**Resilient modulus master curve for BRA modified asphalt mixtures**

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**Abstract**

The objective of this research is to evaluate the resilient modulus of using granular Buton rock asphalt (BRA) modifier binder for modified asphalt mixtures based on the developed resilient modulus master curve. In this research, indirect tensile stiffness modulus tests were conducted on unmodified and BRA modified asphalt mixtures for dense graded aggregates of 10 mm, using UTM25 machine. A twenty percent of BRA natural binder by total weight of asphalt binder was chosen as a substitute for the base asphalt binder in the BRA modified asphalt mixtures. The unmodified and BRA modified were tested under different condition of temperatures and frequencies to develop resilient modulus master curve. The results of investigation indicated that asphalt mixtures modified by granular BRA additives had higher resilient modulus than unmodified mixtures in the high-intermediate temperature range and low frequency, therefore the viscoelastic behavior of BRA modified was higher than for unmodified asphalt mixtures.

*Keywords*: asphalt mixtures, granular Buton rock asphalt, resilient modulus master curve

1. **Introduction**

Resilient modulus has been used in number of studies evaluating and analyzing asphalt mixtures because this test is simple to perform and effective in characterizing the fundamental properties of asphalt mixtures. According to studies, obtaining the resilient modulus of asphalt mixtures using the ITSM test is a means of studying the potential elastic properties of asphalt mixtures in the form of stress-strain measurement [1-4]. The resilient modulus of asphalt mixtures is a very important factor in pavement design with regard to calculating the required pavement thickness. A higher resilient modulus means reduction in the necessary thickness of the asphalt mixtures layer. Resilient modulus is obtained by dividing the applied stress by recoverable strain at a particular temperature and frequency under repeated load [4, 5] as presented in Equation 1.

where *σd* is the deviator stress (axial stress in an unconfined compression test or the axial stress) and *εt* is recoverable strain.

 Furthermore, the need for asphalt modification is caused by limitation in the capability of the base asphalt binder to resist distresses. When the rheological and mechanical properties of base asphalt binder are not ideal for accommodating changes in traffic load, traffic volume, environment and pavement structure requirements, modification has been used as an alternative to improve asphalt binder properties. The rheological and durability properties of base asphalt binders are not sufficient for resisting the distresses caused by increases in traffic and changes in environmental conditions.

 Modified bitumen is formulated with additives to improve its service performance. Bahia [6] has explained that the modification of asphalt binder is performed to improve one or more basic properties of asphalt binder related to one or more types of pavement distress, including rigidity, elasticity, brittleness, storage stability and durability, and resistance to accumulated damage. Many researchers have discovered that modification of pure binder is performed through the use of chemicals, particles or polymers to enhance a target property. Chemical modification improves the physical properties of asphalt binder and produces a binder that shows adequate stiffness at high temperatures or suffers less cracking at low temperatures. Particles such as fillers [7] and cellulose fibres [3, 8] and polymers [3, 8-11] increase the resistance to permanent deformation at certain traffic loads and temperatures. Polymers also form a continuous network in asphalt binder and transmit their elastic properties to the homogenous blend.

 This study, however, deals with the benefit of using granular Buton Rock Asphalt (BRA) modifier binder with the aim of increasing the mechanical performance of asphalt mixtures and to make more effective and efficient use of pavement materials. The raw materials of granular BRA modifier binder are found on Buton Island, Indonesia, and are traditionally known as Buton asphalt (*asbuton*). The objective of this research is therefore to analyze the potential for using granular BRA modifier binder in asphalt mixtures with the purpose of increasing the resilient modulus values over a range of temperature and frequency.

1. **The concept of resilient modulus master curve**

 In MEPDG, the concept of master curve is used to represent the dynamic modulus of asphalt concrete in terms of temperature and loading frequency. The concept is that the dynamic modulus is used to determine the response of the material under dynamic loading in the range between linier elastic and viscoelastic. Asphalt mixtures are considered to be a linear viscoelastic materials when the strain level is 100 με or lower [12]. According to Yao *et al*. [13], the dynamic modulus is referred to as |E\*| obtained by dividing the loading stress amplitude by the resulting peak to peak recoverable strain.

 The data for the dynamic modulus at a range of test temperature and loading frequencies can be combined to develop a master curve for further analysis. Apeagyei [14] described the reasons for constructing a master curve as follows. Master curves for dynamic modulus can be used for predicting dynamic modulus at temperatures and/or frequencies in the laboratory when there are limitations on equipment and time, modeling the pavements under all possible pavement climates and loading conditions, and also comparing the performance of asphalt mixtures. According to Christensen and Anderson [15], the reaction of asphalt mixtures due to the application of loads at a reference temperature over a range of frequencies or time can be represented by a master curve. Furthermore, a master curve can be used to described the viscoelastic behavior of asphalt binder and mixtures [16].

 Master curves are developed based on the time-temperature superposition principle [16-18]. According to Kim [19], a master curve is developed using: firstly, the dynamic moduli measured at test temperatures higher than the reference temperature, horizontally shifted to a lower frequency; secondly, the dynamic modulus measured at a test temperature lower than the reference temperature, shifted to a higher frequency. The data are shifted subject to the time until a single smooth function of the curves is constructed. The master curve of the dynamic modulus is modeled by the sigmoidal function described in Equation 2 [13, 17, 20, 21]. The procedure for constructing the |E\*| can be seen in Apeagyei *et al*. [18]. Figure 1 shows a developing master curve in which the dynamic modulus measured at different temperatures (4.4°C, 21.1°C, 37.8°C and 54°C) was shifted relative to the frequency and then formed a single master curve.

where *fr* is reduced frequency of loading at reference temperature, *δ* is minimum value of E\*, (*δ + α*) is maximum value of E\* and *β, γ* are parameter describing the shape of the sigmoidal function.

 Contrary to *Mr*, the rest period within a given loading time is not included in the standard dynamic modulus test protocol. However, traffic loading is not continuously applied to a pavement structure in the field. Fakhri and Ghanizadeh [22] argued that the standard dynamic modulus test protocol is not accurate to characterize the asphalt mixtures without consideration of the rest period.

The effects of temperature and loading frequency were combined to find out the different susceptibilities of the various asphalt mixtures to temperatures in order to represent the concept of a stiffness modulus master curve. The resilient modulus master curve for asphalt mixtures is developed based on the time-temperature superposition principal. The master curve for the resilient modulus is modelled by the sigmoidal function described by Equation 3 [22].

where *fr* is reduced frequency of loading at reference temperature, *δ* is minimum value of *S*, *(δ + α)* is maximum value of *S* and *β, γ* are parameter describing the shape of sigmoidal function. The reduced frequency (f) is given by the following relation:

where *a(T)* is shift factor as a function of temperature, *f* is loading frequency at desired temperature, *fr* is loading frequency at reference temperatureand *T* is temperature of interest.According to Witczak and Bari [17], the second order polynomial can be used to show the relationship between the logarithm of the shift factor as shown in Equation 3.

where *a(Ti)* is shift factor as a function of temperature *Ti*, *Ti* is time of loading at desired temperature, and a, b, and c are reduced time of loading at reference temperature.

1. **Materials and methods**

**3.1 Materials**

Class-170 (Pen 60/80) base asphalt binder was used for unmodified asphalt mixtures. The binder was classified according to the Australian Standard AS-2008 [23]. A percentage of BRA natural binder, 20% by total weight of asphalt binder, were chosen as a substitute for the base asphalt binder in the BRA modified asphalt mixtures based on previous research [24, 25]. Specification of the base asphalt binder and BRA modified binder are given in Table 1.

 Figure 2 shows the form of BRA modifier binder (pellets) with size of 7 mm to 10-mm in diameter used in this study. In this research, these materials are known as granular BRA modifier binder. Triplicate portion of granular BRA modifier binder were subjected to an extraction process [26]. The bitumen content test results found that, on average, about 70% mineral and 30% natural binder by total weight of materials formed the granular BRA modifier binder. The particle size distribution of minerals is as follows: 2.36 mm (100%), 1.18 mm (97%), 0.6 mm (92%), 0.3 mm (81%), 0.15 mm (61%) and 0.075 mm (36%).

 A crushed granite sourced from a local quarry in Western Australia was used in all of the mixtures. One typical dense graded used for unmodified and BRA modified asphalt mixtures with nominal aggregate size of 10 mm (DG 10) was based on Specification 504 [27]. The coarse and fine aggregates required to prepare the mixes were obtained by sieving on each sieve diameter.

 As stated in mix design and specimen preparation that the same binder contents as for unmodified asphalt mixtures were used for the BRA modified asphalt mixtures in order to maintain consistency for comparison purposes. To focus on the contribution of granular BRA modifier binder, a 20 percent of granular BRA modifier binder was used in a single mix composition to produce nominally identical mixes. Table 2 shows that in the BRA modified asphalt mixtures, the substitution of the base asphalt binder allowed the proportion of fines passing 2.36 to be adjusted. The total mass of crushed fine aggregate was decreased and replaced with mineral contained in the granular BRA modifier with the aim of minimizing the variance in the gradation of aggregates (Table 3).

**3.2 Mix design and specimen preparation**

This study used Marshall mix design method to find out the optimum bitumen content (OBC) of unmodified asphalt mixtures based on specification 504[27]. Specimen in triplicate with dimension of 101 mm in diameter and 63.5 mm in height were compacted by applying 75 blows to each side using an automatic Marshall compactor for various contents of asphalt binder. The result shows that the voids of 5% was chosen to give binder content of 5.4% by mass of the asphalt mixtures as optimum bitumen content (OBC) values. To exhibit the benefit of granular BRA modifier binder mix in the asphalt mixtures, the BRA modified asphalt mixtures was designed to use the same binder content as unmodified asphalt mixtures. Hence, the OAC of 5.4% by weight of total mixtures was also used for BRA modified asphalt mixtures.

 Table 3 shows the proportion of the base asphalt binder and the BRA modifier binder in unmodified and BRA modified asphalt mixtures, as well as the proportion of granular BRA (pellets) mixed into the mixtures. Furthermore, BRA modified asphalt mixtures specimens were manufactured as presented elsewhere[24, 28]. Specimens were cylindrical with dimension of 100±2 mm in diameter and 35-70 mm in height, prepared according to standard AS2891.13.1-1995. Gyratory machine were used to compact the specimens, as set-out in AS2891.2.2-1995. In total fifteen specimens were tested for unmodified asphalt mixtures and fifteen specimens were tested for BRA modified asphalt mixtures in this study (triplicate specimens for each test temperature).

* 1. **Indirect tensile resilient modulus test**

As presented elsewhere [25], ITSM tests were performed to determine the resilient modulus of asphalt mixtures based on standard AS2891.13.1-1995[29] using a universal testing machine (UTM 25) under the test conditions presented in Table 4. The load pulse was applied vertically in the vertical diameter of a cylindrical specimen through a curved loading strip. The resulting horizontal deformation was measured by attaching two linear variable differential transformers (LVDT) at the mid thickness at each end of the horizontal diameter as shown in Figure 3. Initially, the test specimens were conditioned through the application of five load pulses with the specified rise time to the peak load at the specified pulse repetition period, and then the calculation of the modulus was done based on the average of a further five load pulses.

1. **Results and Discussion**

**4.1 Resilient modulus master curve**

 The laboratory resilient modulus data for the five testing temperatures (5°C, 15°C, 25°C, 40°C and 60°C) and three frequencies (0.33 Hz, 0.5 Hz dan 1.0 Hz) for each asphalt mixture were combined to construct the resilient modulus master curve. Equation 3 was used to construct this master curve for a reference temperature of 21°C for all asphalt mixtures. The resilient modulus data were then shifted into a master curve for the analysis of the performance of asphalt mixtures by simultaneously solving shift parameters. Figure 4 shows the relationship between the logarithm of the shift factors (*log a* (*Ti*)) and test temperature for each mixture. The shift factor for unmodified and BRA modified asphalt mixtures was found to be similar. All of the shift factors followed a second order polynomial with respect to temperature. The seven parameters in accordance with Equations 3 and 5 presented in Table 5 were used to calculate the resilient modulus for unmodified and BRA modified asphalt mixtures over the range of temperatures and loading frequencies used in the testing.

 Fitted master curves for asphalt mixtures were shown in Figure 5 plotted in a log-log scale. The measured and master curve resilient moduli were then compared in order to check the accuracy and effectiveness of the master curve. A plot master curve resilient modulus (*Smaster curve*) and laboratory resilient modulus (*Slab*) for unmodified and BRA modified asphalt mixtures are shown in Figure 6. It can be seen that the resilient modulus data obtained from the master curve for both asphalt mixtures is almost identical to laboratory resilient modulus data.

 The resilient modulus master curves for unmodified and BRA modified asphalt mixtures at a reference temperature of 21°C as shown in Figure 5 are plotted in Figure 7. This figure illustrates the comparison of the effect of granular BRA modifier binder on the resilient modulus of asphalt mixtures at a reference temperature and various loading frequencies. The resilient modulus for BRA modified asphalt mixtures was observed to be higher than for unmodified mixtures especially in the high-intermediate temperature range and at low frequency. Therefore, the viscoelastic behaviour of BRA modified asphalt mixtures containing 20% BRA modifier binder was higher than for unmodified asphalt mixtures. The resilient modulus is related to the load spreading capacity [24]. Asphalt mixtures with a high resilient modulus will distribute loads over a wider area. It is expected that BRA modified asphalt mixtures with a higher resilient modulus would have greater tensile strain and resistance to cracking.

**4.2 Statistical analysis**

 The resilient modulus results were also analyzed statistically using the analysis of covariance (Ancova). The purpose of the statistical analysis was to determine whether granular BRA modifier binder seemed to have an effect on the resilient modulus of asphalt mixtures when the test temperature, rise time and pulse repetition period were controlled.

 The response examined was the resilient modulus of the asphalt mixtures. Independent variables included two asphalt mixtures as fixed variables (unmodified and BRA modified asphalt mixtures) and three testing variables as covariates (temperature, rise time and pulse repetition period). The results of the Ancova are summarized in Table 6, indicating which effects are statistically significant at the 95 percent (p < 0.05) probability level and described as thereafter.

 The results of Levene’s test when temperature, rise time, and pulse repetition period are included in the model as covariates are non-significant. This indicates that the variances are equal (hence the assumption of the homogeneity of variances has been met). It is clear that the covariates (temperature, rise time, and pulse repetition period) significantly predict the dependent variable (resilient modulus).

 Looking at the significance values, only the temperature as a covariate significantly predicts the resilient modulus of asphalt mixtures because the significant value is less than 0.05, where F (1, 175) = 614.724, and *p* = 0.000. Therefore the resilient modulus of asphalt mixtures is significantly influenced by the temperature, while rise time and pulse repetition period seem to have no significant effect on the resilient modulus. The significant values for rise time and pulse repetition period were 0.161 and 0.939 respectively.

 Other than that, even though the effects of temperature, rise time and pulse repetition period were not included, the effect of BRA modifier binder on the resilient modulus values of asphalt mixtures was significant, where F (1, 175) = 27.485, and *p* = 0.000. The model as a whole was still significant, therefore it is possible to predict the resilient modulus of asphalt mixtures from these variables (asphalt mixtures, temperature, rise time and pulse repetition periods) where the significance for the corrected model was less than 0.05 (p = 0.000).

 The results of the normal post hoc test showed that using granular BRA modifier binder in the asphalt mixtures had a significant effect on the resilient modulus; specifically the resilient modulus of the BRA modified asphalt mixtures was significantly higher than the unmodified asphalt mixtures.

1. **Conclusion**

 Several tests for determining the resilient modulus of unmodified and BRA modified mixtures were evaluated under the ITSM test. Included in this evaluation was the effect of variation in the test condition variables such as test temperature and frequency, on unmodified and BRA modified asphalt mixtures. The resilient modulus of BRA modified asphalt mixtures was significantly higher than that of unmodified asphalt mixtures. This indicates that the substitution of BRA modifier binder led to an increase in the shear resistance and thus an increase in the stiffness of BRA modified asphalt mixtures. The resilient modulus of unmodified and BRA modified asphalt mixtures was influenced by temperature. The resilient modulus of asphalt mixtures decreased with an increase in temperature. However, the BRA modified asphalt mixtures were less sensitive to the temperature changes than the unmodified asphalt mixtures. Based on statistical analysis using the analysis of covariance (Ancova), two factors, temperature and granular BRA modifier binder, had the greatest and most statistically significant influence on resilient modulus compared to other variables, while the loading time and pulse repetition period seemed to have no statistically significant effect on resilient modulus.

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**Tables:**

Table 1. Properties of bitumen

|  |  |  |
| --- | --- | --- |
| Bitumen property | Standard | Value |
| Base binder  | BRA modified binder  |
| Penetration (25°C; 0.1 mm) | ASTM-D5 | 67 | 59 |
| Softening points (°C) | ASTM-D36 | 48 | 52.8 |
| Ductility (25°C), cm | ASTM-D113 | >100 | >100 |
| Mass loss (%) | ASTM-D1754 | 0.19 | 0.09 |
| Ductility after TFOT (25°C), cm | ASTM-D113 | >100 | >100 |

Table 2. Final crushed aggregate gradation used in this study (percent passing)

|  |  |  |
| --- | --- | --- |
| Sieve size (mm) | BRA modifier content  | Limit values  |
| 0% | 20% |
| 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 |

Table 3. Proportion of materials used in asphalt mixtures

|  |  |
| --- | --- |
| Materials | Percentage by total weight of mixtures (%) |
| BRA modifier content |
| 0% | 20% |
| 1. Total binder content:  | 5.40 | 5.40 |
| 1. Base binder
 | 5.40 | 4.30 |
| 1. BRA modifier binder
 | 0.00 | 1.10 |
| 2. Total aggregate content: | 94.60 | 94.60 |
| 1. Crushed rock
 | 94.60 | 92.10 |
| 1. BRA mineral
 | 0.00 | 2.50 |
| 3. Granular BRA modifier binder (pellets) | 0.00 | 3.60 |

Table 4. Test conditions for the ITSM test

|  |  |
| --- | --- |
| Parameters | Conditions |
| Test temperature, °C | 5, 15, 25, 40, 60 ± 0.5 |
| Rise time *tu* (10% to 90%), ms | 40, 60, 80 ± 5 |
| Pulse repetition period (10% to 10%), ms | 1000, 2000, 3000 ± 5 |
| Recovered horizontal strain, µε | 50 ± 20  |
| Air voids, % | 5 ± 0.5 |
| Content of BRA modifier binder, % | 0, 20 |
| Type of gradation | DG10 |

Table 5. Resilient modulus and shift parameter

|  |  |  |
| --- | --- | --- |
| Asphalt mixtures | Resilient modulus parameter | Shift parameter |
| Δ | α | Β | γ | a | B | c | R2 |
| Unmodified | 1.129 | 2.376 | -1.076 | -0.362 | 0.0004 | -0.287 | 5.823 | 1.0 |
| BRA modified  | 1.357 | 2.301 | -1.112 | -0.234 | 0.0006 | -0.392 | 7.993 | 1.0 |

Table 6. Statistically significant effect of variables in ITSM test

|  |  |
| --- | --- |
| Variables | Resilient modulus |
| Asphalt mixtures | Yes |
| Temperatures | Yes |
| Rise time | No |
| Pulse repetition period | No |

**Figures:**

Figure 1. Development master curve



Figure 2. The form of granular BRA modifier binder (pellets)

Loading jog

Loading strip

Specimen

LVDT

Loading strip

Figure 3. Set-up the ITSM test

Figure 4. Shift factor for unmodified and BRA modified asphalt mixtures

Figure 5. Fitted of resilient modulus master curve of asphalt mixtures

Figure 6. Comparison between the measured and master curve resilient modulus

Figure 7. Resilient modulus master curve for unmodified and BRA modified asphalt mixtures



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