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Evaluation of Permanent Deformation of BRA Modified Asphalt Paving Mixtures Based on Dynamic Creep Test Analysis

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Abstract. The main objective this study is to evaluate the permanent deformation of buton rock asphalt (BRA) modified asphalt paving mixtures using dynamic creep test so that long term deformation behavior of asphalt mixtures can be characterized. The dynamic creep test was conducted on unmodified and BRA modified asphalt mixture using UTM25 machine. Asphalt cement of C170 from a regional supplier in Western Australia was used as the base asphalt binder for unmodified asphalt mixture; and BRA modified asphalt mixtures were made by substituting the base asphalt with 10, 20, and 30% (by weight of total asphalt binder) natural binder continuing granular BRA modified binder. The granular (pellets) BRA modified binder with a diameter of 7-10 mm was produced and extracted according the Australia Standard. Crushed granite was taken from a local quarry of the region; and dense graded for both unmodified and BRA modified asphalt mixture with the nominal size of 10 mm was used. The results of this analysis showed that BRA modified had a good performance as compared with unmodified asphalt mixtures, and increase in the content modified binder to 10%, 20%, and 30% resulted in decrease of the total permanent strain.

Introduction

Pavements are an important part of highway transportation infrastructure that constitutes an enormous investment of public funds [1, 2]. A tremendous of time and money is spent each year on construction of new and existing asphalt pavements [2, 3]. However, Permanent deformation is considered as one of the most common form of distressed associated with the load, and affects the pavement performance of asphalt mixtures. Mokhtari and Moghadas Nejad [4] investigated the performance of asphalt mixtures using the mechanistic approach for fiber and polymer modified SMA mixtures and realized that the quality of asphalt mixture and mechanical properties of other layers has significantly affected by the amount of depression.

Permanent deformation refer to the plastic deformation of flexible pavement under repeated loads [5]. An approach to determine the permanent deformation characteristics of asphalt paving materials is to employ a repeated dynamic load test for several repetitions and record the accumulated permanent deformations as a function of the number of loading cycles (repetitions) over the testing period as stated by [5, 6].

Permanent deformation (rutting) of asphalt pavement has a major impact on pavement performance. Rutting reduces the useful service life of the pavement and, by affect vehicle handling characteristics, creates serious hazards for highway users [7]. Sousa, Craus and Monismith [8] summarized a report on permanent deformation in asphalt concrete and stated that highway materials engineers have been handicapped in their efforts to provide rutting resistance material in that existing methods for testing and evaluating asphalt-aggregate mixture are empirical and do not give a reliable indication of in service performance.

It is believed that the permanent deformation, commonly referred to rutting, which is caused by the accumulation of fatigue damage of unrecoverable deformation on the asphalt pavement concrete under repetitive traffic loading during a period of time [9-11]. Similarly, Apeagyei [12] stated that temperature and loading effects were most affected to rutting. On high temperature and long period of loading, the asphalt binder behaves lime viscous and then, lead to two types of mechanical response: viscous flow and plastic deformation. And finally lead to the occurrence of rutting in asphalt mixtures. Plastic deformation occurs when aggregate particles move each other and then followed by viscous flow in asphalt binder [13].

However, aggregate, asphalt binder, and air void are considered as three components of asphalt mixtures which influence the rutting performance. Improving the material properties and mix characteristics is essential in improving the rutting resistance of asphalt mixtures. Brown [14] stated that permanent deformation is influenced by the aggregate grading and particle characteristic.

It is also important to assess the rut depth regarding the change of the void content in asphalt layer. When air void content decreases below 2-3%, due to the densification by traffic load, the binder acts as a lubricant between the aggregates and reduced contact point between them. This causes the permanent deformation occurs in the form of either in volume or in shear, which is depends on the hot temperature or heavy loads [15].

The main objective of this study is to evaluate the permanent deformation of buton rock asphalt (BRA) modified asphalt paving mixtures using dynamic creep test so that long term deformation behavior of asphalt mixtures can characterized.

Rutting Mechanism and Characterization

Rutting is one of the predominant types of distress observed in hot-mix asphalt [7]. Mallick, Ahlrich and Brown [16] used a dynamic creep to predict rutting. To evaluate the potential of dynamic creep, tests were conducted on the mixture of different aggregates and aggregates graduations to identify mixes with rutting potential. From the results that were obtained, there a good correlation between permanent creep strain and rutting rates of pavements. The dynamic creep test was able to quantify the effect of aggregate type and graduation on rutting potentials of the mixes [16]. Mixes with crushed aggregate performed better in dynamic creep test than with uncrushed aggregate.

According to studies [10, 11, 17], permanent deformation in asphalt pavement has involved two different rutting mechanisms: initial rutting/compactive deformation and secondary rutting/plastic deformation. Initial rutting or compactive deformation is the first stage of rutting, which is caused by the densification of asphalt mixtures for the first year of pavement life. The initial rutting is then followed by secondary rutting, which is also known as shear flow deformation or plastic deformation. Shear flow deformation occurs in well compacted asphalt mixtures as a primary mechanism of rutting and caused a huge impact to threaten the serviceability life time of the pavement. Normally, shear flow is caused by the insufficient shear strength to support the stress.

In the first mechanism (initial rutting), the deform surface is lower than the initial pavement surface, and the wheel path is occurred. In the second mechanism (secondary rutting), the material moves from under the wheel path to between and outside wheel path and causes upheaval on the side [10, 17]. The volume decrease under the wheel path is approximately equal to the volume increase in the upheaval zone. This indicates that most of compaction on the first mechanism is completed and further rutting is caused essentially by the second mechanism.

Dynamic creep test is one of the most commonly employed methods for assessing the mechanism of rutting [10, 11] and was used to observe the permanent deformation/rutting resistance of asphalt mixtures [18-20]. The results of dynamic creep test can be used to characterize the long term deformation behavior of asphalt mixtures. According to Kalyoncuoglu and Tigdemir [17] the creep test had a capability to have a good correlation with measured rut depth and rutting potential estimation of asphalt layer. Rutting on creep failure is a function of time. As viscoelastic materials, the permanent strain component (ε_p) found to follow a simple power model as a function of the number of loading cycles as shown in Equation 1 [21]:

$$\varepsilon_p = a \text{ x } N^b \quad (1)$$

where: ε_p is the accumulated permanent strain due to dynamic vertical loading, a and b is the regression constants, and N is the number of load applications that produced ε_p.

The curve of total permanent strain against number of loading cycles is the most important output of the dynamic creep test. As adopted from [4, 10, 22, 23], the curve was divided into three distinct zones: primary, secondary, and tertiary zone as shown in Figure 1. This figure shows the accumulated strain increases rapidly during the primary zone because of rearrangement of the structure of the asphalt mixtures and thus the volume of asphalt mixtures decreases subject to the densification. Zhou and Scullion described that many defects in asphalt mixtures occurred such as air voids, dislocations in the aggregates and asphalt binder dominated during the primary stages. Under repeated loading, the asphalt mixtures work hardens with the accumulation of pavement strain and then lead the micro cracks initiate and grow [23]. In the secondary zone, the relationship between the number of loading cycles and accumulated strain is linear (constant). The occurrence of micro cracking lead the dislocation in the aggregates to develop and bring about further the asphalt mixtures to become less hard [23]. This zone is identified as a transition zone between the primary and tertiary zone.

In the tertiary zone, the accumulated strain starts to increase again, where this zone is referred to as appearance of the second mechanism of rutting in which the shear deformation starts and rutting (rate of deformation) is increased with each load repetition until failure is reached. Zhou and Scullion stated that the micro cracks propagation is gradually in this stage and coalesce to form macro cracks when loading in continued [23]. According to Alavi et al. [24], the point at which the tertiary zone in creep curve begins is called the flow point, where the minimum slope is found. The corresponding number of cycles to flow point is referred to flow number (FN).

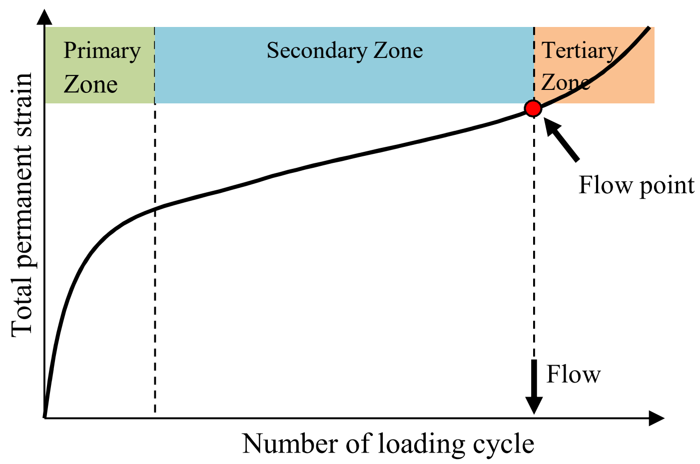


Fig. 1. The curve of total permanent strain versus number of loading cycle

Flow Number (FN)

The concept of flow number has been widely used to determine the characteristics of permanent deformation. Many studies were performed to assess the rutting performance of asphalt mixture using the permanent strain curve and used flow number as an indicator for evaluating the resistance to permanent deformation. Mokhtari and Nejad [4] performed experiment and used the flow number to investigate the service life of six different stone mastic asphalts. Permanent strain and creep modulus was used to evaluate SBS and other different asphalt mixtures [4, 25]. According to Witczak et al. [26], the point at which the tertiary stage initiates is the most important point that determines the rutting performance of asphalt mixtures and regression parameters related to the constant strain rate in the secondary stage shower fair and good correlation with field performance data.

Goh and You [22] developed a simple stepwise method to determine and evaluate the initiation of tertiary zone (flow point) for asphalt mixtures. The method includes the three simple steps to determine the flow number from a curve of permanent strain versus loading cycle. These steps are including: (1) reallocate the measured results of permanent deformation to smooth the curve trend of strain versus loading cycle; (2) determine the strain rate at each loading cycle; (3) establish the flow number by correlating the minimum point of strain rate to the number of loading cycle. Based on the stepwise concept, a sample of determining the flow number is shown in Figure 2.

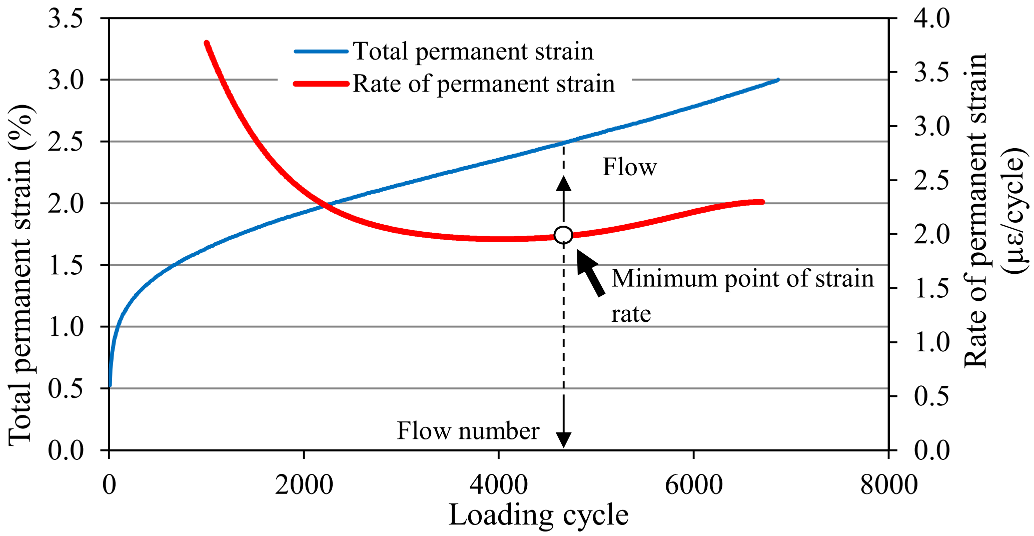


Fig.2. Determining flow point using a simple stepwise method

Goh and You [22] also reported that rate of deformation (slope of secondary flow) had a good correlation with the permanent deformation. They indicated that the flow number of an asphalt mixture is able to compute using the rate of deformation at various temperature and air voids level using Equation 2 below.

$$Flow\ Number = a\ x\ (FN_{Slope})^{b} \tag{2}$$

where, a and b is the regression coefficient, and FN_{Slope} is the rate of deformation (slope of secondary flow). On top of this, other output of the dynamic creep test is resilient modulus and creep modulus. The resilient modulus and creep modulus can be calculated using the formula in Equation 3 and 4 [11]:

$$M_r = \frac{\sigma_d}{\varepsilon_r} \tag{3}$$

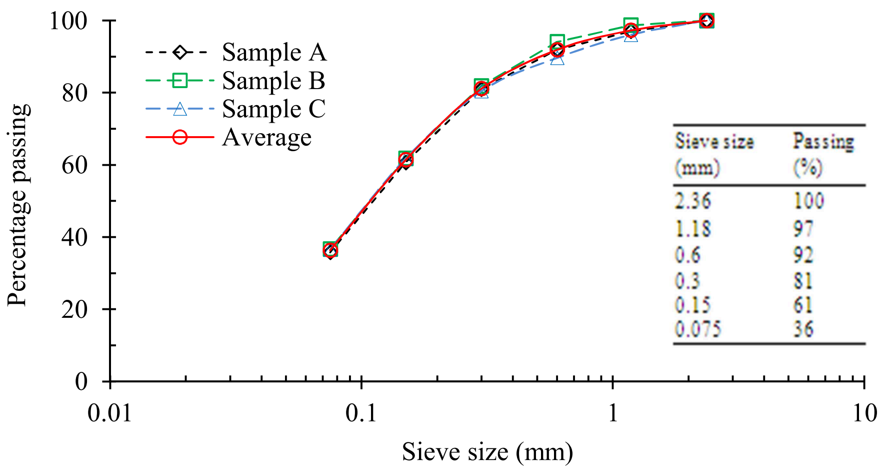
$$M_c = \frac{\sigma_d}{\varepsilon(t)} \tag{4}$$

where, σ_d is the deviator stress (kPa), ε_r is the resilient deformation at a certain number of load application (μs), and $\varepsilon(t)$ is the total deformation including elastic, visco-elastic, plastic, and visco-plastic deformation.

Materials

Asphalt Binder. Asphalt cement of Class 170 (Pen 60/80), from a regional supplier in Western Australia was used as the base asphalt binder for unmodified asphalt mixtures; it classified according to the Australian Standard AS-2008 [27]. In this study, BRA modified asphalt mixtures were made by substituting the base asphalt binder with 10, 20, and 30 % (by weight of total asphalt binder) natural binder containing granular BRA modifier binder. The form of the BRA modifier binder used in this study was granular (pellets) with a diameter of 7-10 mm as shown in Figure 3. Three portion of samples of granular BRA modifier binder were extracted following the standard WA 730.1-2011 [28] and the results showed that the granular BRA modifier binder was composed of 70% mineral and 30% natural binder by total weight. The particle size distributions of BRA mineral are shown in Figure 4.

Fig. 3. The form of granular BRA modifier binder used in this study



Sieve size (mm)	Passing (%)
2.36	100
1.18	97
0.6	92
0.3	81
0.15	61
0.075	36

Fig. 4. Particle size distribution of BRA mineral

Aggregates. One sourced of crushed granite, from a local quarry in Western Australia, was used for all of the asphalt mixtures. One dense graded used for unmodified and BRA modified asphalt mixtures with nominal size of 10 mm were based on Specification 504 used in Australia [29]. In this study, the BRA modified asphalt mixtures were designed according to the fact that the granular BRA modifier binder was composed of 70% minerals. Table 1 shows that in the BRA modified asphalt mixtures, the substitution of the base asphalt binder allowed the proportion of fines passing 2.36 mm to be adjusted. The total weight of the crushed aggregate was reduced by the minerals contained in the granular BRA with the aim of minimizing the variance in the gradation of the aggregates. The percentage of crushed aggregate in the BRA modified asphalt mixture for dense graded 10 mm was decreased by increasing the percentage of granular BRA modifier binder.

Table 1. Final crushed aggregate gradation

Sieve size (mm)	Dense grading10 mm, Passing (%)				Lower-upper Limit [(c)], Passing (%)
	Unmodified asphalt mixes[(a)]	BRA modified[(b)]			
		10%	20%	30%	
13.20	100	100	100	100	100
9.50	97.5	97.5	97.5	97.5	95-100
6.70	83.0	83.0	83.0	83.0	78-88
4.75	68.0	68.0	68.0	68.0	63-73
2.36	44.0	44.0	44.0	44.0	40-48
1.18	28.5	28.5	28.6	28.6	25-32
0.600	21.0	21.1	21.2	21.3	18-24
0.300	14.5	14.8	15.0	15.2	12-17
0.150	10.0	10.5	11.0	11.5	8-12
0.075	4.0	4.9	5.7	6.4	3-5
Crushed aggregate [(d)] (%)	100	98.6	97.4	92.2	

(a) The gradation used for control asphalt mixtures as a target gradation in middle point of limit values.
(b) The gradation used for BRA modified asphalt mixtures in three different percentages of BRA modifier binder by weight of total asphalt binder.
(c) Limit values in accordance with Specification 504 [29].
(d) Crushed aggregate remaining in the mixture by weight of total aggregate.

Methods

Mix Design and Specimen Preparation. The Marshall mix design method was used for determining the optimum binder content for the unmodified asphalt mixtures in accordance with Specification 504 [29]. Three specimens with dimension of 101 mm diameter and 63.5 mm height were produced with compacting energy of seventy-five blows applied to each side. The binder range region was 5.0 to 6.0% with 0.5% increment. The optimum binder content was determined as 5.4% by weight of the mixtures. BRA modified asphalt mixtures were used the same binder content as the unmodified asphalt mixtures in order to maintain consistency for a comparison purposes. The proportion of materials that were used in asphalt mixtures is shown in Table 2.

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 antistrip additives at a dose of 1.5% by weight of total aggregates [29]. The blended aggregates were heated in a controlled temperature oven at 160ºC for at least 12 hours. Base asphalt binder and specific percentages of granular BRA modifiers binder (see Table 4) were put together in a bowl 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. And 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. The aggregates mixtures in laboratory experiment were prepared based on the procedure for sampling loose asphalt that was described in AS 2891.1.1-2008 [30] and then, were immediately compacted.

Table 2. Proportion of Materials Used in Asphalt Mixtures

Asphalt mixture components	Percentage by total weight of mixtures (%)			
	Unmodified asphalt mixtures	BRA Modified asphalt mixtures		
		10%	20%	30%
1. Base asphalt binder	5.4	4.9	4.3	3.8
2. BRA modifier binder	0.0	0.5	1.1	1.6
Total binder content	*5.4*	*5.4*	*5.4*	*5.4*
3. Crushed aggregate	94.6	93.3	92.1	91.0
4. BRA mineral	0.0	1.3	2.5	3.6
Total aggregate content	*94.6*	*94.6*	*94.6*	*94.6*
Granular BRA (Pellets) (%)	*0.0*	*1.8*	*3.6*	*5.2*

Dynamic Creep Test. Dynamic creep test is one the most commonly employed methods for assessing the mechanism of rutting. Dynamic creep test can be used to characterize the long term deformation behavior of asphalt mixture [31]. Dynamic creep test has a various potential outcomes [16] that can be used as a measure of evaluation of permanent deformation.

The UTM25 was used in this test, and based on standard AS 2891.12.1-1995 [32], cylindrical specimens 100±2 mm in diameter and 50±2 mm in height were prepared and a gyratory compactor was used to compact the specimens. The compactions were performed at a gyratory angle of 2º and vertical loading stress of 240 kPa. Before testing was carried out, the specimen was positioned in the loading frame between two circular steel platens. The specimens were placed inside a temperature–controlled cabinet at the required test temperature of 50ºC for at least two hours so that the temperature in the specimen reached equilibrium. The specimens were then exposed to uniaxial and periodically repeated loading using an upper platen under the following conditions: a compressive stress of 200 kPa, loading period of 0.5 s and pulse repetition period of 2.0 s. The test was terminated at 30,000 maximum cyclic counts or 3% accumulative axial strain. Three replicate specimens for the mixtures were prepared and the test frame is shown in Figure 5.

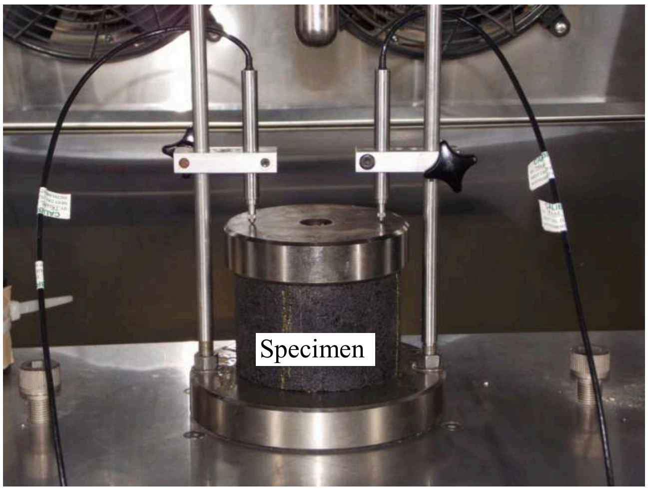


Fig.5. Sample in container under dynamic creep test

Result and Analysis

The permanent compressive strain versus loading cycle curve after fitted is shown in Figure 6. The total permanent compressive strain was calculated from average of three replicates apart two replicates for BRA modified continuing 30% BRA modified asphalt mixtures using a power regression. From the data presented, it can be seen that the testing process for BRA modified continuing 30% BRA modifier binder were automatically stopped after reaching about 30,000 loading cycles. Although the loading cycle were set to reach 3% of total permanent strain for both unmodified and BRA modified binder however, BRA modified continuing 30% BRA modifier binder was not exceeded the standards limit of 3%. This indicates that the binder might have a poor performance mixes that cause failure due to high temperature.

Mixes with highly modified binders often do not achieve a minimum slope before 40, 000 cycles have elapsed. For such kind of asphalt mixes, the minimum slope can occurs at end of the test. Austroads [33] reported in the guide for testing asphalt that a high minimum slope in asphalt modified asphalt mixtures could perform as a result of poor performance asphalt mixes. A pair t-test method with 95% confidence level was used to statistically analyze the mean of the voids and it was found no significant difference in voids for unmodified and BRA modified asphalt mixtures, while the air content were within the range of 5.0±0.5% according Australian Standard [34]

Comparing the number of cycles to achieve 3% accumulation axial strain as shown in Table 3, the BRA modified required a higher number of cycles than unmodified. The increase in the content of BRA modifier binder to 10, 20, and 30% resulted in an increase of the number of cycles to 471, 963, and 1478%, respectively. This indicates that modifying asphalt binder with granular BRA modifier binder decreases the temperature sensitivity of asphalt mixtures. This shows that BRA modified has a lower dependency of permanent deformation on temperature than that of unmodified asphalt mixtures.

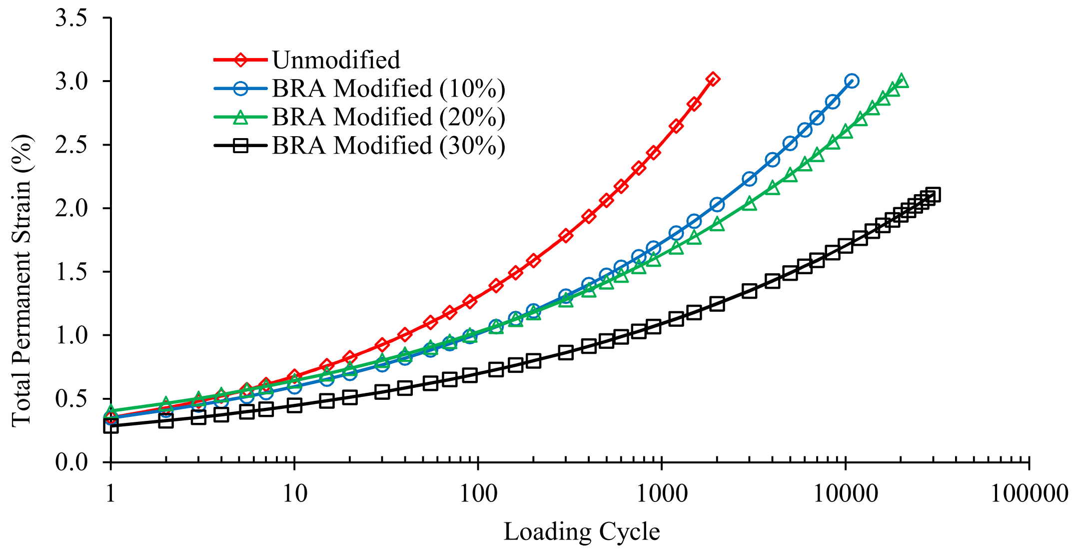


Fig. 6. Permanent strain progression curve during the test after fitted

Apeagyei [12] stated that temperature sensitivity and loading effects are one of the most that caused rutting. For example, when temperature is high in a modifying asphalt binder with granular BRA modifier binder, the asphalt binder behaves viscous and then, lead to plastic deformation. Similarly, Brown [14] and Nega, Nikraz and Al-Qadi [5] also discussed that permanent deformation can be influenced by the various change of temperature sensitivity of flexible pavement asphalt mixture and aggregate grading, and loading cycles effects. Thus improving the material properties and mix characteristics is essential to have improved the rutting resistance of asphalt mixtures.

Table 3. Fatigue Law Parameters and Loading Cycles After Fitted

Asphalt mixtures	Constant		R^2	Loading cycle
	a	b		
Unmodified	0.351	0.285	0.967	1,900
BRA modified (10%)	0.349	0.232	0.981	10,850
BRA modified (20%)	0.402	0.203	0.984	20,200
BRA modified (30%)	0.286	0.194	0.978	30,000[1]

[1] : The cycles obtained only about 2.11% of total permanent strain

Besides the loading cycles after fitted, additional analysis concerning of the number of loading cycles to achieve an accumulative permanent strain after one million cycles is shown in Figure 7. The total permanent strains versus loading cycles were plotted on a log-log scale. The same regression analysis as Figure 6 was used to calculate the fatigue law ($\varepsilon = a\, x\, N^b$) and the coefficient of correlations showed that the criterion for subjective class of goodness, (R^2), is summarized in Table 3. The increase in the content of BRA modifier binder to 10, 20, 30% resulted in a decrease of the total permanent strain,ε, after one million load cycles to 52, 63, and 76%, respectively. This indicated the total permanent strain values reveals that the BRA modified have much better resistance to rutting than unmodified in any percentage level of BRA modifier binder.

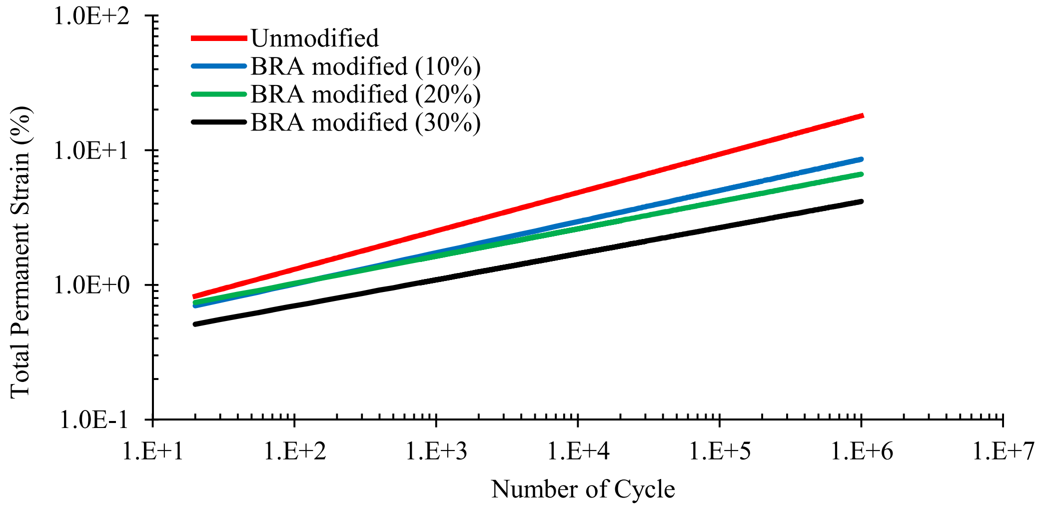


Fig. 7. The fatigue laws from the dynamic creep test by regression analysis

The BRA modifier binder tends to reduced damage in each cycles number on the specimens, and allowing more cycles until the permanent strain attained. The slopes, which were determined between the number of cycles of 20 and one million cycles shows that the average of strain rate for unmodified were higher as compared to BRA modified asphalt mixtures at any percentage of BRA modifies binder. However, the average minimum strain rate of unmodified asphalt mixture was higher than that for BRA modified asphalt mixtures as shown in Figure 8. This suggested that BRA modified were more stable than unmodified because the rate of deformation was lower as compared to the unmodified one.

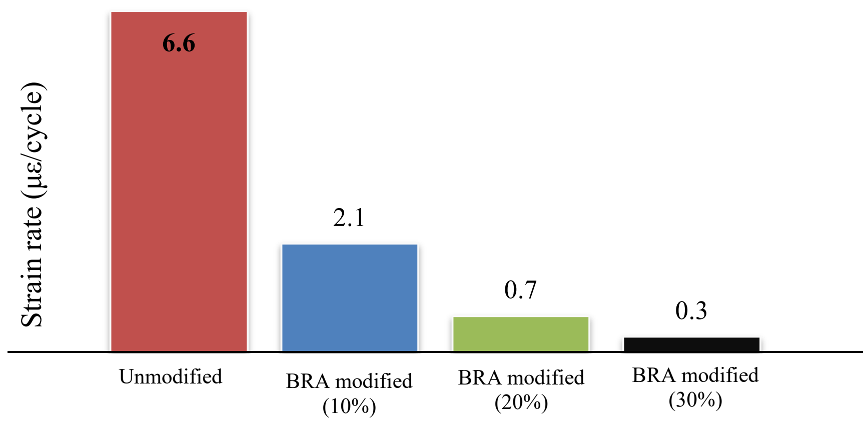


Fig. 8. The average of the strain rate of the asphalt mixtures obtained from the test

Average summary of creep modulus of the asphalt mixtures after fitted is shown in Figure 9. From the data presented, it can be seen that a significant increase in creep modulus for the BRA modified asphalt mixture as compared to unmodified asphalt mixtures even if the creep modulus for all asphalt mixture have shown an action of moving to downward. At 1800 loading cycles, which was 3600 seconds, the creep modulus increases at about 44, 61 and 144% with increasing content of BRA modifier binder with 10, 20 and 30% as a given order. Ali [35] evaluated the mixture characteristics of BRA with 10% of BRA granular and 15% of BRA granular at different temperature of 30°C, 40°C and 50°C using the indirect tensile stiffness modulus test and the samples were tested at 45% using dynamic creep test. It was observed that the effectiveness of using BRA as granular showed better performance in asphalt mixture. From the results, the use of 15% BRA granular showed the highest stiffness modulus and the highest permanent deformation resistance as compared with 10% BRA granular.

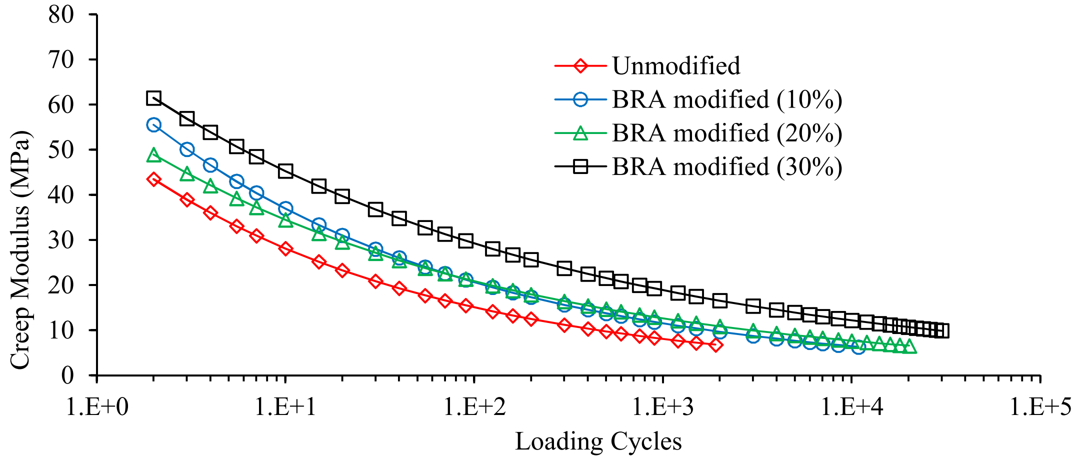


Fig. 9. The average of the creep modulus of the asphalt mixtures after fitted

The stepwise concept was used in this study to determine FN, flow point, and minimum strain rate for unmodified and BRA modified asphalt mixtures. The summary of flow number, flow point and minimum strain rate based on the stepwise concept is shown in Table 4. While the relationship between flow number and rate of deformation is shown in Figure 10. The flow number, equation (2), was built at 50°C testing temperature, and 5±0.5% air voids level. From the date presented, it can be seen that there was a strong correlations between flow number (FN) and rate of deformation slope at steady state [R^2=0.96]. This showed that the criteria for subjective class of goodness fit is good according to [26]. Similarly, Goh and You [22] reported that rate of deformation had a good correlation with permanent deformation. They indicated that the flow number (FN) of an asphalt mixture has a capacity to compute using the rate of defamation at various temperature and air voids level using the flow number equation that was described in (Equation 2) so that FN and slope at steady state can have a good relationship in between on the stepwise concept.

Table 4. Flow Number, Flow Point and Minimum Strain Rate Based on the Stepwise Concept

Asphalt mixtures	Flow number (cycles)	Flow point (%)	Minimum strain rate (με/cycle)
Unmodified	1506	2.8	7.1
BRA modified (10%)	4664	2.6	2.2
BRA modified (20%)	8876	2.5	0.8
BRA modified (30%)	25521	2.4	0.3

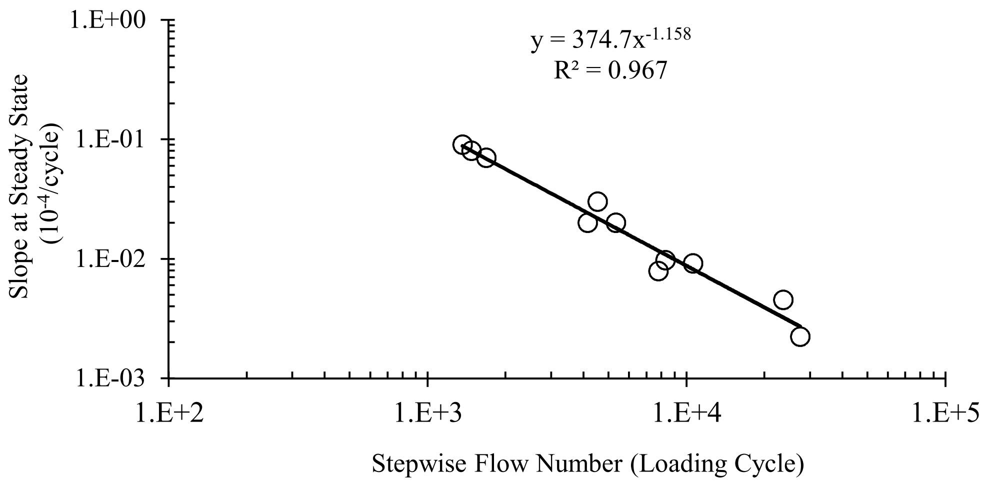


Fig. 10. The relationship of flow number and slope

Conclusions

The performance evaluation of buton rock asphalt (BRA) modified asphalt paving mixtures based on dynamic creep laboratory testing are achieved and compared.

The BRA modified (10%, 20%, and 30%) binder asphalt mixtures had a good performance with all analytical categories as compared to unmodified asphalt mixtures. BRA had a lower dependency of permanent deformation at the 50^{o}C dynamic creep temperature testing. The increase in the content modifier binder to 10, 20, and 30% resulted in decrease of total permanent strain. The loading cycle were set to reach 3% of total permanent strain for both unmodified and BRA modified binder however, BRA modified continuing 30% BRA modifier binder was not exceeded the standards limit of 3% because it automatically stopped after 30, 000 loading cycles but still with reasonable results.

The BRA modifier tends to reduced damage in each loading cycle. This suggested that BRA modified asphalt paving mixtures are more stable than that unmodified asphalt mixtures because the rate of deformation was lower as compared to the unmodified one. Another, a significant increase in creep modulus for the BRA modified asphalt mixtures was achieved as compared to unmodified asphalt mixtures. BRA granular showed the highest stiffness modulus and the highest permanent deformation resistance as compared to unmodified.

The flow number (FN) was high for BRA modified asphalt binder as compared with unmodified asphalt mixtures. Flow number of asphalt mixtures has a capacity to compute using a rate of deformation at various temperature and air voids level. BRA modified with 30% had a high FN as compared to 10 and 20% BRA modified binder. And then, there was a strong correlations on criteria for subjective class of goodness fit between flow number and rate of deformation slope at steady rate [R^2=0.96].

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