially reduces from 14% and 8% when incorporating 10% and 40% RAP, respectively. However, as the frequency progressively increases, the phase angle also increases up to 19% at 40% RAP. For specimens tested at 40°C, the phase angle slightly increases at 0.1 Hz for all RAP percentages but decreases up to 25% for the rest of the loading frequencies compared to control samples. At 50°C, in comparison with control mixtures, the phase angle increases up to loading frequency equivalent to 10 Hz. However, at 25 Hz frequency, the phase angles slightly decreases up to 9%. This decrease in phase angle can be explained in terms of aggregate interlocking effects.

An analysis of variance (ANOVA) is carried out to determine the effects of RAP content, test temperature, frequency and interaction of the main effects on the measured phase angle. Table 6 shows the ANOVA results which indicate that all the main effects as well as their interactions have significantly influence the measured phase angle at 5% significance level. Similar to dynamic modulus, temperature is a dominant main effect since temperature exhibits the highest *F*-ratio which indicates that temperature increase will significantly affects the phase angle of the asphalt mixtures.

Figure 4 shows the interaction plot of temperature and RAP against phase angle at 10 Hz. The plot

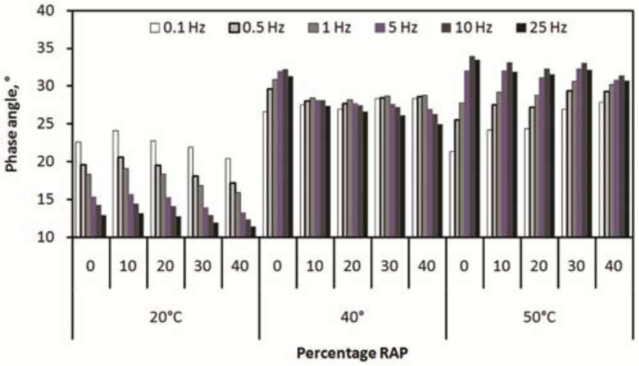


Fig. 3—Phase angle at different RAP content, temperature and frequency

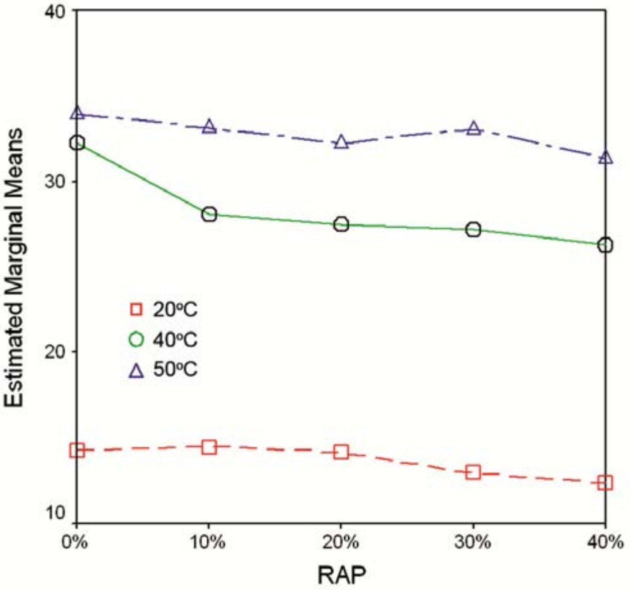


Fig. 4—Interaction plot of temperature and RAP against phase angle at 10 Hz

Table 6—ANOVA results on main and interaction effects on phase angle

Source	Sum of squares	df	Mean square	*F*	*p*-value	Significant
Intercept	111122.244	1	111122.244	2214865.125	<0.001	Yes
RAP	40.843	4	10.211	203.517	<0.001	Yes
Temperature	6129.408	2	3064.704	61085.032	<0.001	Yes
Frequency	37.189	5	7.438	148.250	<0.001	Yes
RAP * Temperature	119.215	8	14.902	297.020	<0.001	Yes
RAP * Frequency	87.996	20	4.400	87.696	<0.001	Yes
Temperature * Frequency	1126.096	10	112.610	2244.511	<0.001	Yes
RAP * Temperature * Frequency	57.246	40	1.431	28.525	<0.001	Yes
Error	4.515	90	.050			
Total	118724.752	180				
Corrected total	7602.508	179				

clearly indicates that generally the estimated marginal means of the phase angle decreases as RAP content increases. Improvement in elastic component (*E*') of asphalt mixture incorporating RAP compared to control mixtures is particularly evident at 40°C. The contribution of aged bitumen from reclaimed asphalt pavement has effectively enhanced the mixture viscoelastic characteristics which results in improved stiffness of the asphalt mixtures at high temperature.

Figure 5 illustrates the Cole-Cole curve of the relationship between the elastic component or storage modulus (*E*′) and the viscous or loss modulus (*E*″) of the asphalt mixtures based on results obtained from the AMPT. The Cole-Cole curve is suggested to validate the test data for a master curve at any frequency or temperature[11]. The acceptable data are independent of temperature and frequency and form a single curve. As illustrated in Fig. 5, the relationship between *E*′ and *E*″ are linear and form a single curve with R2 equal to or greater than 90%, for all test temperatures. This implies that the data from the master curves illustrated in Figs 1 and 3 are valid.

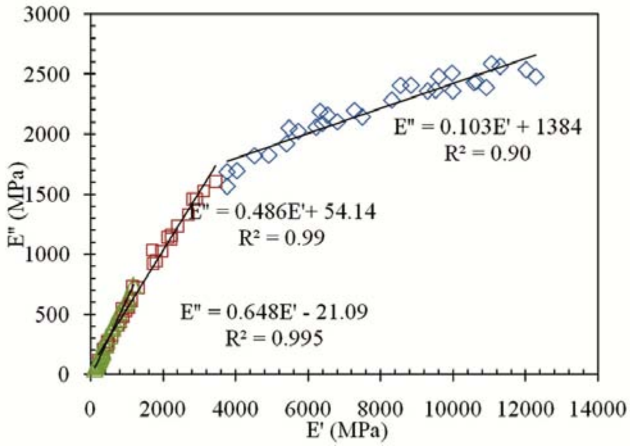


Fig. 5—Cole-Cole curve of the relationship between *E*′ and *E*″

Effect size of the main and interaction effects

The effect size of the main and interaction effects on measured dynamic modulus and phase angle are categorized into 3 Groups as shown in Table 7. It can be seen that effect size of temperature is distinctly large for both dynamic modulus and phase angle when temperature becomes one of the main effects as in Groups 1 and 2. In Group 3, frequency has the largest effect size compared to main effect of RAP on dynamic modulus. However, with the same main effects (frequency and RAP), the effect sizes are comparable in the measured phase angle. Even though RAP has significantly contributed to asphalt mixture stiffness at high temperature, the effect size is fairly low compared to temperature and frequency except for measured phase angle where its effect size is 0.24. Similarly, the effect size for the interaction effects is considerably low compared to the main effects except when measuring the phase angle. The interaction effect between frequency and RAP in phase angle has effect size of 0.51, is the highest among the interaction effects (temperature × frequency and temperature × RAP) in the tests. Even though the effect size of the interaction effect analysis is limited to two main effects only, it can be expected that the effect size of the interaction effect of three main effects (RAP × temperature × frequency) is much less than the interaction effect of two main effects based on the lowest *F*-ratio of the interaction effect of RAP × temperature × frequency compared to other interaction effects.

Asphalt mixture stiffness

Figure 6 displays the dynamic modulus master curve for mixtures with 5 RAP contents, tested at three test temperatures (20°C, 40°C and 50°C) and six loading frequencies (25, 10, 5, 1, 0.5 and 0.1 Hz). The master curve was developed taking 25°C as the reference test temperature. Generally, the mixture stiffness increases as the RAP content increases.

Table 7—Effect size(ω_2) of the main and interaction effects

Group	Measured parameter	Main effect		Interaction effect
		Temperature	Frequency	Temperature × Frequency
1	Dynamic modulus	0.83	0.11	0.05
	Phase angle	0.84	0.005	0.15
		Temperature	RAP	Temperature × RAP
2	Dynamic modulus	0.99	0.01	0.003
	Phase angle	0.97	0.006	0.02
		Frequency	RAP	Frequency × RAP
3	Dynamic modulus	0.92	0.07	0.007
	Phase angle	0.22	0.24	0.51

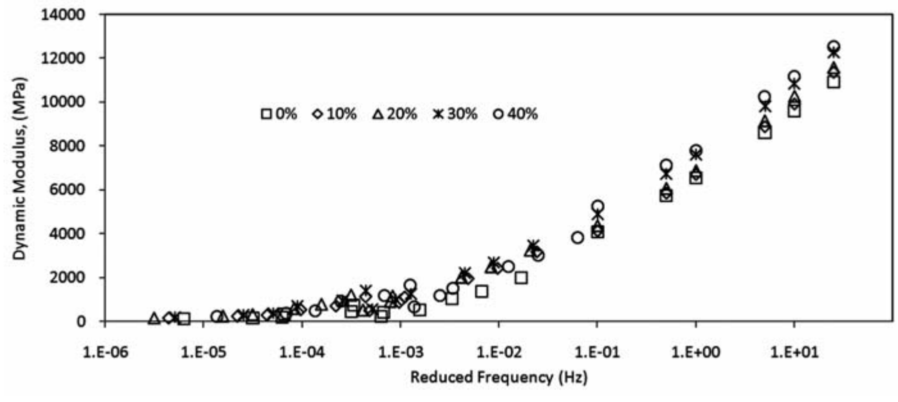


Fig. 6—Master curves at different RAP percentages

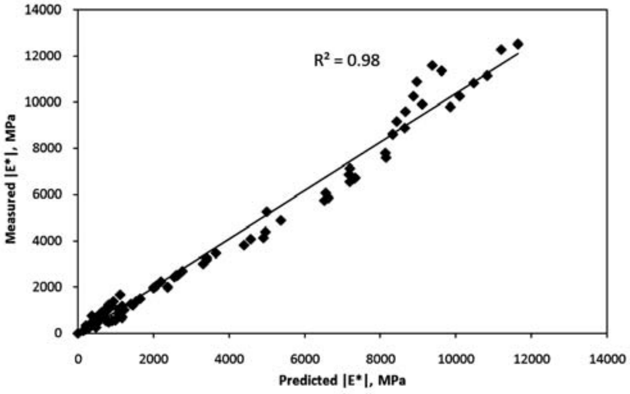


Fig. 7—Relationship between measured |*E**| and |*E**| predicted

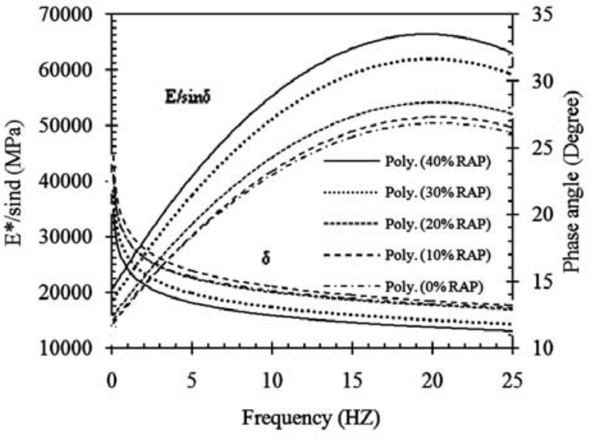
These increases in RAP content have significantly increase the dynamic modulus which directly translates into improved load spreading ability of the asphalt mixtures incorporating RAP. Figure 7 shows that the measured dynamic modulus |*E**| matches reasonably well with the predicted dynamic modulus |*E**| calculated based on Witczak *et al.*[6] model without any significant bias with regression coefficient equal to 0.983.

An improved resistance to rutting and fatigue in mixtures incorporating RAP is further illustrated in Figs 8 and 9, respectively. For instance, rutting factor, |*E**|/sin δ at 50°C and 10 Hz has significantly increased by 37% and 64%, respectively for mixtures incorporating 10% and 40% RAP. Interestingly, the fatigue parameter, |*E**|.sin δ at 20°C and 10 Hz slightly increased up to 5% at 20% RAP and 1% for mixture incorporating 40% RAP, and which is comparable to the fatigue parameter of control mixtures.

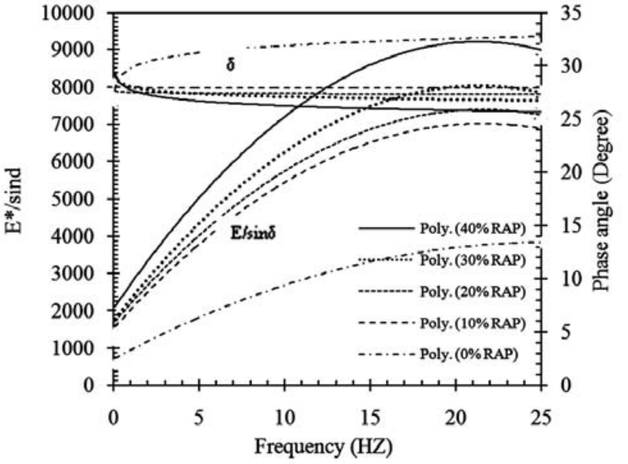
From Figs 8(a)-(8c), it can be seen that the maximum rutting factor takes place at approximately 20 Hz at each test temperature, while the maximum fatigue factor is from 15 Hz to 20 Hz as shown in Figs 9(a)-9(c). Therefore, it is recommended that the frequency of total traffic loading to achieve maximum rutting and fatigue performance should be in the range 15-20 Hz for the asphalt mixtures tested using RAP from DPE. Since aged binder in RAP materials supplied from various sources may have different rheological properties, it is expected to affect the engineering properties of asphalt mixtures containing RAP from different sources[17]. Therefore, the recommended range of frequency to obtain maximum rutting factors can vary for asphalt mixtures constructed using RAP from other sources.

Conclusions

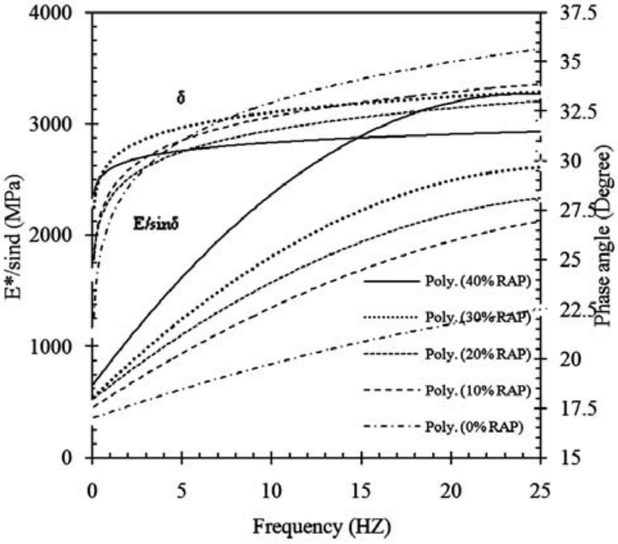
At constant test temperature, the dynamic modulus increases as the loading frequency and RAP content increase. The phase angle decreases as the loading frequency and RAP content increase at 20°C. However, at 40°C and 50°C, the phase angle increases up to loading frequencies 1 Hz and 10 Hz, respectively beyond which it reduces. At constant frequency, the dynamic modulus decreases as temperature increases, while the phase angle increases as temperature increases. Temperature and frequency have significant effects with high effect size on the measured dynamic modulus and phase angle. The interaction effect of frequency and RAP has the highest effect size among the interaction effects on the dynamic modulus test particularly on the phase angle. Rutting parameter increases as RAP content increases and fatigue parameter is well below the maximum limit and in fact the fatigue parameter further decreases with addition of more than 20% RAP. From the rutting versus frequency master curves, the recommended frequency of loading to obtain higher strength for the asphalt mixtures tested ranges from 15 to 20 Hz.



(a) 20°C

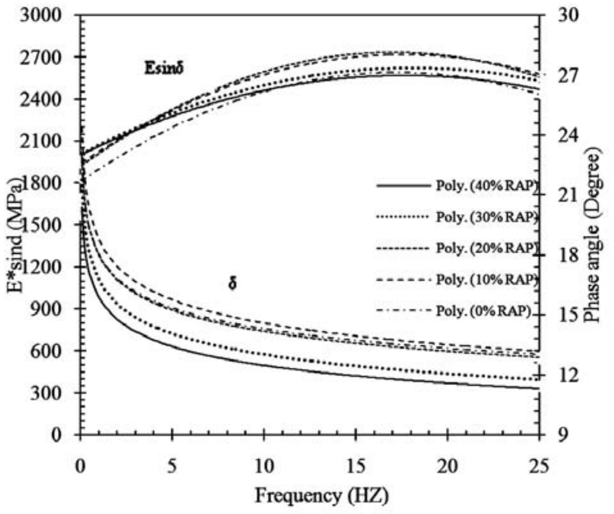


(b) 40°C

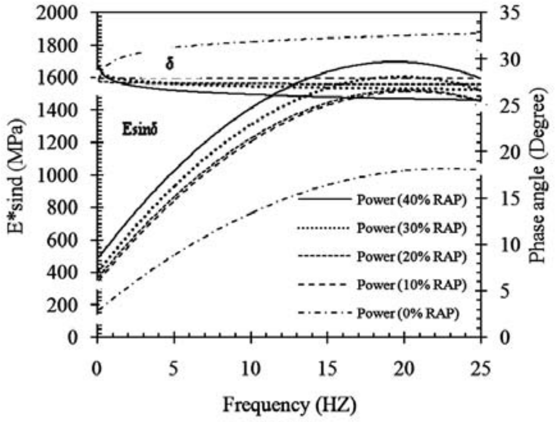


(c) 50°C

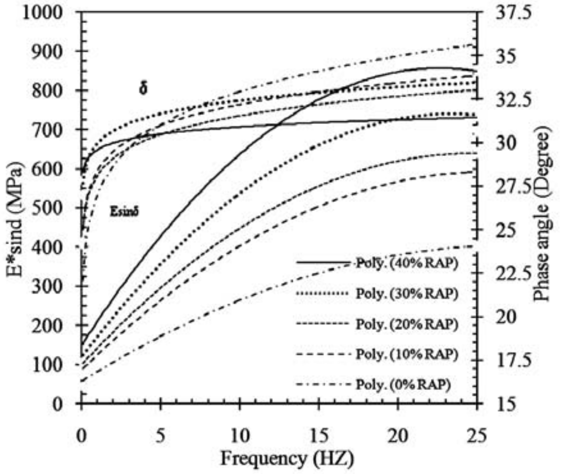
Fig. 8—Master curve of rutting factor versus frequency sweep at designated temperatures



(a) 20°C



(b) 40°C



(c) 50°C

Fig. 9—Master curve of fatigue factor versus frequency sweep at designated temperatures

Acknowledgements

The authors would like to acknowledge the Universiti Sains Malaysia for funding this research through the Research University grant scheme. Many thanks are also due to technicians of the Highway Engineering Laboratory at the Universiti Sains Malaysia.

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