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Dynamic Shear Rheometer to Measure the Improvement of Asphalt Properties with the Addition of Buton Natural Asphalt-Rubber (BNA-R)

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Abstract

The characteristic of asphalt was influenced from temperature and load. Modifications of the characteristics of asphalt can improve their performance. Changes to the complex shear modulus will affect the stiffness modulus of asphalt. Indonesia has considerable deposits of natural asphalt, namely Buton natural asphalt, which has the potential to be used as an asphalt modifier. Buton natural asphalt-rubber (BNA-R) is one of the products of Buton natural asphalt mixed with rubber. This study uses a dynamic shear rheometer (DSR) to examine the effects of BNA-R on the rheology of virgin asphalt. Tests were carried out on samples before and after aging. The added quantity of BNA-R was varied from 2.5 % to 20 % with respect to Pen 64.2 virgin asphalt. The addition of BNA-R increased the hardness and improved the rheological properties of asphalt by increasing its performance grade (PG) and complex shear modulus (G*). The black diagram and master curve analysis show that the phase angle value (δ) decreases with the addition of BNA-R and increases the resistance to temperature.

Keywords: Modified Asphalt, Stiffness Modulus, Complex Shear Modulus, Buton Asphalt Rubber, Temperature

I. INTRODUCTION

Asphalt or bitumen is one of the oldest building materials and has been used extensively since ancient times. Initially, natural asphalt was processed at high temperatures to remove oil fractions and maintain high molar mass. Asphalt materials show thermoplastic properties and because of their superiority to water and their adhesive properties, they are used in various applications. Currently, asphalt is produced from crude oil via distillation, where an increase in temperature reduces the volatile-component content. Bitumen is a complex hydrocarbon which is regarded as a colloidal system consisting of high molecular weight asphaltenes dispersed in a lower molecular weight maltenes [1], [2].

Deposits of natural rock asphalt in Indonesia is found on Buton Island; the material is also known as Asbuton. There is a massive reserve of natural rock asphalt with a 5-30 % asphalt content and the estimated deposit amount is up to 677 million tons [3]. Asbuton has a great chance of being used partially or completely as a substitute for asphalt oil in asphalt mixtures. Asbuton is produced by extracting Buton rock asphalt and is more widely used as a modifier or added material because its penetration is extremely low [4]. Buton natural asphalt-rubber (BNA-R) is a mixture of Buton rock asphalt and crumb rubber. BNA-R contains 60 % asphalt as a result of semi-extraction from Buton rock asphalt and 40 % crumb rubber and has several advantages such as high stickiness, high softening point, high stiffness modulus, high resistance to fracture, and a durable and economical value [5], [6].

A mixture of asphalt and aggregates produces a heterogeneous material, generally consisting of original or used aggregates (recycled from industrial processes or otherwise), an asphalt binder, and air cavities. The mechanical properties of aggregate asphalt mixtures are mainly influenced by the nature of the asphalt. In general, aggregate asphalt mixtures show a time-dependent behavior with a characteristic nonlinear visco elastic stress-strain response (except under very low stresses or strains) [7].

As a thermoplastic material, asphalt has visco elastic properties under the conditions of most pavement operations. These properties determine the behavior of asphalt mixtures, usually measured by the relationship between stress and strain. The rheological properties of asphalt are usually presented in the form of complex shear modulus curves (G*) and phase angles (δ). G* is defined as the ratio of maximum stress (shear) to maximum strain when experiencing shear loads. δ is the phase difference between the voltage and strain in harmonic oscillation. Furthermore, the master curve helps to understand the behavior of asphalt binders for various loading frequencies under different temperature conditions. The main laboratory equipment for obtaining these parameters is a dynamic shear rheometer (DSR). Even at low temperature, the DSR still suitable to investigate the rheological properties of bitumen [8]–[13].

One of the most common flexible pavement damage in high-temperature countries such as Indonesia is rutting. The Superpave rutting factor (G*/Sin δ) has been used to evaluate the potential resistance to rutting of asphalt at high temperatures [11]. Other researchers call this value an anti-rutting factor [8], [14]–[18]. G*/Sin δ is derived from the dissipation energy concept (ΔU) (AASHTO T315-15). The ΔU value for the loading cycle can be calculated using Eq. (1) [11].

$$\Delta U = \pi \varepsilon_{max} \sigma_{max} sin\, \delta \qquad (1)$$

where ε max is the maximum shear strain, σ max is the maximum shear stress, and δ is the phase angle. Under stress control conditions, the value of ΔU for rutting can be estimated using Eq. (2) [11].

$$\Delta U = \frac{\pi \sigma_{max}^2}{G^*/\sin\delta} \qquad (2)$$

In accordance with equation (2) above, it can be clearly noted that the value of G*/Sin δ is inversely proportional to ΔU. The higher G*/sin δ, results in the lower ΔU, which exhibiting beter resistant to rutting failure [11].

Master curves have been developed to evaluate asphalt rheology. The master curve helps to understand the behavior of asphalt stiffness at various temperatures and loading frequencies [11], [12], [19]. Thus, the stiffness of the asphalt (E*) measured for several temperatures is combined into a single master curve by shifting the individual curves to the reference temperature.

The shift factor can be estimated using the Williams-Landel-Ferry equation (WLF) as shown in Eq. (3) [11].

$$\log \alpha_T = \frac{-C1\,(T-T_d)}{C2+T-T_d} \qquad (3)$$

Where log αT is the shift factor, T is the temperature (°K), and Td is the reference temperature (°K). C1 and C2 are parameters.

This knowledge can help in developing a better understanding of the characteristics and effects of BNA-R mixtures with basic asphalt.

II. MATERIALS AND METHODS

II.1 Materials

The asphalt binder used in this study is Pen 60/70 cement asphalt, which is commonly used in Indonesian roads. The characteristics of the base asphalt are shown in Table 1.

Table 1. Basic physical characteristics of asphalt Pen 60/70

No	Properties	Test Method	Unit	Indonesian Specification	Result
1.	Penetration at 25 °C	ASTM D-5	0.1 mm	60 -70	64.2
2.	Softening Point	ASTM-D36	°C	≥ 48	51.5
3.	Flash Point	ASTM D-92	°C	≥ 232	338
4.	Ductility at 25 °C	ASTM-D113	Cm	≥ 100	>100
5.	Specific Gravity at 25 °C	ASTM-D70	kg/m^3	≥ 1.0	1.037
6.	Loss on Heating (TFOT)	ASTM-D1754	%	≥ 0.8	0.1
7.	Penetration after TFOT	ASTM-D5	0.1 mm	≥ 54	61.3
8.	Kinematic Viscosity at 135 °C	ASTM-D21 70-67	cSt	≥ 300	459.6

II.2 Preparation of Modified Asphalt

The additive material used for mixtures with virgin asphalt Pen 60/70 is a BNA-R additive, with weight contents of 2.5 %, 5 %, 7.5 %, 10 %, 12.5 %, 15 %, 17.5 %, and 20 % show in Table 2. Modified asphalt is produced by stirring the mixture using an asphalt stirrer at 2,000 rpm and at 140 °C for 30 minutes. BNA-R was produced from rock asphalt in Buton Island (Indonesia) called Asbuton. Rock asphalt is composed of asphalt and minerals and used as an additive material. The rock asphalt is extracted to separate the minerals from the asphalt. Buton Natural Asphalt (BNA) from the extraction of rock asphalt mixed with rubber became BNA-R [5]. In this study BNA-R used was a industrial product where the composition of Asbuton and crumb rubber as reported by producent was 60% and 40%. Based on the scanning electron microscope, the structure of BNA-R shown in Figure 1.

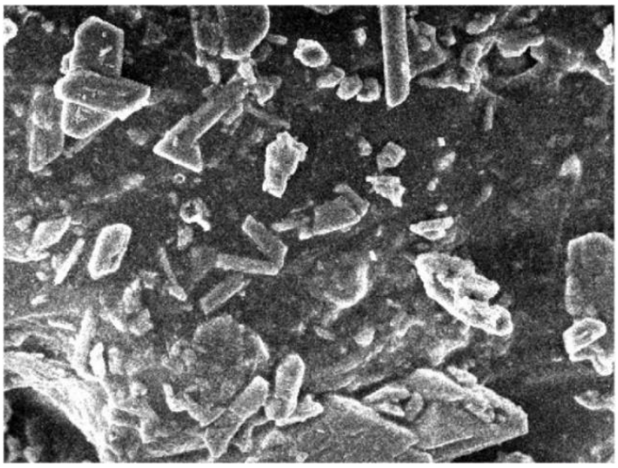

Fig 1. Structure of BNA-R (x1,000)

Table 2. Physical characteristics of modified asphalt

Properties	Virgin Asphalt	BAR 2.50%	BAR 5.00%	BAR 7.50%	BAR 10.00%	BAR 12.50%	BAR 15.00%	BAR 17.50%	BAR 20.00%
Penetration at 25 °C	64.2	58.8	55.6	54.8	52.40	51.1	50.8	45.8	46.9
Softening Point (°C)	51.5	51.7	52	52.3	53	53.3	53.75	54	54.25
Penetration Index (PI)	-0.219	-0.394	-0.459	-0.423	-0.366	-0.356	-0.266	-0.451	-0.341

II.3 Dynamic Shear Rheometer (DSR)

Rheology testing was conducted using an AR 1500 rheometer equipment to obtain rheological parameters such as G* (complex shear modulus), δ (phase angle) and G* / sin δ. The test was carried out under two conditions, before aging (original) and after aging with a rolling thin-film oven test (RTFOT). The first condition describes the first stage of the asphalt age during the process of transportation, storage, and handling. The asphalt aging process in a RTFO simulates the second stage, namely during the production and construction process or short-term aging. The temperature range of the DSR tests was 52 °C to 76 °C, with intervals of 6 °C.

The DSR tool used is shaped like a sandwich because it is pressed by two plates: on the top (oscillating plate) and at the bottom (static base). The top plate speed (oscillating plate) can be set to 10 rad/s. The DSR movement uses an angle frequency of 10 rad/s (1.59 Hz) which is intended to provide a shear force equivalent to a traffic speed of about 90 km/h.

III. RESULTS AND DISCUSSION

III.1 Master Curve and Black Diagram

The master curve of the asphalt stiffness modulus (E*) for unmodified and modified asphalt is shown in Figure 1. The asphalt rigidity (E*) can be calculated based on the complex shear modulus values, as shown in Eq. (4) [20].

$$E^* = 2G^* (1+ \upsilon) \qquad (4)$$

Where υ is the Poisson ratio, assumed to be equal to 0.5.

The modulus calculation results and complex modulus values with a variety of temperature changes are shown in Table 3.

Table 3. Effect of temperature and frequency on shift factor (Fr = 1.59 Hz)

No	Asphalt	Temperature (°K)	Log (α_T)	α_T	Log (α_T.Fr)	Complex Shear Modulus (G*) (Pa)	Stiffness Modulus (E*) (Pa)
1	Virgin Asphalt	325.15	-5.45	0.004	-5.25	30,840	92,520
		331.15	-6.05	0.002	-5.85	12,630	37,890
		337.15	-6.60	0.001	-6.40	5,292	15,876
		343.15	-7.11	0.001	-6.91	2,329	6,987
		349.15	-7.58	0.001	-7.37	1,088	3,264
2	(+ BNA-R 2.5%)	325.15	-5.45	0.004	-5.25	22,360	67,080
		331.15	-6.05	0.002	-5.85	8,936	26,808
		337.15	-6.60	0.001	-6.40	3,814	11,442
		343.15	-7.11	0.001	-6.91	1,733	5,199
		349.15	-7.58	0.001	-7.37	836	2,507
3	(+ BNA-R 5%)	325.15	-5.45	0.004	-5.25	23,850	71,550
		331.15	-6.05	0.002	-5.85	10,170	30,510
		337.15	-6.60	0.001	-6.40	4,448	13,344
		343.15	-7.11	0.001	-6.91	1,985	5,955
		349.15	-7.58	0.001	-7.37	939	2,817
4	(+ BNA-R 7.5%)	325.15	-5.45	0.004	-5.25	22,570	67,710
		331.15	-6.05	0.002	-5.85	9,853	29,559
		337.15	-6.60	0.001	-6.40	4,403	13,209
		343.15	-7.11	0.001	-6.91	2,008	6,024
		349.15	-7.58	0.001	-7.37	967	2,900
5	(+ BNA-R 10%)	325.15	-5.45	0.004	-5.25	23,550	70,650
		331.15	-6.05	0.002	-5.85	10,170	30,510
		337.15	-6.60	0.001	-6.40	4,524	13,572
		343.15	-7.11	0.001	-6.91	2,051	6,153
		349.15	-7.58	0.001	-7.37	983	2,949
6	(+ BNA-R 12.5%)	325.15	-5.45	0.004	-5.25	16,240	48,720
		331.15	-6.05	0.002	-5.85	7,024	21,072
		337.15	-6.60	0.001	-6.40	3,146	9,438
		343.15	-7.11	0.001	-6.91	1,441	4,323
		349.15	-7.58	0.001	-7.37	703	2,108
7	(+ BNA-R 15%)	325.15	-5.45	0.004	-5.25	17,210	51,630
		331.15	-6.05	0.002	-5.85	7,487	22,461
		337.15	-6.60	0.001	-6.40	3,353	10,059
		343.15	-7.11	0.001	-6.91	1,540	4,620
		349.15	-7.58	0.001	-7.37	754	2,263
8	(+ BNA-R 17.5%)	325.15	-5.45	0.004	-5.25	27,390	82,170
		331.15	-6.05	0.002	-5.85	11,840	35,520
		337.15	-6.60	0.001	-6.40	5,237	15,711
		343.15	-7.11	0.001	-6.91	2,386	7,158
		349.15	-7.58	0.001	-7.37	1,143	3,429
9	(+ BNA-R 20%)	325.15	-5.45	0.004	-5.25	29,230	87,690
		331.15	-6.05	0.002	-5.85	12,630	37,890
		337.15	-6.60	0.001	-6.40	5,609	16,827
		343.15	-7.11	0.001	-6.91	2,557	7,671
		349.15	-7.58	0.001	-7.37	1,228	3,684

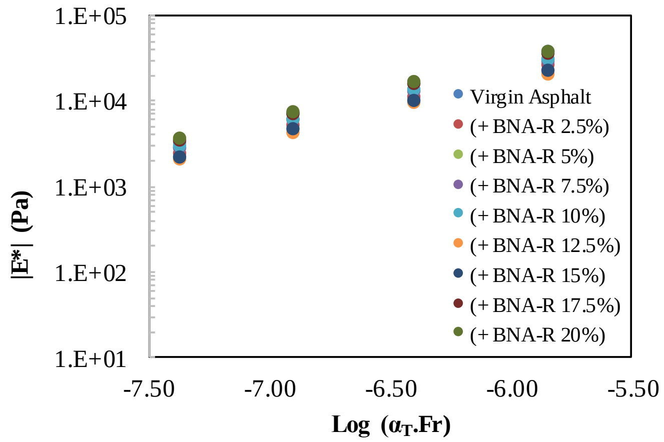

Fig. 2. Master curve

The master curve, |E*| plotted versus a reduced parameter X, where (X = log (αT.Fr)), gives the temperature-frequency dependence of the stiffness modulus for a fixed reference temperature. The advantage of this procedure is that once the master curve is established, it is possible to derive an interpolated value for the combination of temperature [20]. Fig. 2 shows the relationship between the stiffness modulus values and the log αT.Fr values at a frequency of 1.59 Hz.

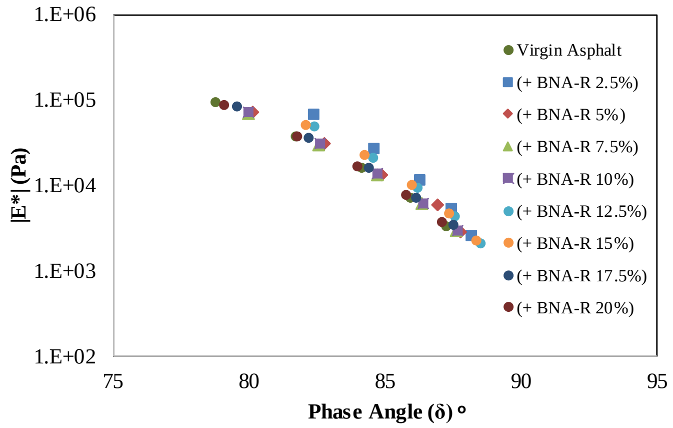

Fig. 3. Black diagram

The durability of asphalt can be evaluated from a black diagram, with the stiffness modulus (E*) and the phase angle (δ). From Fig. 3 shows the black diagram of the asphalt before and after modification. Asphalt with a low phase angle will last longer than asphalt with a high phase angle. The phase angle decreases as the BNA-R content increases. The addition of BNA-R increases the rigidity modulus of asphalt and decreases the phase angle. The modified asphalt is more durable than virgin asphalt.

The strength of asphalt concrete is essential to avoid rutting; asphalt requires a high stiffness modulus (high E*) and elasticity (low δ).

III.2 Complex Shear Modulus (G*) vs Temperature

The selected test temperatures are 52 °C, 58 °C, 64 °C, 70 °C, and 76 °C, in accordance with the climatic conditions of several places in Indonesia. The complex shear modulus (G*) increases with the addition of BNA-R and decreases when the test temperature increases show in Fig. 4. At the highest temperature (76 °C), the addition of BNA-R does not affect the complex modulus value. The benefits of adding BNA-R as an additive are the positive impacts on the value of the complex modulus at low temperatures. The performance grade (PG) of asphalt can be evaluated from the relationship between G* and the temperature. From Fig. 4, at a G* value of 1 kPa, which is the failure limit of asphalt, the temperature obtained for virgin asphalt is 64 °C. The addition of BNA-R to asphalt increased PG, as indicated by the higher temperatures achieved (more than 64 °C).

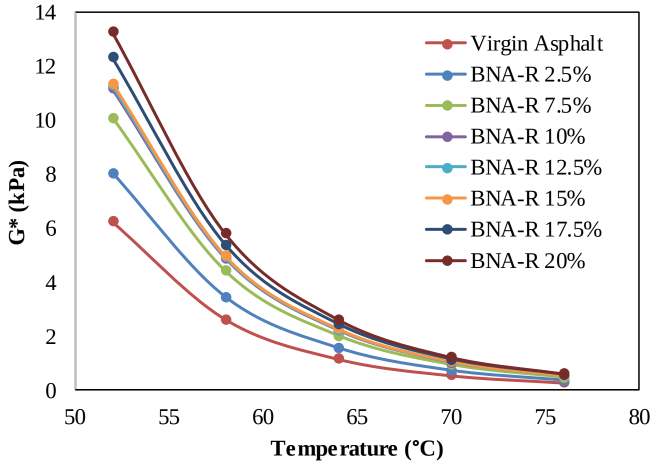

Fig. 4. Correlation of G* and temperature (unaged)

III.3 Phase angle (δ) vs. temperature

In contrast, the phase angle (δ) decreases with the addition of BNA-R and increases when the test temperature is higher. From Fig. 5 shows that the addition of BNA-R to asphalt Pen 64.2 causes the asphalt resistance to rutting to increase.

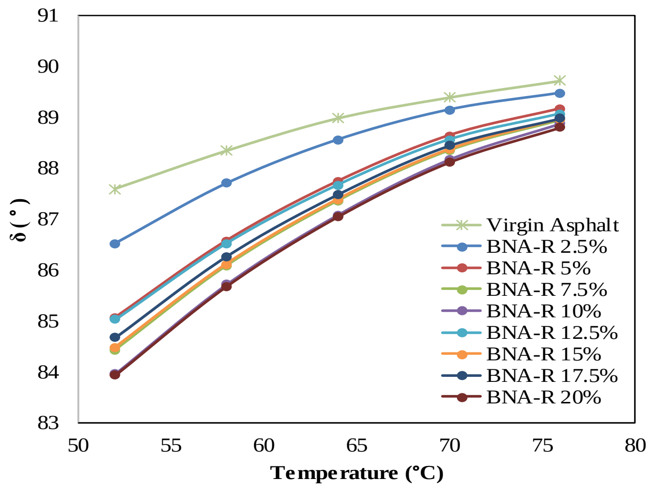

Fig. 5. Correlation of δ and temperature (unaged)

The decrease in phase angle values on BNA-R modified asphalt shows that the viscous component of asphalt decreases; this means that the asphalt becomes more elastic. Hence, the asphalt mixture will be more durable and resistant to rutting. This is also indicated by the values of the anti-rutting factor, with an increase in BNA-R content.

III.4 Shear Modulus (G*/Sin δ) vs Temperature

From Figs. 4-6 shows the temperature dependence of rheological parameters such as the complex shear modulus (G*), phase angle (δ), and shear modulus (G*/sin δ). As a viscoelastic material, asphalt can be evaluated via its complex shear modulus and phase angle. A higher value of the shear modulus shows that the asphalt becomes more rigid. The decrease in phase angle shows that the bitumen tends to be elastic. At low test temperatures, the addition of BNA-R to virgin asphalt shows a significant effect on the complex shear modulus values, as opposed to high test temperatures

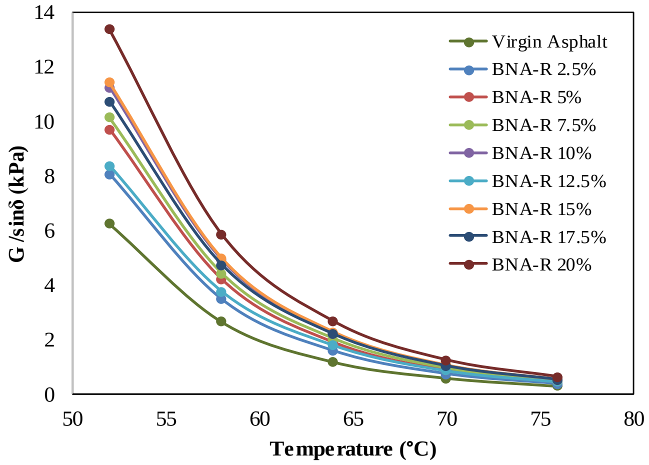

Fig. 6. Correlation of G*/sin δ and temperature (unaged)

III.5 Rolling Thin Film Oven Aged Asphalt

As mentioned above, RTFO was carried out to simulate short-term aging of asphalt caused by production and construction process. The value of the complex shear modulus after aging with RTFO is lower than that before aging. From Figs. 7-9 show the relationship between rheological parameters and the temperature for specimens subjected to RTFO. The temperature increase from 52 °C to 76 °C resulted in a decrease in the complex modulus (G*); on the contrary there is an increase in the phase angle value (δ). The RTFO changed the rheological properties of modified asphalt. BNA-R contents of17.5 % and 20 % resulted in complex modulus values that were almost the same as virgin asphalt for each temperature.

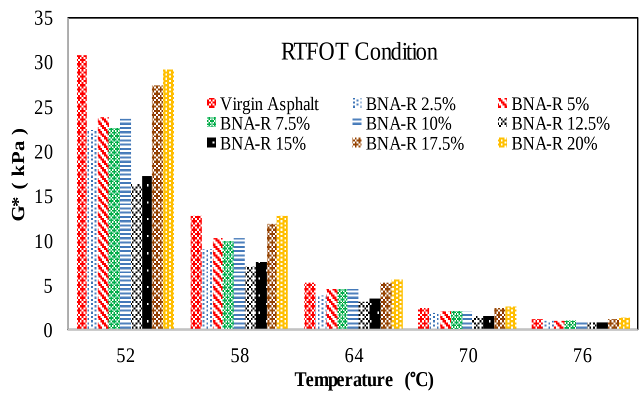

Fig. 7. Correlation of G* and temperature (RTFO aged)

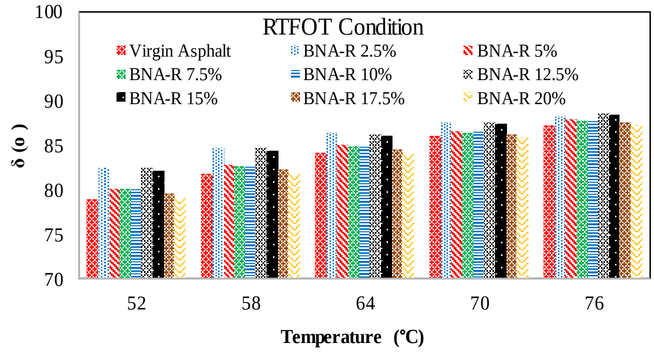

Fig. 8. Correlation of δ and Temperature (RTFO aged)

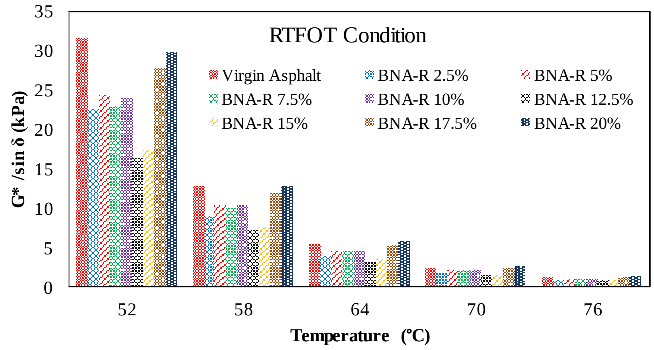

Fig. 9. Correlation of G*/sin δ and temperature (RTFO aged)

The process of mixing asphalt with aggregates in an asphalt mixing plant (AMP) results in aging; this process is simulated with RTFO in the laboratory. In this condition, the asphalt ages and the rheology behavior was changes. The rheology of modified asphalt that undergoes an aging process generally shows the same tendency as the original asphalt. The phase angle or the elasticity of asphalt is decreases with the addition of BNA-R.

III.6 Aging and Temperature Susceptibility

From Fig. 10 shows the value of the aging index (AI) obtained from the comparison between the G*/sin δ values for aged and un-aged asphalt, which can be used as a short-term rutting factor parameter. It is reported that a higher value of AI indicates a higher degree of aging susceptibility [11]. The addition of BNA-R to virgin bitumen decreases the AI value. The addition of 2.5 % BNA-R significantly reduced the AI compared to virgin asphalt. The decrease in the AI value continues up to BNA-R contents of 15 % (the lowest AI value) but the trend is reversed for BNA-R contents above 17.5%.

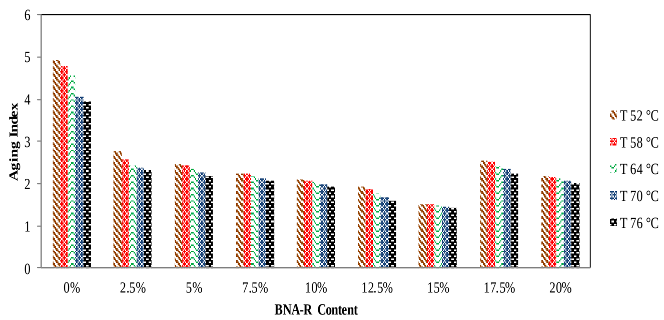

Fig. 10. Aging index of modified asphalt

The addition of 15 % BNA-R has a relatively constant AI value for temperatures from 52 °C to76 °C. The value of the rutting factor increased for BNA-R contents up to 15%.

IV. CONCLUSIONS

This study has been carried out to develop BNA-R modified asphalt by evaluating the influence of temperature on the samples. The increase in temperature on the modified asphalt surface is represented by the penetration index (PI), while the increase in temperature during the production and construction process is represented by the aging index (AI) factor. Based on the analysis of the DSR test results, the following conclusions can be drawn:

1. Local materials such as BNA-R, which is a product of Buton natural rock asphalt, can be used as asphalt modifiers with good results in terms of stiffness and flexibility. The stiffness modulus (E*) increases with increasing BNA-R content, the durability is also increased.
2. The addition of BNA-R to virgin asphalt makes it more elastic as evidenced by the decreasing phase angle of modified asphalt.
3. From the DSR and PI test results, it can be seen that a BNA-R content of 15 % shows the best performance.
4. In general, most of the performance of aggregate asphalt mixtures depends on the asphalt characteristics; the better the characteristics of the asphalt, the better the performance of aggregate asphalt mixtures used as pavement in new construction and maintenance applications.

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REFERENCES

[1] M. Jasso, R. Hampl, O. Vacin, D. Bakos, J. Stastna, and L. Zanzotto, "Rheology of conventional asphalt modi fi ed with SBS , Elvaloy and polyphosphoric acid," *Fuel Process. Technol.*, vol. 140, pp. 172–179, 2015.

[2] N. Saboo and P. Kumar, "Use of flow properties for rheological modeling of bitumen," *Int. J. Pavement Res. Technol.*, vol. 9, pp. 63–72, 2016.

[3] N. Suaryana, "Performance evaluation of stone matrix asphalt using indonesian natural rock asphalt as stabilizer," *Int. J. Pavement Res. Technol.*, vol. 9, no. 5, pp. 387–392, 2016.

[4] S. P. Hadiwardoyo, E. S. Sinaga, and H. Fikri, "The influence of Buton asphalt additive on skid resistance based on penetration index and temperature," *Constr. Build. Mater.*, vol. 42, pp. 5–10, 2013.

[5] N. Wahjuningsih, S. P. Hadiwardoyo, and R. J. Sumabrata, "Characteristics of permanent deformation rate of warm mix asphalt with additives variation (BNA-R and zeolite)," in *AIP Conference Proceedings*, 2017, vol. 1855.

[6] N. Anagi, S. P. Hadiwardoyo, R. J. Sumabrata, and N. Wahjuningsih, "Performance of skid resistance of warm-mix asphalt with buton natural asphalt-rubber (BNA-R) and zeolite additives as a result of road surface temperature changes," in *AIP Conference Proceedings*, 2017, vol. 1855.

[7] G. Dondi, V. Vignali, M. Pettinari, F. Mazzotta, A. Simone, and C. Sangiorgi, "Modeling the DSR complex shear modulus of asphalt binder using 3D discrete element approach," *Constr. Build. Mater.*, vol. 54, pp. 236–246, 2014.

[8] W. Zhao, F. Xiao, S. N. Amirkhanian, and B. J. Putman, "Characterization of rutting performance of warm additive modified asphalt mixtures," *Constr. Build. Mater.*, vol. 31, pp. 265–272, 2012.

[9] F. Morea, R. Marcozzi, and G. Castaño, "Rheological properties of asphalt binders with chemical tensoactive additives used in Warm Mix Asphalts (WMAs)," *Constr. Build. Mater.*, vol. 29, pp. 135–141, 2012.

[10] H. Kim, S. J. Lee, and S. N. Amirkhanian, "Rheology of warm mix asphalt binders with aged binders," *Constr. Build. Mater.*, vol. 25, no. 1, pp. 183–189, 2011.

[11] A. Kumar and M. Panda, "Investigation on rheological performance of sulphur modified bitumen (SMB) binders," *Constr. Build. Mater.*, vol. 149, pp. 724–732, 2017.

[12] G. Mazurek and M. Iwański, "Relaxation modulus of SMA with polymer modified and highly polymer modified bitumen," *Procedia Eng.*, vol. 172, pp. 731–738, 2017.

[13] X. Lu, P. Uhlback, and H. Soenen, "Investigation of bitumen low temperature properties using a dynamic shear rheometer with 4 mm parallel plates," vol. 10, pp. 15–22, 2017.

[14] J. Liu, K. Yan, and J. Liu, "Rheological properties of warm mix asphalt binders and warm mix asphalt binders containing polyphosphoric acid," *Int. J. Pavement Res. Technol.*, vol. 11, no. 5, pp. 481–487, 2018.

[15] Y. Q. Tan, L. Zhang, W. Q. Gong, and M. Guo, "Investigation of the effects of wax additive on the properties of asphalt binder," *Constr. Build. Mater.*, vol. 36, pp. 578–584, 2012.

[16] K. Z. Yan, H. Bin Xu, and H. L. Zhang, "Effect of mineral filler on properties of warm asphalt mastic containing Sasobit," *Constr. Build. Mater.*, vol. 48, pp. 622–627, 2013.

[17] S. W. Goh, M. Rosli, M. Hasan, and Z. You, "Performances Evaluation of Cecabase ® RT in Warm Mix Asphalt Technology," *Procedia - Soc. Behav. Sci.*, vol. 96, no. Cictp, pp. 2782–2790, 2013.

[18] Y. Li, S. Liu, Z. Xue, and W. Cao, "Experimental research on combined effects of flame retardant and warm mixture asphalt additive on asphalt binders and bituminous mixtures," *Constr. Build. Mater.*, vol. 54, pp. 533–540, 2014.

[19] M. Iwański, M. Cholewińska, and G. Mazurek, "Viscoelastic Properties of Polymer Modified Bitumen in Warm Mix Asphalt Technology in Terms of Ageing," *Procedia Eng.*, vol. 172, pp. 401–408, 2017.

[20] M. Partl and L. Francken, "Background of RILEM interlaboratory tests. Basic elements of a testing methodology for bituminuous pavement materials and significant features for testing," in *Bituminous Binders and Mixes - State of the Art and Interlaboratory Tests on Mechanical Behaviour and Mix Design*, New York: Taylor & Francis e-Library, 2005, pp. 5–6.