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Using advanced materials of granular BRA modifier binder to improve the flexural fatigue performance of asphalt mixtures

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Abstract

The objective of this research is to determine the effect on the flexural fatigue performance of asphalt mixtures of using granular Buton rock asphalt (BRA) modifier binder. A repeated flexural bending test under the controlled-strain mode of loading in accordance with Austroads AG:PT/T233 test method was conducted to examine fatigue behaviour of the BRA modified asphalt mixtures and the unmodified asphalt mixtures (as control mixtures) for a dense grading of 10 mm. Beam specimens were tested at the temperatures of 20°C and three different peak tensile strain (400, 600 and 800 με) and used classical and energy-stiffness ratio approach to analyse fatigue life of the asphalt mixtures. According to the test results, the fatigue lifes of the BRA modified asphalt mixtures were higher than that for the unmodified asphalt mixtures at the test temperature and tensile strain. Moreover, based on the initial flexure stiffness and phase angle values, BRA modified asphalt mixtures showed more elastic and less viscous behaviour than unmodified mixtures.

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Keywords: Granular BRA modified; asphalt mixtures; flexural fatigue performance.

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1. Introduction

The fatigue resistance of asphalt mixes is defined as the capability of the mixes to withstand the repetitive loading without any significant failure such as cracking or premature failure, developed under other circumstances such as environmental conditions. According to studies, fatigue cracking is a result in fatigue failure due to repetitive stress and strains caused by load and environmental factors which is considered as a major distress happening in asphalt

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mixtures [1-3]. The cracking is initially started from micro-crack and it then grows to form macro-crack and finally penetrate the surface of pavement [4].

According to Baburamani, generally, the factors influencing the fatigue cracking can be categorized as follows: loading variables (such as traffic speed, rest period, axle loads and axle distribution), environmental factors (such as temperature and ageing), construction variables, and materials characteristics [5]. Vazquez et al. stated that the most factors affecting the resistance to fatigue cracking of asphalt mixtures are asphalt binder grade, asphalt binder content, and air void content. Hence the adequate binder content and density should be used in asphalt mixtures to increase the resistance to fatigue cracking [6]. In addition, according to Guler [7] and Khiavi [1], binder type is considered as an important factor among the others such as aggregate gradation, aggregate type, binder content, compaction temperature, and traffic loading that can give a significant effect to fatigue life of the bituminous mixes.

The use and development of modified binders in asphalt mixes is important with the aim of increasing the fatigue performance. Many studies have carried out on asphalt mixtures to improve the resistance to fatigue failure. Polymer modified binder have been found to improve several properties of asphalt mixtures such as fatigue life [8-10]. Sibal *et al.* reported that the addition of crumb rubber obtained from waste tires in the form of fine aggregates increased the fatigue life of asphalt mixes [11].

This research considered the use of granular Buton rock asphalt (BRA) modifier binder as advanced materials with the aim to improve the fatigue performance of bituminous mixtures. The raw materials of granular BRA modifier binder are found in the island of Buton in Indonesia that is traditionally known as Asphalt Buton (Asbuton). A few researches have been done on the asphalt mixtures modified with Asbuton or Asbuton products. Zamhari *et al.* [12] conducted the laboratory research on asphalt mixtures using raw materials of Asbuton and found that the addition of Asbuton in a certain amount increased the stiffness modulus values and rutting performance. Affandi [13] reported that the stiffness modulus is increased and the temperature sensitivity of asphalt mixtures is improved by using BRA modifier binder semi-extraction. Other Asbuton products, for example, filler, were studied and resulted in an increase in the resilient modulus and rutting potential [14], and also in the fatigue performance of asphalt mixtures [15]. With the processing technologies have been developing in recent times, the granular BRA modifier binder are now produced. The developments have aimed to enhance the characteristics of granular BRA modifier binder to meet the requirements for use in asphalt mixtures, such as increased fatigue life. However, there is a lack of research conducted to develop the use of material derived from Buton Rock Asphalt on asphalt mixtures, especially in term of using granular BRA in asphalt mixtures. Hence, the main purpose of this study is to compare the fatigue performance for the unmodified and BRA modified asphalt mixtures, focused on analyzing by using the phenomenological and energy stiffness ratio approach.

2. Materials and methods

2.1. Asphalt binder

This research used a type of asphalt cement, C170, as the base asphalt binder, for unmodified asphalt mixtures. This binder is classified according to the Australian Standard AS 2008 [16]. Some properties of the base binder are shown in Table 1. In this study, BRA modified binder used for BRA modified asphalt mixtures consist of replacing 20% of the base asphalt binder (by total weight of asphalt binder in the mixtures) with 20% of the BRA natural binder, with the purposes of improving the resistance of BRA modified asphalt mixture to fatigue.

The form of granular BRA modifier binder was pellets with a size of 7 to 10 mm in diameter, as shown in Fig. 1. Three samples of granular BRA modifier binder were extracted in accordance with Standard WA 730.1-2011 [17]. The test results show that granular BRA modifier binders were composed of 70% mineral and 30% natural binder by total weight. The particle size distributions of BRA mineral are as follows: 2.36 mm (100%), 1.18 mm (97%), 0.6 mm (92%), 0.3 mm (81%), 0.15 mm (61%), 0.075 mm (36%).It can be seen that the maximum size of the mineral was 2.36 mm. Therefore the mineral is considered to be a fine aggregate because its diameter is less than 4.75 mm, and it can also be defined as a mastic binder because it contained a mineral size smaller than 2 mm [18].

Table 1. Properties of bitumen C-170.

Properties	Test Method	Value	Properties	Test Method	Value
Density, Kg/L	ASTM D-1298	1.03	Viscosity at 60°C, Pa.S	ASTM D-445	170
Flash point, °C	ASTM D-93	>250	Viscosity at 135°C, Pa.S	ASTM D-445	0.35

Fig. 1. The form of granular BRA modifier binder (pellets).

2.2. Aggregates

A crushed granite aggregate from a local quarry in Western Australia was used in all of mixtures. The coarse and fine aggregates required to prepare the mixes were obtained by sieving on each sieve diameter. One dense graded used for unmodified and BRA modified asphalt mixtures with maximum aggregate size of 9.5 mm were based on Specification 504 [19] used in Western Australia. Regarding the mineral content in the granular BRA modifier binder, in this study, the aggregate gradation of crushed aggregate for BRA modified asphalt below 2.36 was adjusted to accommodate the mineral content in the granular BRA modifier binder as shown in Table 2. Therefore, it was necessary that the weight of the crushed aggregate was reduced by the BRA mineral in order to minimize the variance of aggregate gradation. Thus, it was considered that the aggregate gradations of the unmodified asphalt mixtures and the final gradation of the BRA modified asphalt mixtures was the same as a constant parameter.

Table 2. Aggregate gradation used in this study.

Sieve size (mm)	Passing (%)				Lower-upper Limit [19], Passing (%)
	Unmodified mixtures	BRA modified mixtures			
	Crushed aggregate	Crushed aggregate	BRA mineral	Final	
13.20	100	100		100	100
9.50	97.5	97.5		97.5	95-100
6.70	83.0	83.0		83.0	78-88
4.75	68.0	68.0		68.0	63-73
2.36	44.0	44.0	100	44.0	40-48
1.18	28.5	28.6	99.9	28.5	25-32
0.60	21.0	21.2	99.8	21.0	18-24
0.30	14.5	15.0	99.5	14.5	12-17
0.15	10.0	11.0	99.0	10.0	8-12
0.075	4.0	5.7	98.3	4.0	3-5

2.3. Mix design and specimen preparation

The Marshall mix design method was carried out to determine the optimum binder content for control asphalt mixtures. According to Specification 504 [19], specimens of 101 mm diameter and 63.5 mm height were compacted by applying 75 blows to each side using an automatic Marshall compactor for various contents of asphalt binder. The optimum binder content (OBC) was determined as 5.4% by the weight of the mixture. In this study, the same binder content was used for the BRA modified asphalt mixtures and the unmodified asphalt mixtures in order to maintain consistency for comparison purposes (Table 3).

After the OBCs were determined, the BRA modified asphalt mixtures were manufactured as follows: First, dried hydrated lime was included in the blended aggregates in the form of anti-strip additives at a dose of 1.5% by weight of total aggregates in accordance with Specification 504 [19]. The blended aggregates were heated in a controlled temperature oven at 105ºC for at least 24 hours. Base asphalt binder and specific percentages of granular BRA modifiers binder (pellets) (Table 3) were put in a bowl together and then heated in another oven at 150±5ºC for 30 min to one hour with frequent manual stirring in order to blend and incorporate the two binders. Then the previously blended aggregates were put in the same bowl and mixed with the BRA modified asphalt binder using mixer equipment for 1.5 minutes. Laboratory mixtures were prepared based on the procedure for sampling loose asphalt described in Standard AS 2891.1.1-2008 [20], and then were immediately compacted in a slab mold by using a roller compactor in accordance with Austroads AG:PT/T220 [21]. After 24 hours prior to compaction process, slabs size of 400 mm in length, 400 mm in width and 100 mm in height, were then cut to produce the final beam specimens with dimensions 390±5 mm in height, 50±5 mm in depth and 63.5±5 mm in width.

Table 3. The composition of materials in asphalt mixtures.

	Percentage of materials (%) by total weight	
	Unmodified mixtures	BRA modified mixtures
1. Total binder content:	5.4	5.4
Base binder	5.4	4.3
BRA modifier binder	0.0	1.1
2. Total aggregate content:	94.6	94.6
Crushed rock	94.6	92.1
BRA mineral	0.0	2.5
3. Granular BRA modifier binder (pellets)	0.0	3.6

2.4. Repeated flexural bending test

Fatigue performance of unmodified and BRA modified asphalt mixtures in this study were performed using repeated flexural bending test under the controlled-strain mode of loading in accordance with Austroads AG:PT/T233 [22]. According to this test method, beam specimens were tested under the test conditions are as follows: test temperature of 20 ºC, loading frequency of 10 Hz, mode of loading is continuous haversine, peak tensile strain is 400, 600, and 800 $\mu\varepsilon$, and air void content is 5%.

Before each testing was started, the specimen was placed inside the device cabinet for two hours to ensure that the temperature recorded during the test was the temperature of the test specimen and to maintain the temperature during the test. Then, the specimen was positioned in the loading frame cradle and clamped at the four points to hold the specimen in place as seen in Fig. 2. After clamped and before the test was run, the specimen was allowed a minimum of 30 minutes to enable the specimen clamping stress to be relieved. Initially, the test specimens were conditioned through the application of 50 load cycles and then the calculation of the initial flexural stiffness was at the 50th load cycles.

3. Results and discussion

The tensile strain happened in the bottom of the asphalt layer is considered as a parameter controlling fatigue cracking. Therefore, many researchers have developed various concepts for evaluating fatigue resistance of mixes. Beam fatigue test is one of the most common methods used to study the fatigue behavior of bituminous mixes. Beam fatigue can be used to simulate the pattern of flexural stress found in situ and may reflect the weakness that may occur in the asphalt mixtures. Recently, three concepts are widely used to study fatigue failure criteria of asphalt mixtures, including the classical (phenomenological), fracture mechanics and damage energy approach [1,5,23-27]. Two loading modes carried out during the test are either in the controlled stress or in the controlled strain mode to simulate the real condition of pavement [1,26]. However, to find out the fatigue life of unmodified and BRA modified asphalt mixtures, this study used classical and energy ratio concepts, and control strain mode during the test.

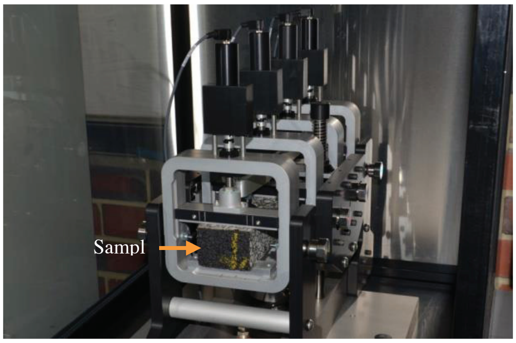

Fig. 2. The set-up of the repeated flexural bending test.

3.1. Initial flexural stiffness and phase angle

Table 4 summarizes the statistics analysis for air void content, initial flexural stiffness and phase angle, of unmodified and BRA modified asphalt mixtures. A paired sample t-test method with 95% level of confidence was used to statistically analyze using IBM SPSS statistic 21 program. Table 5 shows the mean, standard deviation (S), and coefficient of variation (CV) of void contents, initial flexural stiffness and phase angle for both unmodified and BRA modified asphalt mixtures. The CV values of both mixtures are maximum 10%. These same values of the initial flexural stiffness and phase angle are illustrated in Fig. 3.

As presented in Table 4, the difference in the initial tensile strain did not affect significantly the initial flexural stiffness values for both unmodified and BRA modified asphalt mixtures. However, comparison of unmodified and BRA modified flexural stiffness in the same strain level, indicates that the initial flexural stiffness of BRA modified mixtures was statistically significantly higher than for unmodified mixtures. The initial flexural stiffness for BRA modified asphalt mixtures at 400, 600, and 800 με was 71, 61, and 67%, respectively, higher than for unmodified asphalt mixtures as seen in Fig. 3, and that the behavior of the BRA modified mixtures at a given initial tensile strain and measured at loading frequency of 10 Hz was more elastic.

The density of asphalt mixtures was related to fatigue cracking potential [28]. Baburamani [5] stated that compaction level (air voids) achieved in the mix affect the flexural stiffness and fatigue life of the asphalt mixtures. Hence, the beam fatigue samples in this study were provided with statistically the same density (air voids) with the aim to limit the effect of density on flexural stiffness as seen in Table 4.

Table 4. A paired *sample t-test* results of air voids, initial flexural stiffness, and phase angle.

Asphalt mixtures	Initial tensile strain (με)	Air void				Initial flexural stiffness				Phase angle			
		t	df	Sig. (2-t)	d	t	df	Sig. (2-t)	d	t	df	Sig. (2-t)	d
Unmodified	400 – 600	1.7	2	0.225	1.75	-0.3	2	0.779	-0.18	-0.196	2	0.862	-0.19
	400 – 800	0.5	2	0.667	0.49	-2.6	2	0.118	-1.53	-0.206	2	0.856	-0.21
	600 – 800	-0.8	2	0.529	-0.75	-0.8	2	0.484	0.49	0.813	2	0.502	0.47
BRA modified	400 – 600	-2.0	2	0.184	-2.03	0.2	2	0.831	0.14	-4.223	2	0.052	-4.22
	400 – 800	-2.0	2	0.184	-2.03	-2.8	2	0.106	-1.63	-1.623	2	0.246	-1.62
	600 – 800	0.0	2	1.000	0.00	2.3	2	0.151	1.31	1.623	2	0.246	1.62
Unmodified-BRA modified	400	3.4	2	0.074	3.46	-8.8	2	0.013	-5.09	14.321	2	0.005	14.33
	600	1.0	2	0.423	1.00	-16.3	2	0.004	-9.42	5.657	2	0.030	5.66
	800	1.7	2	0.225	1.73	-16.6	2	0.004	-9.58	8.738	2	0.013	8.73

Fig. 3 also shows the phase angle of unmodified and BRA modified in a given initial tensile strain. The phase angle for the two asphalt mixtures did not indicate sensitivity to initial tensile strain, while the phase angle values for the unmodified mixtures are significantly higher than the values obtained for the BRA modified mixtures for a given initial tensile strain (Table 4), which means the BRA modified mixtures show less viscous behavior than the unmodified mixtures.

Table 5. Air void, initial flexural stiffness and phase angle of asphalt mixtures.

Asphalt mixtures	Initial tensile strain (με)	Air void (%)			Initial flexural stiffness (MPa)			Phase angle (degree)		
		Mean	S	CV	Mean	S	CV	Mean	S	CV
Unmodified	400	5.1	0.06	1.1	5044	509	10.0	33.8	2.4	7
Unmodified	600	5.0	0.06	1.1	5155	174	3.4	34.1	0.3	1
Unmodified	800	5.1	0.10	2.0	5365	309	5.7	33.7	1.1	3
BRA modified	400	4.9	0.06	1.2	8639	197	2.3	21.9	0.9	4
BRA modified	600	5.0	0.00	0.0	8562	396	4.6	25.9	2.6	10
BRA modified	800	5.0	0.10	2.0	9002	135	1.5	22.8	1.1	5

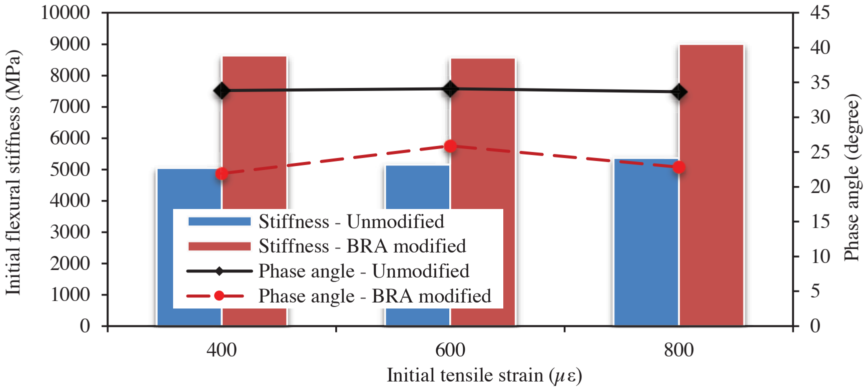

Fig. 3. The initial flexural stiffness values for unmodified and BRA modified asphalt mixtures.

3.2. Fatigue life

The results of the flexure fatigue tests obtained in this study were analyzed using the classical approach and energy stiffness ratio method developed by Abojaradeh [29]. In classical method, failure point is assumed as the number of loading corresponding to the 50% reduction of initial flexural stiffness. Furthermore, the energy stiffness ratio method defines energy stiffness ratio as the ratio of the flexure stiffness at cycle-*i* (S_i) to the initial flexure stiffness (S_o) multiplied by the load cycle value at cycle-*i* (N_i) as shown by Equation 1. Fatigue failure is defined as the number of cycles where the energy stiffness ratio produces a peak value, by plotting the energy stiffness ratio *versus* the number of load cycles. The results of the fatigue lives using both approaches are summarized in Table 6. It can be seen that the BRA modified asphalt mixtures shows 1.5 – 2.7 times higher fatigue lives when compared to unmodified asphalt mixtures. The flexural stiffness ratio values (S_{Nf}/S_0) obtained by using energy-stiffness ratio method were 38.0-45.9 for unmodified asphalt mixtures and 46.3-49.3 for BRA modified asphalt mixtures.

$$Energy\ stiffness\ ratio = \frac{N_i\ x\ S_i}{S_o} \qquad (1)$$

Table 6. Fatigue life of unmodified and BRA modified asphalt mixtures (cycles).

Initial tensile strain (με)	Classical		Energy ratio		Flexural stiffness ratio	
	Unmodified	BRA modified	Unmodified	BRA modified	Unmodified	BRA modified
400	122,550	324,830	149,040	348,060	43.9	47.5
400	142,880	293,980	168,520	332,400	45.2	46.3
400	138,030	301,990	171,780	345,400	44.0	49.3
600	39,000	95,400	61,030	98,050	38.1	48.7
600	35,570	72,540	47,610	75,150	41.8	48.2
600	53,420	88,000	60,100	91,650	45.9	48.4
800	11,420	23,250	13,200	24,300	44.7	47.5
800	8,770	21,550	11,920	22,650	38.0	47.8
800	8,660	24,000	10,850	25,200	42.0	49.2

3.3. Fatigue life prediction

In this study, the strain approach and strain-mix stiffness approach are used to predict the fatigue life of unmodified and BRA modified asphalt mixtures. A simple form of strain approach model was established for control strain test using the linier regression analysis between fatigue life logarithm (log N_f) and the initial strain logarithm (log ε_t). The strain approach model can be represented as Equation 2 [8,30-32]. Furthermore, as cited in Baburamani, asphalt mixtures stiffness strongly influenced the critical horizontal strain or stress due to traffic load in the asphalt layer. The incorporating of applied strain and the stiffness in the mix were expressed as Equation 3 [5].

$$N_f = a\left(\frac{1}{\varepsilon_t}\right)^b \qquad (2)$$

where N_f is number of repetition to failure, a and b are regression coefficients, and ε_t is initial tensile strain applied.

$$N_f = A\left(\frac{1}{\varepsilon_t}\right)^b\left(\frac{1}{S_{mix}}\right)^c \qquad (3)$$

where N_f is number of cycles to failure, ε_t is the tensile strain, S_{mix} is the initial asphalt mix stiffness, and A, b, and c are regression constant.

Based on the Equation 2, the relationship between fatigue life and initial tensile strain for unmodified and BRA modified mixtures are shown in Fig. 4. Further, the fatigue life from three replicates of each initial tensile strain for unmodified and BRA modified were plotted in the format X-Y plots. Using a power regression, regression equations were developed between fatigue life - initial tensile strain for unmodified and BRA modified asphalt mixtures. The developed regression equations for every mixture are presented in Table 7. From Fig. 4, it can be concluded that for a given initial tensile strain, the BRA modified mixtures results in a longer fatigue life compared to unmodified asphalt mixtures tested at 20 °C. Furthermore, Awanti *et al.* described that the tensile strains at the bottom of bituminous layer in a typical pavement are about 30 to 200 $\mu\varepsilon$ under a standard axle load [8]. Hence, for this reason, using fatigue life-initial tensile strain (Table 7) the fatigue lives of unmodified and BRA modified were compared at 200$\mu\varepsilon$ levels. It was found that at testing temperature of 20°C, the BRA modified asphalt mixtures shows 1.91 times higher fatigue lives when compared to unmodified asphalt mixtures. Furthermore, comparing the fatigue lives obtained by using strain method and strain-stiffness method as seen in Table 7, the strain-stiffness method shows about 10% longer fatigue lives than strain method in both classical and energy approach.

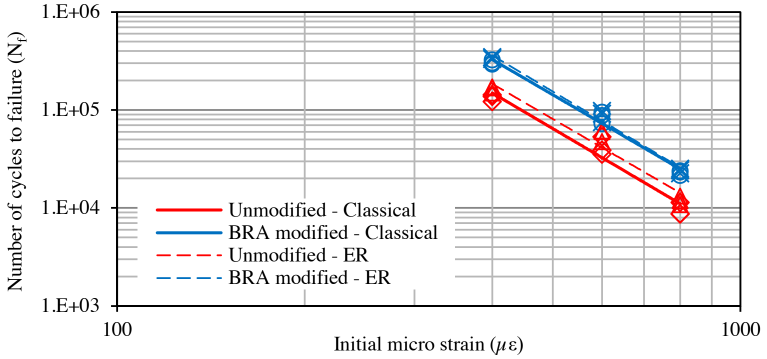

Fig. 4. Fatigue characteristics of unmodified and BRA modified asphalt mixtures.

Table 7. Regression equation developed for unmodified and BRA modified asphalt mixtures

	Classical				Energy ratio			
Asphalt mixtures	Strain method		Strain-stiffness method		Strain method		Strain-stiffness method	
	Equation	R2	Equation	R2	Equation	R2	Equation	R2
Unmodified	Nf =8.662E+14(ε)-3.752	0.958	Nf=1E+17.708(ε)-3.711(Smix)-0.770	0.937	Nf = 7.534E+14(ε)-3.694	0.953		
BRA modified	Nf = 1.430E+15(ε)-3.705	0.984			Nf = 2.777E+15(ε)-3.800	0.988		

4. Conclusion

It is important to note that the bitumen type used in the asphalt mixtures has an important influence on the fatigue life of the asphalt mixtures. Results from this study showed that the granular BRA modifier binder was beneficial in term of improved fatigue lives of asphalt mixtures. Results also indicated that BRA modified asphalt mixtures showed more elastic and less viscous behavior. In addition, using two methods, strain and strain-stiffness methods, it was found that the initial flexural stiffness influenced the longer fatigue lives of asphalt mixtures.

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