International Journal of GEOMATE, Oct., 2021, Vol.21, Issue 86, pp.63-71
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2021.86.j2279
Geotechnique, Construction Materials and Environment

CORRELATION ANALYSIS OF DYNAMIC MODULUS AND RESILIENT MODULUS OF ASPHALT MIXTURE USING THE PG76 MODIFIED ASPHALT

Bambang Sugeng Subagio[1], Ratih Purnama Sari[2], Jongga Jihanny[1] and *Siti Raudhatul Fadilah[1]

[1] Department of Civil Engineering, Institut Teknologi Bandung, Indonesia; [2] Graduate School of Highway Engineering, Institut Teknologi Bandung, Indonesia

*Corresponding Author, Received: 21 July 2021, Revised: 07 Sept. 2021, Accepted: 23 Sept. 2021

ABSTRACT: Road infrastructure is still a mainstay for mobility. The primary issue that happened frequently is early damage due to overload and high pavement surface temperatures. Existing materials, such as penetration grade asphalt and modified asphalt, could not overcome these problems. However, the development of materials using the modified asphalt equivalent to PG76 (EPG76) is expected to provide better performance obtained through mechanistic testing, i.e., Marshall, Dynamic Modulus, and Resilient Modulus. The rheology test for EPG76 modified asphalt was carried out using DSR and showed that the value of EPG76 modified asphalt has increased to above Pen 60/70 asphalt. The polymer content of EPG76 modified asphalt can prevent asphalt properties became more rigid and more resistant to high temperatures. This mixture has a higher Resilient Modulus than Pen 60/70 asphalt at high temperatures and gives better crack resistance. Overall, the EPG76 modified asphalt mixture shows better performance under overload and high-temperature conditions.

Keywords: Dynamic modulus, Resilient modulus, Modified asphalt, Pen 60/70 asphalt

1. INTRODUCTION

Early damage on the asphalt pavement often occurs due to the overloading and high surface temperature. Unfortunately, the types of bitumen that exist so far, both normal Pen 60/70 and modified asphalt, have not overcome this problem. However, the recent development and testing of new technology by utilizing Performance Grade asphalt are expected to provide better performance under overload and high surface temperatures. Therefore, this study aims to analyze the laboratory performance in terms of the Dynamic Modulus and Resilient Modulus of Asphaltic Concrete-Wearing Course (AC-WC), which is the topmost pavement layer that acts as a wear layer, using Pen 60/70 asphalt and modified asphalt equivalent to Performance Grade 76 (EPG76).

Resilient modulus, which is based on the form of loading with a rest period, is measured at a particular temperature and loading time. Whereas the dynamic modulus derived from sinusoidal loading without rest time is measured in a specific temperature and frequency range [1]. These two critical parameters are used to analyze the mechanical behavior of asphalt pavements [2]. Moreover, the Resilient Modulus continues to be a key parameter for pavement [3, 4].

In order to acknowledge the behavior of bitumen, it is necessary to test at various temperatures and loading times. This technique has a significant role in asphalt concrete pavement performance [5]. A frequently used method is to apply a sinusoidal load to the specimen and use the measured stress-strain ratio as the stiffness modulus of the specimen at various combinations of temperature and loading time.

The use of a Dynamic Shear Rheometer (DSR) is one of the most common experiments conducted to examine the rheological properties [6]. Asphalt rheological parameters that can be measured through asphalt layer testing using DSR, include complex shear modulus (G*) and phase angle (δ) for each variation of temperature and loading time [7]. Phase angle can be defined as immediate elastic and the delayed viscous responses of the binder, which are obtained from the lag between the induced stress and measured strains [8]. Meanwhile, complex shear modulus (G*) parameter indicates the resultant elastic storage, represented by the notation G' (storage modulus), and the viscous storage in the notation G" (loss modulus). The parameter G' provides an overview of the elasticity of asphalt under certain conditions, while G" provides an overview of non-elastic (viscous) materials. These two values (G' and G") are determined by the phase angle (δ), where the greater value of δ means the non-elastic material properties of the bitumen are observed.

Furthermore, the Complex Dynamic Modulus describes the stress-strain relationship of viscoelastic materials [9, 10]. Denoted as |E*|, the Complex Dynamic Modulus is the ratio between a maximum stress and maximum strain representing the overall stiffness value of the mixture. The measured angle between the strain setting and the material response varying between 0º and 90º (fully elastic to fully viscous response) is called the phase angle. The elastic material does not reveal any differences between the applied stress and the strain that occurs. At low temperatures and high frequencies, a small phase angle occurs due to the elastic behavior of bitumen. Otherwise, the phase angle becomes more extensive at higher temperatures and lower frequencies due to the characteristic bitumen approach being vicious.

Evaluation of Dynamic Modulus Test requires an understanding of linear viscoelastic, a stress-strain relationship under continuous sinusoidal loading. For one-dimensional sinusoidal loading conditions, stress and strain can be represented by Eq. (1) and Eq. (2), respectively. The stress and strain amplitudes are indicated by σ_0 and ε_0, ω is the angular velocity, and δ is the phase angle. At the same frequency and time, this condition produces a stable response as shown in Fig. 1.

$$\sigma = \sigma_0 \sin(\omega t) \quad (1)$$
$$\varepsilon = \varepsilon_0 \sin(\omega t - \delta) \quad (2)$$

The Dynamic Modulus test results analysis is fundamentally used to generate a master curve [12], which is created using the frequencies and temperatures superposition principle. Data at various temperatures will be routed according to frequency until the curves merge into a single smooth function. The master curve, as a function of frequency, explains the frequency dependence of the material. The amount of temperature change required to create the master curve describes the degree of dependence of the material on temperature, where 200°C is the reference temperature in Dynamic Modulus. To create a Dynamic Modulus sinusoidal master curve, further calculation analysis is needed from the test results using Asphalt Mixture Performance Tester (AMPT) mathematically [13].

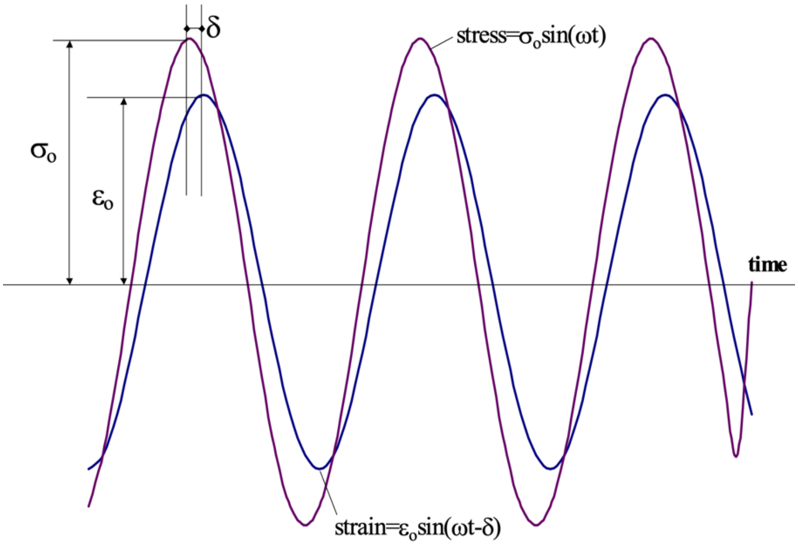


Fig.1 Stress and strain in dynamic loading [11]

2. RESEARCH SIGNIFICANCE

As one of the parameters that describe the mechanical behavior of asphalt pavements, the Resilience Modulus is generally used in European countries, while the Dynamic Modulus is a laboratory measure in the USA. In the case of Indonesia, both parameters are still valid and allowed to be implemented according to needs and objectives. Thus, by conducting this research, the comparison of these two essential parameters in a certain temperature range control can be identified. The mixture of test specimens used are asphalt with Pen 60/70 and modified asphalt, which is equivalent to Performance Grade 76 (EPG76). In the end, the results of this study are expected to be a reference in determining the most appropriate type of asphalt in terms of behavior and characteristics to be applied to road infrastructure in Indonesia.

3. THE BASIC MATERIAL TEST RESULTS

The basic materials for testing asphalt Pen 60/70, EPG76 modified asphalt, and aggregate, including two types of test specimens: AC-WC with a mixture of Pen 60/70 asphalt and AC-WC with a mixture of modified EPG76 asphalt, were thoroughly prepared beforehand. After determining the optimum asphalt content value, further tests were conducted, i.e., Marshall Immersion, Dynamic Modulus using AMPT, and Resilient Modulus using Universal Material Testing Apparatus (UMATTA). The asphalt test using DSR was done to generate the Performance Grade (PG) value of bitumen [14], whereas the mixture test was carried out to identify the properties and characteristics.

3.1 Aggregate Test Results

Aggregate testing aims to identify the characteristics of coarse aggregate, fine aggregate, and filler, as well as to check their conformity with the specified requirements. In her research, Sari [15] concluded that the results of the aggregate characteristics test have been sufficient to the General Specifications issued by the Indonesian Ministry of Public Works and Housing [16].

3.2 Pen and Modified Asphalt Tests Results

As reported in Sari [15], the test results of asphalt Pen 60/70 (Table 1) have met the General Specifications required by the Indonesian Ministry of Public Works and Housing [16]. Also, the test results of EPG76 modified asphalt listed in Table 2 have complied with the Special Specifications required by the Indonesian Ministry of Public Works and Housing [17].

The dynamic shear stress test using a DSR at varying temperatures aims to measure the modulus at a constant frequency with a gradual increase in temperature until the sample fails, shown in Fig. 2 to Fig. 4. Those tests were conducted on EPG76 modified asphalt, while the data for Pen 60/70 asphalt was adopted from Permata [18]. The DSR test was performed for three different conditions: the original, Rolling Thin Film Oven Test (RTFOT) related to the AR-viscosity grading system [19], and the Pressure Aging Vessel (PAV).

3.3 Pen 60/70 Asphalt Viscosity Test Results

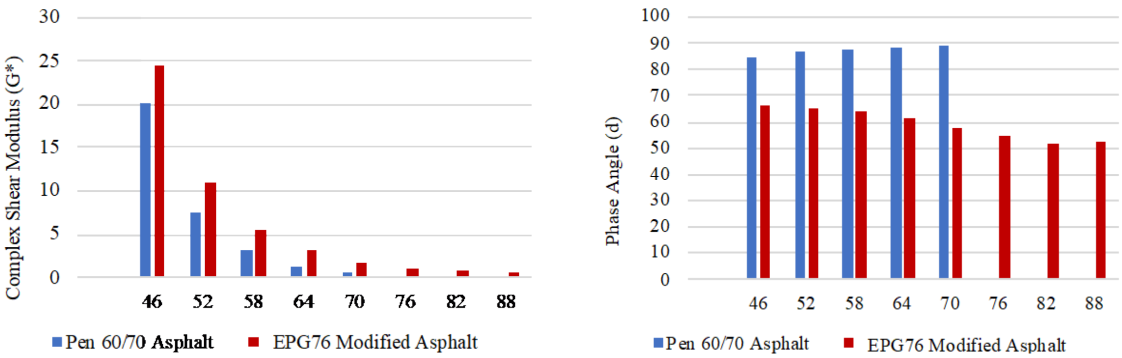
Regarding the kinematic viscosity test result, it is showed that the polymer contained in EPG76 modified asphalt, gives a different mixing temperature of the mixtures; from 155ºC to 146ºC and compacting temperature; from 146ºC to 174ºC, compared to the normal asphalt Pen 60/70.

Table 1 The result of the EPG76 modified asphalt characteristic test

No.	Parameter Test	Specification	Result
1	Penetration at 25°C (dmm)*	60-70	64
2	Viscosity dynamic 60°C	160-240	210.3
3	Viscosity kinematic 135 °C (cst)	≥ 300	515
4	Softening Point, (°C)	≥ 48	49.5
5	Dactility at 25°C	≥ 100	≥ 100
6	Flash point (°C)	≥ 232	341
7	Specific gravity* gr/cm^3	≥ 1.0	1.040
TFOT Residual Test			
8	Viscosity dynamic 60°C	≤ 800	236.1
9	Penetration at 25°C, dmm *	≥ 54	54
10	Ductility at 25°C, (cm)	≥ 100	≥ 100

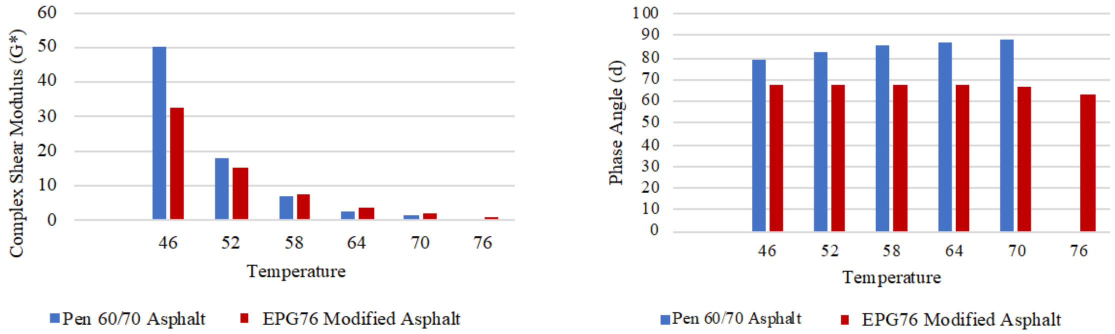
Table 2 The result of the EPG76 modified asphalt characteristic test

No.	Parameter Test	Indonesian Specification	Results
1	Viscosity dynamic at 135°C (Pa.S)	≤ 3.0[1]	2.5
2	Dynamic shear strain, G*/sin δ by 10 rad/s, 76°C (kPa)	≥ 1.0	1.504
3	Penetration at 25 °C, 100 gr, 5 sec (0,1 mm)	reported	57
4	Flashing point (^{0}C)	≥ 230	318
5	Elasticity (%)	≥ 75	97.5
6	Storage stability: difference between softening point (^{0}C)	≤ 2.2	2
RTFOT Residual Test			
7	Dynamic shear strain, G*/sin δ by 10 rad/s, 76°C (kPa)	≥ 2.2	1.421*
8	Elasticity (%) after RTFOT	≥ 75	100
Asphalt Residual PAV			
9	Dynamic shear strain, G*.sin δ by 10 rad/s, 25°C (kPa)	≤ 5000	3529



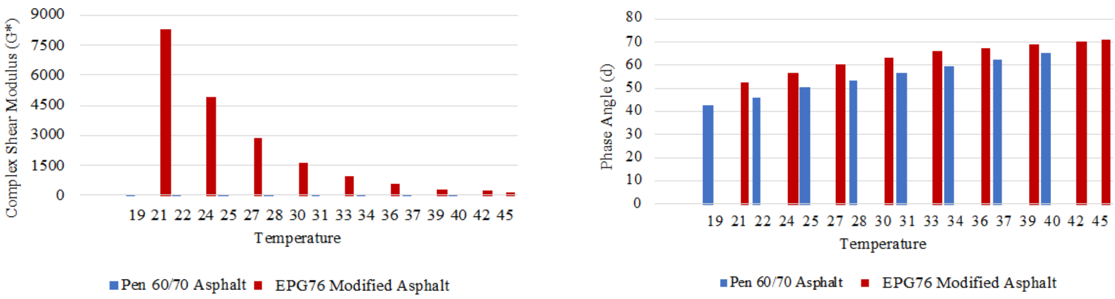
(a) (b)

Fig. 2 The result of DSR testing in original condition (a) Complex Shear Modulus (b) Phase Angle



(a) (b)

Fig. 3 The result of DSR testing in RTFOT condition (a) Complex Shear Modulus (b) Phase Angle



(a) (b)

Fig. 4 The result of DSR testing in PAV condition (a) Complex Shear Modulus (b) Phase Angle

3.4 Marshall and Marshall Immersion Test

Marshall Test parameters consist of stability, flow, density, void in the mixture, void in mineral aggregates, void filled with asphalt, and refusal void in the mixture. The results showed that the EPG76 modified asphalt mixture had a higher Marshall stability value than the Pen 60/70 asphalt mixture. This can be explained by the penetration value of EPG76 modified asphalt, which has a lower value than Pen 60/70 asphalt, meaning that the asphalt becomes stiffer and has higher stability.

Mixtures with a lower flow generally have better resistance to deformation. However, the flow value should be limited so that it is not too low because the lowest flow makes the mixture stiff and prone to cracking. Regarding the results, the EPG76 modified asphalt mixture has a higher flow than the Pen 60/70 asphalt mixture. The higher value of flow causes the mixture to be more flexible.

Marshall Immersion Test aims to determine the durability of the mixture. The immersion test using warm water at a temperature of 60ºC is conducted to measure the performance of the mixture's resistance against the water disturbance. The comparison between the Marshall Stability of the immersed specimen and the standard Marshall Stability, expressed as a percentage, is called the Marshall Remaining Strength Index. The test results show the remaining strength index obtained was 83.9% for Pen 60/70 asphalt and 88.1% for EPG76 modified asphalt, which is less than 90% as required in the specifications by the Ministry of Public Works and Housing [16, 17]. Nonetheless, the value of the remaining strength index of the EPG76 modified asphalt mixture is higher than Pen 60/70 asphalt mixture. Thus, the EPG76 asphalt mixture is more resistant to temperature and water.

3.5 Dynamic Modulus Test Results

The Dynamic Modulus Test is carried out by following the Standard Specification for Transportation Materials and Methods of Sampling and Testing [20]. It was conducted by using three various temperatures (25°C, 35°C, and 45°C) and different frequencies (10 Hz, 1 Hz, 0.1 Hz, and 0.01 Hz). The test results are shown in Table 3.

3.6 Resilient Modulus Test Results

Resilient Modulus is a modulus of elasticity in accordance with the strain that can be recovered due to repeated loading [21]. This essential parameter is used to determine pavement performance and analyze pavement response to traffic loads. The Resilience Modulus is influenced not only by the characteristics of the mixture but also by the loading conditions, which are test temperature and the loading time. The higher the test temperature, the value of the Resilient Modulus will decrease, given the viscous-elastic nature of the asphalt.

Resilient Modulus Test was done by measuring the indirect tensile strength using repeated loads, utilizing the UMATTA equipment. A diametric specimen, such as Marshall specimens, is used and measured at the optimal asphalt rejection content. The test method refers to ASTM D 4123-82 (1987) so that the temperatures applied for testing are 25°C, 35°C, and 45°C. As a result, the Resilient Modulus for the two types of asphalt mixtures at different temperatures is shown in Table 4.

Table 3 The result of the Dynamic Modulus Test

Test Condition		Mixture Types			
		Pen 60/70 Asphalt		EPG76 Modification Asphalt	
Temperature (°C)	Frequency (Hz)	Modulus Dynamic (MPa)	Phase Angle (°)	Modulus Dynamic (MPa)	Phase Angle (°)
25	10	7720.71	21.90	4982.59	32.41
	1	4139.09	31.30	2061.07	36.67
	0.1	1771.94	35.96	957.26	28.61
	0.01	657.81	25.66	592.21	20.31
35	10	4845.39	29.08	6784.03	31.36
	1	2176.04	36.54	2775.29	37.35
	0.1	862.72	33.88	1074.11	31.51
	0.01	438.36	19.12	512.63	14.56
45	10	5434.52	27.24	3258.07	40.44
	1	2514.31	34.43	1165.82	40.50
	0.1	1075.17	33.57	545.17	27.08
	0.01	443.40	16.79	417.53	15.76

Table 4 The result of the Resilient Modulus Test

Specimen Types	Test Temperature (ºC)	UMATTA Test				
		Total Recoverable Horizontal Deformation (μm)	Peak Load Force (N)	Coefficient Variant Resilient Modulus	Std. Dev Resilient Modulus	Resilient Modulus (MPa)
Pen 60/70	25	5.90	1992	1.91%	69.50	3631
	35	13.46	1233	3.15%	31.21	990
	45	33.99	925	3.92%	11.44	292
Asphalt Modified EPG76	25	7.83	2026	2.92%	81.40	2789
	35	18.58	1265	3.39%	25.20	743
	45	30.54	896	1.68%	5.34	317

4. ASPHALT MIXTURE ANALYSIS

4.1 Dynamic Shear-Strain Analysis

The DST results in the original condition shown that Pen 60/70 asphalt can only be tested up to a temperature of 70°C, while the EPG76 modified asphalt has a maximum test temperature of 88°C. Under RTFOT conditions, Pen 60/70 asphalt and EPG76 modified asphalt can be tested until a temperature of 70°C and 76°C, respectively.

Based on the Performance Grade (PG), the upper limit of PG value for the asphalt material is determined from the DSR test under original and RTFOT conditions [22]. The upper limit of PG is obtained from the lowest value between the temperature at G*/sin δ with an original state of 1 kPa and the temperature at the G*/sin δ with an RTFOT condition of 2.2 kPa, as shown in Table 5.

Table 5 The upper limit of PG value

PG Value	Pen 60/70	Mod EPG76
Original condition	66.81	83.23
RTFOT condition	66.35	70.41
Smallest	66.35	70.41
Round-off	64	70

The results of the DSR test under PAV conditions were used to determine the intermediate limit of the PG value, which was obtained at G*.sin δ of 5,000 kPa. This results in a medium value or Pen 60/70 asphalt and EPG76 modified asphalt is 25°C. Therefore, the PG value for Pen 60/70 asphalt is PG64 (25) and for the EPG76 modified asphalt is PG70 (25). Thus, on the whole, the bitumen modification EPG76 has a broader temperature range for resistance to permanent deformation. In addition, the relationship between the value of G*/sin δ and the temperature at the original, RTFOT, and PAV conditions is illustrated in Fig. 5 to Fig. 7.

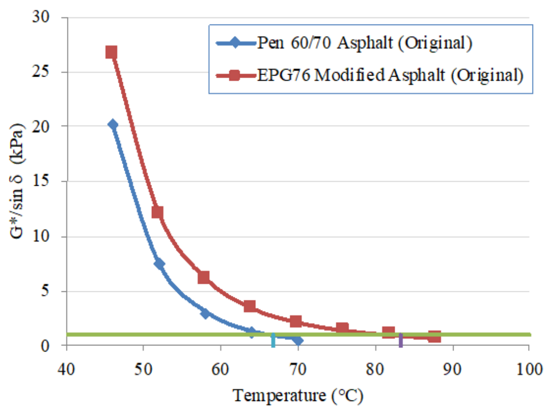


Fig. 5 Relationship of G*/sin δ (original condition)

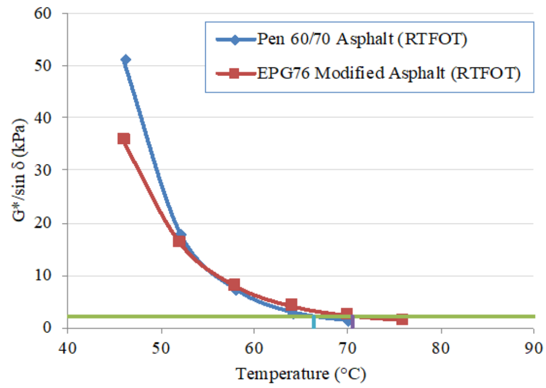


Fig. 6 Relationship of G*/sin δ (RTFOT condition)

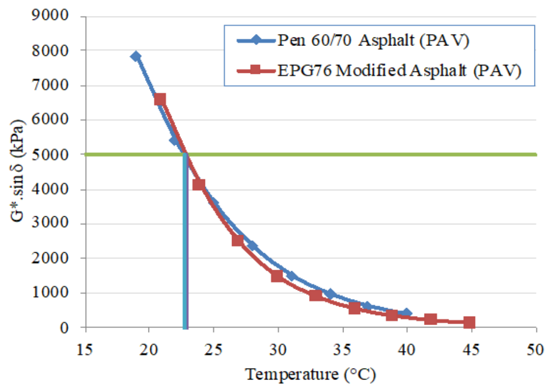


Fig. 7 Relationship of G*/sin δ (PAV condition)

Pen 60/70 asphalt has a steeper gradient than the EPG76 modified asphalt (see Fig. 8). A master curve can be created from the modulus values obtained at varying temperatures and frequencies by shifting the results along the frequency scale by the log factor (αT) [23]. In conclusion, Pen 60/70 asphalt is more sensitive to temperature than EPG76 modified asphalt. A black diagram is then created using the data from the DSR test results.

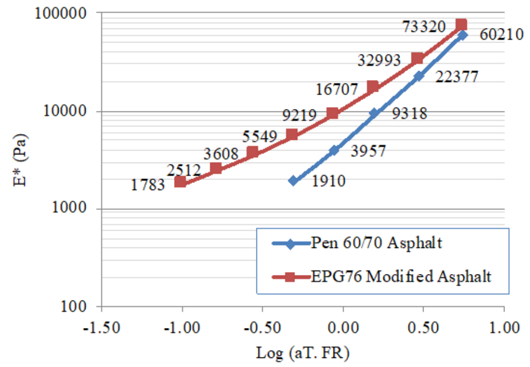


Fig. 8 Master curve for both asphalt

The black diagram describes the asphalt behavior as measured by the stiffness modulus and phase angle parameters. Fig. 9 indicates that for Pen

60/70 asphalt, the bitumen stiffness modulus value decrease corresponds to the reduction of phase angle. Whereas for EPG76 modified asphalt, the decline in bitumen stiffness modulus is inversely proportional to the phase angle value. The phase angle value for Pen 60/70 asphalt mixture is relatively higher than the EPG76 modified asphalt mixture. The decrease in the phase angle value for the EPG76 modified asphalt mixture has a wide range of 14°C, but it is only about 4°C for the Pen 60/70 asphalt mixture. This condition indicates that the EPG76 modified asphalt mixture is more elastic as the test temperature increases.

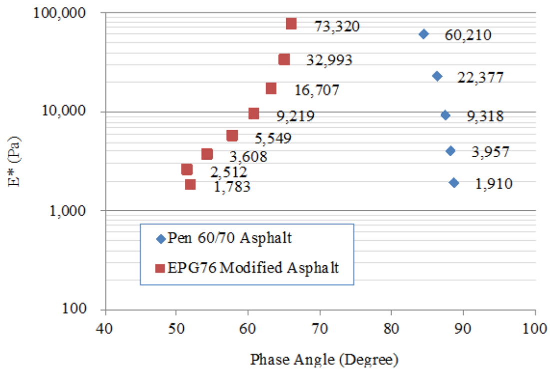


Fig. 9 Black diagram for both asphalt

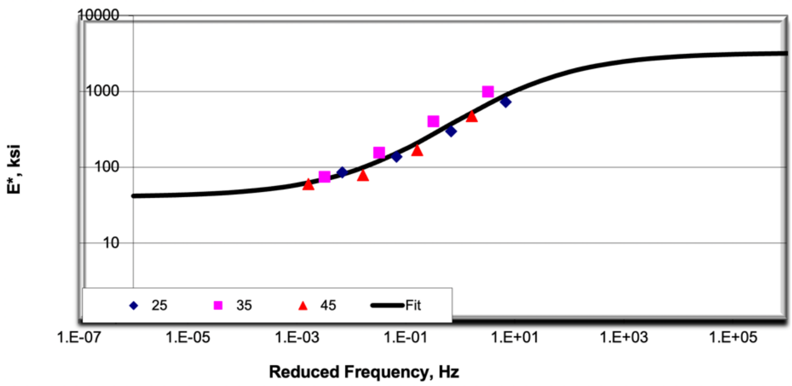
4.2 Dynamic Modulus Test Analysis

Analysis of Dynamic Modulus test data is used to form the master curve. The master curve of modulus determined by this method, as a function of frequency, explains the dependence of the material frequency. The dynamic modulus master curves can be created using sigmoidal equations [24, 2] in Eq. (3), referring to AASHTO [25].

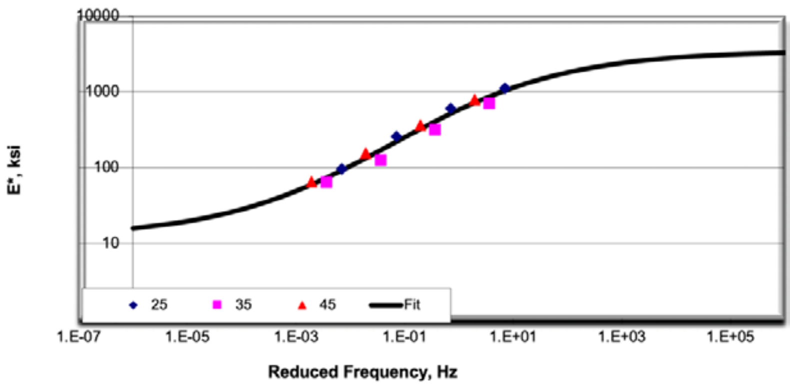
$$Log\ |E^*| = \delta + \frac{(Max-\delta)}{1+e^{\beta+\gamma(log\ fr)}} \quad (3)$$

The term $|E^*|$ is defined as modulus term in psi, fr is the reduction of loading frequency in Hz. *Max* indicates the maximum limit frequency, and δ, β, γ are the parameters of the function form.

Fig. 10 shows the master curves generated from the ITC master solver program. The resulting lines are formed by the Dynamic Modulus value based on the reduced frequency obtained by adjusting the test temperature and loading frequency. From the two master curves below, it can be concluded that the EPG 76 modified asphalt mixture has a higher slope than Pen 60/70 asphalt mixture. Overall, the EPG 76 has better resistance to temperature fluctuation and loading frequency.



(a)



(b)

Fig. 10 Master curve of asphalt mixture: (a) Pen 60/70 asphalt (b) EPG76 modified asphalt

4.3 Resilient Modulus Test Analysis

Fig. 11 shows that the Pen 60/70 asphalt mixture produces a higher Resilient Modulus than the EPG76 modified asphalt mixture at testing temperatures 25°C and 35°C. In contrast, at a test temperature of 45°C, the Pen 60/70 asphalt mixture has a smaller Resilient Modulus than the EPG76 modified asphalt. These results indicate that the modified EPG76 asphalt mixture is stiffer and more resistant to permanent deformation at high temperatures than the Pen 60/70 asphalt mixture, which is in accordance with the statement in the Shell Bitumen Handbook Theory [26] that *Cariphalte* asphalt has greater penetration than asphalt Pen 50 at low temperatures.

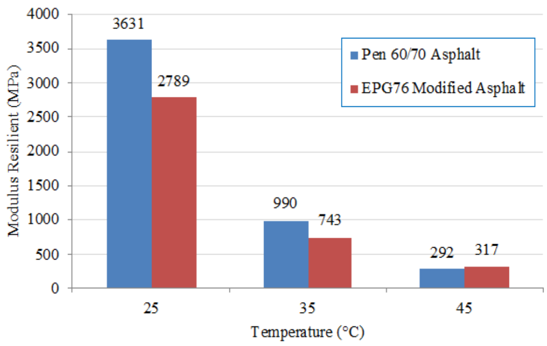


Fig. 11 Comparison of Resilient Modulus

As the temperature increases, *Cariphalte* asphalt penetration is lower than Pen 50 asphalt, resulting in higher viscosity. This condition gives a greater value of Resilient Modulus for Pen 60/70 asphalt mixture than the EPG76 modified asphalt mixture at 25°C and 35°C. In contrast, the Resilient Modulus of the EPG76 modified asphalt mixture is higher than Pen 60/70 asphalt mixture at 45°C. Therefore, at a lower temperature, a high Resilient Modulus is not required to accelerate cracking. It can be concluded that the EPG76 Modified Asphalt has better crack resistance at low temperatures.

5. CONCLUSION

Regarding the results of the asphalt characteristics, it is known that the polymer contained in the EPG76 modified asphalt mixture causes the asphalt to become more viscous and harder. As a result, the Performance Grade values for EPG76 modified asphalt generally have higher performance than the Pen 60/70 asphalt. Meanwhile, the results of Marshall characteristics analysis show that the optimum asphalt content for EPG76 modified asphalt is higher than the Pen 60/70 asphalt mixture. Also, it is found that Marshall stability value and Marshall Immersion Index for EPG76 modified asphalt have higher values than the Pen 60/70 asphalt.

According to the Dynamic and Resilient Modulus analysis results in this study, the Pen 60/70 asphalt mixture produces a better Dynamic Modulus performance than the EPG76 modified asphalt. This is indicated by the Resilient Modulus of Pen 60/70 asphalt, which is higher than the EPG76 modified asphalt mixture at 25°C and 35°C. However, this condition did not become similar when the sample was tested at 45 ° C, where the Resilient Modulus of EPG76 modified asphalt mixture is higher than the Pen 60/70 asphalt mixture.

6. REFERENCES

[1] Subagio B.S., Nirwan E., Rahman H., Comparison Between Resilient Modulus and Dynamic Modulus of AC-BC Mixture Using RAP Material. Paper Presented at the 8th International Conference on Maintenance and Rehabilitation of Pavements, 2016, pp. 64.1-10.

[2] Ruan L., Luo R., Hu X., Pan P. Effect of Bell-Shaped Loading and Haversine Loading on the Dynamic Modulus and Resilient Modulus of Asphalt Mixtures. Construction and Building Materials, Vol. 161, 2018, pp. 124-131.

[3] Buchanan S., Resilient Modulus: What, Why, and How. Vulcan Materials Company, 2007, pp. 19-28.

[4] Sihombing A.V.R., Subagio B.S., Hariyadi E.S., Yamin A., Development of Resilient Modulus Model Proposed for Bio-Asphalt as Modifier in Asphalt Concrete Containing Reclaimed Asphalt Pavement. International Journal of GEOMATE, Vol. 19, 2020, Issue 71, pp. 130-136.

[5] Anderson D.A., Christensen D.W., Bahia H.U., Dongre R., Sharma M.G.G., Antle C.E., Button J., Binder Characterization and Evaluation. Strategic Highway Research Program, 1994.

[6] Khodary F., Evaluation of Fatigue Resistance for Modified Asphalt Concrete Mixtures Based on Dissipated Energy Concept. Technische Universitat Darmstadt, 2010, pp. 19-28.

[7] Huang W., Wang D., He P., Long X., Tong B., Tian J., Yu P. Rheological Characteristics Evaluation of Bitumen Composites Containing Rock Asphalt and Diatomite. Applied Sciences, Vol. 9, Issue 5, 2019, pp. 1023.

[8] Bahia H.U., Anderson D.A., Strategic highway research program binder rheological parameters: background and comparison with conventional properties. Transportation

Research Record, 1995, pp. 32-39.
[9] Huang Y.H., Pavement Analysis and Design (Second Edition), 2004.
[10] Yoder E. J., Witczak M.W. Principles of Pavement Design Second Edition. John Wiley & Sons, Inc, New York, 1975.
[11] Clyne T., Li X., Marasteanu M., Skok E., Dynamic and Resilient Modulus of Mn/DOT Asphalt Mixtures. FHWA Report, Minnesota University, United States, 2003, pp. 3-14.
[12] Liu H., Luo R., Development of Master Curve Models Complying with Linear Viscoelastic Theory for Complex Moduli of Asphalt Mixtures with Improved Accuracy. Construction and Building Materials, Vol. 152, 2017, pp. 259–268.
[13] Suaryana N., Subagio B.S., Kosasih D., Sjahdanulirwan, S. Development of A Correlation Model Between Resilient Modulus and Dynamic Modulus for Stone Matrix Asphalt Mixture. Jurnal Teknik Sipil Institut Teknologi Bandung, Vol. 21, No. 2, 2014, pp. 171-178. (in Bahasa Indonesia).
[14] Hospodka M., Hofko B., Blab R. Introducing A New Specimen Shape to Assess the Fatigue Performance of Asphalt Mastic by Dynamic Shear Rheometer Testing. Material and Structures, Vol. 51, 2018, pp. 1–11.
[15] Sari R. P., Dynamic Modulus, Resilient Modulus, and Fatigue Performance of AC-WC Mixture Using Equivalent to PG76 Modified Asphalt. Master Thesis of Graduate Program of Highway Engineering, University Library, Institut Teknologi Bandung, 2016.
[16] Directorate of Highways, Indonesia Ministry of Public Works and Housing. General Specifications for Road and Bridges, 2018. (in Bahasa Indonesia)
[17] Directorate of Highways, Indonesia Ministry of Public Works and Housing. Special Specifications for Interim Mixture of Asphalt Concrete with PG76 Equivalent Modified Asphalt, 2015. (in Bahasa Indonesia)
[18] Permata D.Y., Subagio B. S., Ayunigtyas K.N. S., Performance of Resilient Modulus (SMix) and Dynamic Modulus (|E*|) on Asphalt Concrete-Wearing Course (AC-WC) Using Pen 60/70 Asphalt and Styrene-Butadiene-Styrene Polymer. Accepted at the International Journal on Advanced Science, Engineering, and Information Technology, 2021.
[19] The Asphalt Institute, The Asphalt Handbook Manual Series No. 4 (MS-4), 1989.
[20] AASHTO, Standard Specification for Transportation Materials and Methods of Sampling and Testing, 2008.
[21] Subagio B.S., Maha I., Affandi F., Rahman H. Performance and Development of Resilient Modulus and Fatigue Life Predictive Model of Warm Mix Asphalt Concrete Binder Course (AC-BC) Containing Reclaimed Asphalt Pavement. Presented at the 8th International Conference on Maintenance and Rehabilitation of Pavements, Singapore, 2016, pp. 105.1-8.
[22] The Asphalt Institute, Principles of Construction of Hot Mix Asphalt Pavement (Manual Series No. 22), 1983.
[23] Francken L. Bituminous Binders and Mixes. Rilem Report 17, 2005, pp. 6-40.
[24] Ali Y., Irfan, M., Zeeshan M., Hafeez I., Ahmed S., Revisiting the relationship of dynamic and resilient modulus test for asphaltic concrete mixtures. Construction and building materials, Vol. 170, 2018, pp. 698-707.
[25] AASHTO, Standard Practice for Developing Dynamic Modulus Master Curves for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT), 2015, pp. 1-8.
[26] Read D.J., David D.W., The Shell Bitumen Handbook. Shell Bitumen, 2003.