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COMPARISON OF THE MECHANICAL PERFORMANCE OF DENSE GRADING AND POROUS GRADING MIXTURE UTILIZED WITH CRUMB RUBBER MODIFIED BINDER

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ABSTRACT: Pavement and road networks play a very huge role in everyone's daily lives to connect from one point to another point. With globalization, growth in the economy, and development, the number of vehicles traveling each day on the road increases rapidly over the years. Thus, the constant application of heavy loads together with Malaysia's climatic factors lead the pavement to be susceptible to deterioration such as potholes and cracking. The service life and resistance of the pavement to deterioration can be improved with the incorporation of crumb rubber modified binder (CRMB) for asphaltic pavement. Hence, the objective of this research is to do a comparative evaluation of the mechanical performance of the CRMB that is utilized in dense grading and porous grading mixtures with varying percentage of crumb rubber replacement. The experimental portion of the research was done by substituting the crumb rubber at the replacement percentages of 12%, 14%, 16% and 18% (from the weight of asphalt binder) in preparing the modified binder that was further evaluated by conducting physical testing (penetration and softening point test). Then, the mechanical evaluation of dense and porous grading asphalt mixtures incorporating the crumb rubber was performed with Marshall stability and flow prior to comparing the strength performance for both asphalt mixtures. Based on the result obtained, it was found that the highest percentage of crumb rubber replacement, which is 18%, would give the highest level of stiffness and softening point on the binder. Furthermore, from the Marshall test, it was established that 16% of crumb rubber replacement on asphaltic binder is the most optimum for a porous mixture, given that the CRMB is 5% of the total mix. Nonetheless, at the same 16% of crumb rubber replacement, the value for Marshall test on the dense mixture shows an adverse result when compared to the control. Hence, it was concluded that the mechanical performance of CRMB utilized with porous mixtures shows more impressive results compared CRMB utilized with dense mixtures.

ABSTRAK: Turapan dan rangkaian jalan raya memainkan peranan besar dalam kehidupan harian setiap orang dalam berhubung dari tempat ke tempat lain. Melalui globalisasi dan pertumbuhan ekonomi dan pembangunan, bilangan kenderaan bergerak setiap hari di atas jalan raya telah meningkat mendadak beberapa tahun kebelakangan ini. Oleh itu, beban berat berterusan bersama-sama faktor iklim Malaysia menyebabkan turapan jalan terdedah kepada kerosakan seperti jalan berlubang dan keretakan. Jangka hayat perkhidmatan dan rintangan turapan terhadap kerosakan jalan boleh diperbaiki melalui turapan asfaltik yang diubah suai dengan pengikat serbuk getah (CRMB). Justeru, kajian ini bertujuan bagi membanding prestasi mekanikal CRMB yang digunakan dalam campuran penggredan padat dan campuran berliang dengan peratusan penggantian serbuk getah berbeza. Kajian dijalankan dengan menggantikan serbuk getah pada peratusan penggantian pada 12%, 14%, 16% dan 18%

(daripada berat pengikat asfalt) dalam menyediakan bahan pengikat yang diubah suai dan seterusnya dinilai melalui ujian fizikal (ujian takat penembusan dan takat lembut). Kemudian, penilaian mekanikal dijalankan ke atas campuran serbuk getah bersama asfalt bergred padat dan berliang. Kajian dijalankan mengguna pakai ujian kestabilan dan aliran Marshall sebelum membandingkan prestasi kekuatan bagi kedua-dua campuran asfalt. Keputusan menunjukkan dapatan peratusan pada 18% memberikan tahap kekakuan dan takat lembut tertinggi pada bahan penggantian pengikat serbuk getah. Tambahan, ujian Marshall menunjukkan 16% daripada penggantian serbuk getah pada pengikat asfaltik adalah paling optimum pada campuran berliang, di mana 5% daripada jumlah campuran merupakan CRMB. Namun, ujian Marshall pada campuran padat dengan penggantian serbuk getah 16% yang sama, menunjukkan dapatan nilai buruk berbanding pada kawalan. Oleh itu, prestasi mekanikal CRMB yang digunakan bersama campuran berliang menunjukkan dapatan lebih mengagumkan berbanding CRMB yang digunakan melalui campuran padat.

KEYWORDS: *crumb rubber modified binder (CRMB); dense grading; porous grading mixture*

1. INTRODUCTION

In line with the rapid growth of Malaysia's population and economy, pavement or roadways serve for 24 hours per day and 7 days per week as a medium for the road users to perform daily responsibilities or duties. As the massive loads from vehicles are constantly applied onto the pavement together with Malaysia's tropical climate factor and copious rainfall, this has consequently caused the pavement to be very much susceptible to deterioration and degradation over the years throughout its in-service life. Examples of the common deteriorations that can be seen in Malaysia's pavement are potholes and cracking. Although some maintenance and restoration to the pavement can be done, this will require great expense to the government if constant rehabilitation work needs to be done. Thus, a modification on the binder at this point would be worth its expense to increase the strength and the resistance of pavement to rutting and cracking. Polymer is one of the examples of binder modifier that could enhance the properties of the asphalt binder and pavement. Nonetheless, some types of polymers can be quite expensive and not cost effective to cater to this issue. Hence, modification of asphaltic binder by using recycled tire rubber is introduced to tackle the deterioration issue without compromising on the enhancement effect to the pavement [1].

According to the author of [2], the incorporation of crumb rubber with asphalt binder extends the service life of roads and intensifies the adhesion of aggregates, ultimately leading to better strength and stability, and reducing the risk of stripping. Moreover, the Arizona Department of Transportation (ADOT), which conducted an observation on asphalt rubber pavement for 30 years, stated that asphalt rubber pavement expands resistance to deformation, diminishes the chance of reflective cracking, contributes to the desired rutting and smoothness which is below 0.25 inches and below 93 inches per mile respectively, as well as improves on noise reduction properties. These conclusions are supported with the findings from [3], who reported that the combination of crumb rubber and asphalt binder would produce a modified binder with higher fatigue and rutting resistance based on the higher value of the complex shear modulus, G^* achieved. This leads to the enhancement of $G^*/\sin \delta$ and $G^* \times \sin \delta$ which respectively represent rutting resistance and fatigue resistance. Furthermore, as established by [4], the modification of asphalt binder through replacement with crumb rubber also could contribute to the noise reduction that occurs due to tire and pavement interaction. Noise is reported to be reduced by 2.5 dB for vehicles that are driven at 50 mph on the pavement with CRMB. The noise reduction arises due to the "cushion" effect provided by the swelling of the crumb rubber, thus leading to the reduction of noise of around 3-5 dB [5]. In terms of physical properties, superior results are recorded for the enhancement of stiffness and softening points with the increased content of crumb rubber, thus validating the credibility of crumb rubber as a binder modifier.

In order to incorporate crumb rubber with asphalt binder, there are two methods that can be adopted namely, the dry method and wet method. These two processes are known to produce different end products of asphalt rubber pavement in terms of the performance and properties [1]. The dry method is achieved by adding the shredded tire rubber to replace the fine aggregate, where the crumb rubber is introduced to the aggregate before the asphalt binder is added to the mixture. As for the wet method, the crumb rubber particles are first incorporated and blended together with the asphalt binder at 175-200 °C for 45 to 60 minutes before aggregate is introduced to the mixture.

However, it was reported by the author of [6] that the CRMB may have exceptional field performance, but its effects may be diminished due to the poor design, varying properties of CRMB, and poor construction practices. Furthermore, the research findings claimed that the performance of the CRMB may be dependent on the crumb rubber size, surface area, percentage of replacement, time, and temperature for the mixing process, as well as the aggregate gradation used. Previous findings only focused on the conventional mixture, which is dense graded, without considering porous grading which is usually applied to reduce water runoff on the pavement surface. Porous graded mixtures should be emphasized since they comprise different aggregate gradings that might exhibit diverse interaction effects with crumb rubber and eventually affect the mixture performance.

Thus, this research paper intends to determine the performance of modified asphalt binder containing crumb rubber while comparing the effect of mechanical performance for different types of gradation utilized with crumb rubber in modified binder. The investigation on the mechanical performance of modified binder with crumb rubber in different gradations of dense and porous mixture is significant since functional effect of the crumb rubber as a modifier will differ in dense and porous asphalt mixture gradations, since they comprise different properties inside the bituminous mixture.

2. METHODOLOGY

As the main focus of this research is to assess the performance of modified binder rather than modified aggregate, thus the wet method is implemented to introduce the crumb rubber into the asphaltic mixture. The crumb rubber that is first obtained from end-of-life tires (ELTs) is ground to form crumb rubber powder and sieved through a 300 µm mesh to obtain a specific size that passes through the sieve. This ensures the usage of only fine crumb rubber size. This is vital, as finer crumb rubber size would lead to better storage stability and prevent the segregation of crumb rubber. Furthermore, smaller crumb rubber size also would lead to a higher rate of interaction between the crumb rubber and asphalt binder [1,7,8]. In this laboratory work, asphalt binder with a penetration grade of PEN 60/70 was used as a control sample. Binder source was supplied from Eksklusif Alfa Enterprise Company located in Shah Alam, Selangor, Malaysia. Basic physical and rheological properties of the binder were tested to meet all standard requirements. Upon preparing CRMB stock with a percentage of crumb rubber replacement of 12%, 14%, 16% and 18% (from the weight of asphalt binder), the physical properties for each of the modified binders with CRMB were tested via the penetration and softening point test and the results were then compared with the control binder. The small scale of replacement percentage of crumb rubber was selected since this modifier is categorised under the polymer group, even small content would contribute to superior strength that could improve the rutting resistance in the mixture. It is predicted that large amount replacement of crumb rubber gives adverse impact of strength which leads to cracking deterioration thus reducing the mechanical performance of the asphalt mixture.

Before incorporating the asphaltic binder with aggregate, some tests and checks must be executed to evaluate the performance and liability of the aggregates by performing aggregate properties testing. In order to check on the aggregates' resistance towards abrasion and crushing, Los Angeles Abrasion test and Aggregate Crushing value test were conducted. Both tests were conducted according to ASTM C131-96 and ASTM D5821, respectively.

Next, 5% of CRMB stocks was then mixed with the aggregate to form modified asphaltic mixes incorporating crumb rubber, in which, each of the CRMB percentages would have two samples where one sample is for dense mixture while the other sample is for porous mixture. For the dense mixture, gradation size AC 14 is utilized while for the porous mixture, Grading B is used. For the mixing of the asphaltic binder and aggregate, the aggregates were first heated at 110 °C. Then, the asphaltic binder and aggregate were mixed homogeneously at 160 °C for both the dense mixture and the porous mixture. After ensuring the aggregates were well coated, the sample was transferred into the mould and tamped manually for 15 blows per layer using steel rod. The samples were then compacted using a manual compactor for 75 blows per face for dense mixture and 50 times blow per face for porous mixture. The compacted sample was left for 24 hours at room temperature and then extracted from the moulds. Later, the samples were tested for the mechanical performance through the Marshall stability and flow test.

2.1 Penetration Test

The penetration test was carried out according to ASTM D5-97. A penetration test is a physical property test conducted to analyse the consistency of the asphaltic binder. Asphaltic binders are known to have a viscous property; hence the test is conducted to check on whether the binder has a high level of viscosity and stiffness or low level of viscosity with high fluidity. The test was done by firstly heating the bitumen until it liquidized and became sufficiently fluid to be poured into a sample container. Any air bubbles that formed in the asphalt were eliminated by stirring it. The samples were then kept at ambient temperature for a day before transferring them into a transfer dish and submerging them in a water bath. Then, the sample was removed from the water bath, and was ready to be tested with the penetrometer machine. After placing the sample right on the penetrometer, the needle was carefully adjusted and brought in contact with the surface of the sample. The penetrometer reading was adjusted to zero and the needle was released for exactly 5 seconds. Lastly, the readings were then recorded in tenths of millimeters and the test was repeated thrice to obtain the average penetration value and improve the accuracy of the penetration result.

2.2 Softening Point Test

The softening point test was conducted in accordance with ASTM D36-95, as shown in Fig. 1. The softening point test was conducted to attain the specific temperature at which the asphaltic binder would achieve a specific degree of softening. During the sample preparation, the metal rings and the glass surface were coated with glycerin to prevent the asphalt binder from adhering to it. As the asphalt binder liquidized, the sample was then poured into a ring that was placed on top of a glass surface. After waiting for the asphalt binder to cool down and stiffen at the ambient room temperature for 30 minutes, the excess asphalt was removed using a heated spatula. The ring and ball apparatus were assembled, and the beaker was filled with distilled water beyond the upper surface of the rings. To reach a starting temperature of 5 °C, the beaker was filled with ice and the steel balls were immersed into the water as well for them

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to have the same starting temperature. As the water was maintained at the desired starting temperature for 15 minutes, the balls were then placed at the center of the ring. The beaker containing the samples was then heated while ensuring uniform heat distribution in the beaker. Lastly, the temperature at which the asphalt binder melts and reaches the bottom plate was recorded and the data was graphically presented for proper result analysis.

Fig. 1: Softening point equipment testing.

2.3 Los Angeles Abrasion Value Test

The Los Angeles abrasion test, was performed based on ASTM C131-96 in order to evaluate on the resistance of the aggregate to abrasion, crushing, and degradation. This test was performed using a rotating steel drum to simulate the way aggregate was going to be impacted in real life situations during the mixing and compaction or during the in-service time when loads are applied on it. For the test procedure, the aggregate samples and the steel spheres (charge) were placed into the rotating drum and the machine was rotated at a speed of 30 to 33 r/min for 500 revolutions. Then, the aggregate was removed from the drum, and it was sieved through sieve no. 12. The weight of aggregate retained on the sieve was recorded to find the difference between the retained weight and the original weight of the aggregates in terms of percentage for the LA abrasion loss value.

2.4 Aggregate Crushing Value Test

Similar to the Los Angeles abrasion test, the aggregate crushing test was conducted to determine its resistance to crushing. However, for this test, different equipment was utilized, where compressive load was applied to the aggregate. The procedure was done according to ASTM D 5821. Prior to the aggregate test, the aggregates were filtered through sieves with size openings of 12.5 mm and 10 mm. For this test, only aggregates that passed the 12.5 mm sieve but retained on the 10 mm sieve were utilized. A steel cylinder was filled with aggregates until they met 1/3 of its height and the cylinder was slowly compacted with a tamping rod for 25 blows per layer. More layers of aggregate were added until the cylinder are fully filled with aggregates, the samples were then weighed. Next, the plunger was inserted into the steel cylinder and positioned so that it would rest horizontally on top of the aggregate. By using the compression machine, a compressive load of around 393 kN for 10 minutes was applied to the sample. Upon finishing, the aggregates were removed from the steel cylinder, and it was sieved through a sieve with openings of 2.36 mm. Lastly, the weight of the aggregate that retained on the sieve was recorded.

2.5 Marshall Test

Marshall stability and flow test, as depicted in Fig. 2, was performed by first letting the asphaltic mixture cure at ambient room temperature after the compaction process. During the curing, the asphaltic binder had to be placed on a smooth flat surface to ensure consistent thickness throughout the mold. The checking of the bulk specific gravity and the specimen thickness had to be made 24 hours after the compaction using the ASTM D2726 and ASTM D3549, respectively. The cured asphaltic mixture was then soaked in a water bath for 30 to 40 minutes at 60 °C. The sample was then removed from the water bath and placed on the lower segment of the testing head and the assembly of the overall machine completed. The flowmeter was placed over the guide rods, adjusted to zero, the flowmeter sleeve was released, and the micrometer dial reading was recorded.

Fig. 2: Marshall testing.

Upon receiving the results of Marshall stability and Marshall flow for each of the samples, the results for Marshall stiffness were computed based on the formula below.

$$\text{Marshall stiffness} = \frac{Marshall\ stability\ (kN)}{Marshall\ flow\ (mm)}$$

All of the results were then tabulated into graphs to have proper analysis on the result. Additionally, by preparing graphs, the pattern or the relationship between the percentage of crumb rubber replacement and Marshall stability, flow, and stiffness also could be assessed by the value of the coefficient of correlation, R. Thus, the strength of the relationship could be concluded, and it was easier to examine the percentage of crumb rubber replacement that would contribute to the most superlative stability and flow performance to the asphalt mixture sample.

3. RESULTS AND DISCUSSION

3.1 Penetration

Figure 3 shows the relationship between the percentage of crumb rubber and the depth of the penetration needle. The readings of the penetration depth were taken from the average of three readings. Based on the graph, it can be seen that before the modification of binder with crumb rubber, the value of penetration is as according to the supposed value for asphalt binder PEN 60/70 which is 6 cm. However, with the 12% replacement of crumb rubber, the penetration depth reduced by 19.5% to 4.82 cm. With further replacement to 14% and 16%, the depth reduced more significantly to 4.44 cm and 4.18 cm respectively. Lastly, at the highest percentage of replacement of 18%, the depth reduced to the lowest value of 3.94 cm. From the pattern, it can be observed that control binder gives the highest penetration depth while the

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highest percentage of replacement, 18% gives the lowest value for penetration. Thus, it is apparent that, as the percentage of crumb rubber increases, the penetration depth decreases progressively. This represents a strong enhancement of the asphalt binder in terms of viscosity and stiffness as the percentage of crumb rubber increases. Not to mention, from the graph, the coefficient of correlation obtained was,

$$R = \sqrt{0.8672} \quad = 0.93$$

Since the coefficient of correlation, R is closer to 1, it is proven that the percentage of crumb rubber signifies an influential impact on the stiffness and viscosity of the asphaltic binder. Nonetheless, stiffer binder does not necessarily prove an enhancement of the pavement during later use. The authors of [9] established that the higher stiffness of the asphaltic binder that occurred due to the swelling of the crumb rubber is advantageous for pavement that is in use in hot climate regions due to its higher flow resistance, which leads to improvement in the pavement's flexibility. However, if it is constructed at a cold climate region with low temperatures, the asphaltic mixture may have issue on the ductility, thus leading to higher risk of thermal cracking. This is supported by [10], in which bitumen underwent high brittleness rate and was prone to experience cracking failure at low temperature exposure.

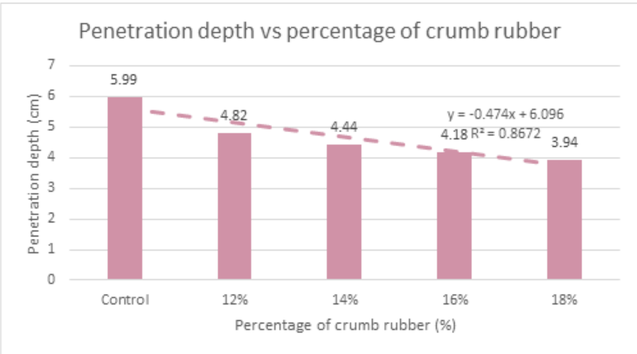

Fig. 3: Penetration depth of asphalt binder with percentage of crumb rubber varying from 0% to 18%.

3.2 Softening Point

Figure 4 proves how the higher percentage of crumb rubber replacement would result in the softening point increasing continuously. At 0% of crumb rubber replacement, the softening point achieved is the lowest, which is at 49.5 °C. However, the value is still valid for asphalt binder PEN 60/70 as it is still within the range of 49 to 56 °C. As the crumb rubber replacement increases to 12%, the softening point of the asphaltic binder raises up to 50.5 °C, validating the improvement of the binder to lower temperature susceptibility. Next, with further replacement of the binder with 14% and 16% crumb rubber, the softening point continues to climb to 51.5 and 54 °C respectively. At the maximum percentage of crumb rubber replacement, which is 18%, the binder eventually met its maximum softening point value at 56.5 °C. Hence, a conclusion can be made in which the higher the percentage of crumb rubber used for replacement, the higher the softening point of the asphaltic binder. Relating this with the stiffness of the asphaltic binder results from the penetration test, since the stiffness increases with higher crumb rubber replacement, a higher temperature would be required for the asphaltic binder to change its physical property from solid to liquid form.

Therefore, this signifies that as the content of crumb rubber replacement increases, the lower the temperature susceptibility of the asphaltic binders, since higher temperatures are required for the asphaltic binder to change its form. Hence, the pavement that is incorporated with crumb rubber will be less likely to go through any deterioration due to hot climatic weather such as rutting. This conclusion can also be supported by the authors of [6], as the authors mentioned on the research paper that the results of inclining softening point value with increment of percentage of crumb rubber indicate that pavements that is constructed using CRMB would be less susceptible to traffic deformation distress at high temperatures compared to conventional asphalt pavements. According to [11], high softening point was desirable for hot and warm climates application. In order to prove the strength of the influence of crumb rubber towards the softening point, the coefficient of correlation was computed, as shown below.

$$R = \sqrt{0.9486} = 0.97$$

The calculation above shows how close the value of the coefficient of correlation is to 1. Therefore, this signifies that the softening point of the asphaltic binder is highly influenced by the incorporation of crumb rubber.

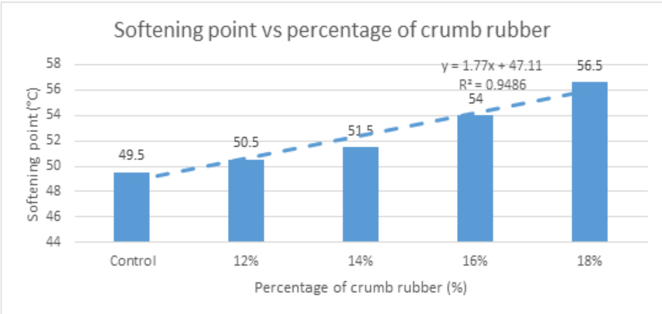

Fig. 4: Softening point of asphalt binder with percentage of crumb rubber varying from 0% to 18%.

3.3 Los Angeles Abrasion Value

According to the result, for the first test, the weight of aggregate retained on sieve no. 4 was 2.5 kg while the weight of retained aggregate on sieve no.12 was 0.82 kg. Hence, the computed value of the LAAV based on those two weights was 32.8% whereas for the second test, the weight of aggregate retained on sieve no. 4 was 2.5 kg while the weight of retained aggregate on sieve no.12 was 0.76 kg. Therefore, the value of LAAV obtained was 30.4%. The mean was determined from these two values, which is 31.6%.

According to ASTM C131, the Los Angeles Abrasion Value must be not more than 40%. As a result, the aggregates employed in this research are appropriate and fulfil the standard criterion. Based on the results, it is possible to infer that the aggregates utilised have a high hardness value and are appropriate for usage. According to [12], the strength of the aggregate is very important as it does impact the overall strength of the pavement. Aggregates with high resistance towards abrasion are less likely to wear down or be broken apart under the friction and grinding forces from vehicle loads. It is quite vital for the aggregates to resist breaking apart as this could contribute to more even load distribution on the pavement. Thus, this remarkably could enhance the longevity of the pavement as well.

First Test:

Weight of retained aggregate on no. 4 ASTM sieve (kg) = 2.5 kg

Weight of retained aggregate on no.12 ASTM sieve (kg) = 0.82 kg

Los Angeles abrasion value (%) = $\frac{0.82}{2.5} \times 100\%$ = 32.8%

Second Test (Repetition):

Weight of retained aggregate on no.4 ASTM sieve (kg) = 2.5 kg

Weight of retained aggregate on no.12 ASTM sieve (kg) = 0.76 kg

Los Angeles abrasion value (%) = $\frac{0.76}{2.5} \times 100\%$ = 30.4%

Taking Average Based on Both Test:

Los Angeles abrasion value (%) = $\frac{32.8+30.4}{2}$ = 31.6%

3.4 Aggregate Crushing Value

The calculation to determine the aggregate crushing value is as shown below. Prior to the crushing of the aggregate via the compression machine, the total initial weight of the aggregates was 2.65 kg. After the aggregates were crushed and filtered through sieve with an opening of 2.36 mm, the weight of aggregate passing through the sieve was 0.65 kg. Therefore, proving that only 24.53% of the total aggregates underperformed and were not impervious against the gradually applied compressive load.

Based on the result obtained, the aggregate crushing value of the aggregates is within the acceptable range. This is because, the aggregate crushing value for wearing course should not exceed 30% according to BS 812-110:1990. In another interpretation, the aggregate is suitable for use in wearing course layer construction as it has high resistance to impact. According to [13], aggregates are highly responsible in determining the load carrying capacity of the pavement, thus, it is paramount to choose aggregates that are sufficiently strong and durable towards the applied load. Not to mention, aggregates are constantly exposed to crushing and impact not only during the pavement in-service, but also throughout the process of constructing the pavement, such as during the stockpiling of the aggregate and during the compaction of the pavement. Therefore, if the aggregates are too substandard and have low impact resistance, the aggregates would be most likely to break apart or be broken down right before the pavement was even in-service. Hence, ensuring the aggregates are highly durable and tough is very beneficial to avoid early defects on the pavement surface.

Aggregate crushing value (%) = $\frac{Weight\ of\ aggregate\ passing\ (\text{kg})}{weight\ of\ aggregate\ (\text{kg})} \times 100\%$

Weight of aggregate (kg) = 2.65

Weight of aggregate passing sieve (kg) = 0.65

Aggregate crushing value (%) = $\frac{0.65}{2.65} \times 100\%$ = 24.53%

3.5 Marshall Stability, Flow and Stiffness

Based on the Figs. 5-7, it is noticeable how the same percentage of crumb rubber would give different impact and end-result to the stability, flow, and stiffness of the asphaltic mixture with different grading. From Fig. 5, it can be seen that within dense mixture, with the introduction of 12% crumb rubber, the stability suddenly decreased from 17.8 kN (control mixture) to 12.03 kN for dense mixture. The stability steadily decreased until the percentage of crumb rubber replacement was 18%. At 18% the value struck back to 15 kN, in which the value was still lower than the control mixture but was the highest within all the modified CRMB mixtures. As for the porous graded mixture, it is recorded that with the introduction of crumb rubber of 12%, the stability increased slightly from 5.04 to 5.37 kN. With further replacement to 14% and 16%, the value kept on rising to 9.33 kN and 12.88 kN, respectively. However, at 18% of crumb rubber replacement, the result started to turn counterproductive as the value dropped back to 11.8 kN. This is because at larger content percentage of crumb rubber, high stiffness tendency was exhibited by the asphalt mixture, thereby reducing the stability performance when subjected to the load due to the loss of one-to-one contact points of the aggregate particles in the bituminous mixture.

As for the correlation between the percentage of crumb rubber and Marshall stability result for both dense mixture and porous mixtures, it can be computed as below:

$$Rdense = \sqrt{0.1346} = 0.367$$

while for porous mixture,

$$Rporous = \sqrt{0.8539} = 0.924$$

Based on the coefficient of correlation calculated above, it certainly can be concluded that the CRMB contributes to more significant impact on the porous mixture than dense mixture as the coefficient of correlation for porous mixture is closer to 1. This may be happening due to the porous mixture grading containing fewer fine particles compared to dense mixture grading. Hence, porous mixture would be comprised of bigger air voids in between the coarse particles. As the crumb rubber swelled during the mixing process, it then could eventually fill up the space, thus increasing the overall stability of the mixture. From the result of the Marshall stability on the porous mixture as well, it can be established that the optimum percentage of crumb rubber replacement is 16% as the mixture achieved the highest value of stability, where the stability rises up by 85.1%. This proves that the incorporation of crumb rubber in porous mixture would influence the overall strength and resistance towards applied loads.

In terms of the Marshall flow for dense mixtures as shown in Fig. 6, with a replacement of crumb rubber of 12%, the value of flow decreases from 3.05 mm to 2.96 mm, but the value rises back to 3.16 and 3.88 mm with a replacement of 14% and 16%. Nonetheless, at 18%, the value of flow drops back to 2.8 mm which is the lowest value from the overall. As for the porous mixture, in contrary with the stability result, the percentage of 16% of crumb rubber replacement also seems to produce the utmost flow value, where the value obtained is the lowest within the CRMB mixed with porous grading with a value of 4 mm. Marshall flow is one of the paramount mechanical properties of the pavement that needs to be checked. Marshall flow is signifying on the deformation rate potential that is undergone by the pavement at the highest value of load applied. High flow indicated that the high tendency in pavement mixture easily exposed the deformation. Thus, having the lowest value of Marshall flow is preferred since it would lead to the higher resistance towards deformation such as rutting. The strength of the relationship between the percentage of crumb rubber and the Marshall flow are as shown below:

$$Rdense = \sqrt{0.0252} = 0.159$$

while for porous mixture,

$$Rporous = \sqrt{0.7651} = 0.875$$

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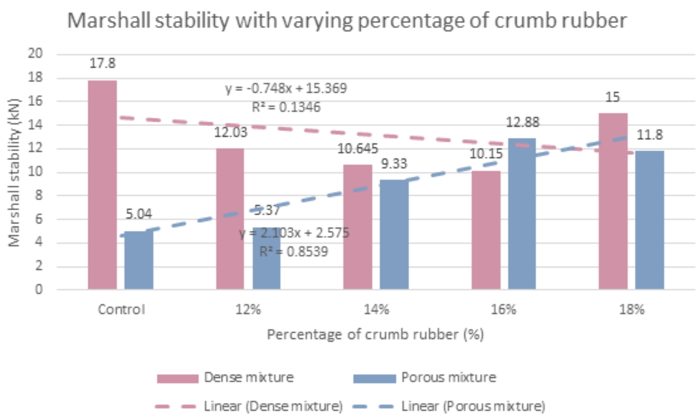

Fig. 5: Marshall stability for asphaltic binder utilizes to both dense mixture and porous mixture with percentage of crumb rubber varying from 0% to 18%.

Similar to the Marshall stability, the porous mixture seems to exhibit a stronger relationship for the Marshall flow with increasing percentage of crumb rubber replacement as the value for Rporous is closer to 1 compared with the value for Rdense. This ultimately signifies that the introduction of crumb rubber in the porous mixture could help influence and increase the resistance of the pavement towards permanent deformation or instability.

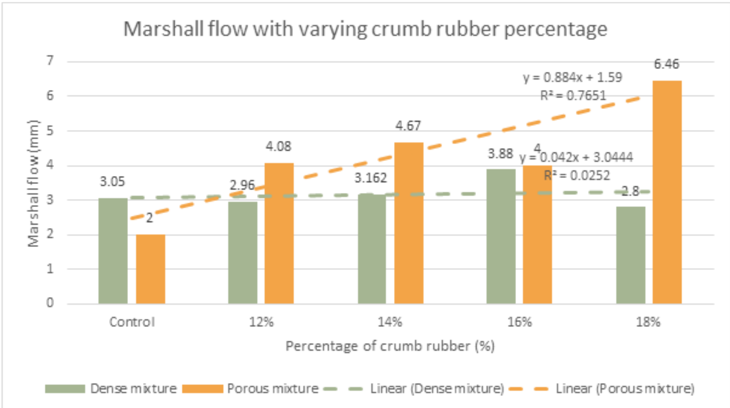

Fig. 6: Marshall flow for asphaltic binder utilizes to both dense mixture and porous mixture with percentage of crumb rubber varying from 0% to 18%.

Upon computing the values for stiffness using the equation in section 2.5 of this paper, the results were tabulated into the graph shown in Fig. 7. From the figure, it can be concluded that 18% of crumb rubber replacement gives the overall highest value of stiffness. Therefore, 18% is chosen as the most optimum percentage for dense graded mixtures. For porous mixtures, 16% of crumb rubber is the most ideal for porous grading aggregate as at this percentage, the stiffness value is the highest among all other crumb rubber replacement percentages with a value of 3.22 kN/mm. Established by the authors of [14], it is paramount for the value of the stiffness to be high as it signifies the higher ability of the pavement layer to spread the applied load and resistance relatively. In order to establish and compare the influence of the crumb rubber on both dense mixture and porous mixture, the coefficient of correlation for both dense mixture and porous mixture were computed as shows below.

$$Rdense = \sqrt{0.0801} = 0.283$$

while for porous mixture,

$$Rporous = \sqrt{0.0127} = 0.113$$

Nonetheless, as for the dense mixture, it is fair to say the crumb rubber does not signify any improvement on it, as the value of Marshall stability and Marshall stiffness for control mixture is higher compared to any dense mixture that is incorporated with CRMB. However, when comparing the result within the mixture with CRMB itself, 18% or the highest percentage of CR replacement, is shown to produce asphalt mixtures with the highest Marshall stability and stiffness of 15 kN and 5.36 kN/mm respectively and lowest Marshall flow value of 2.8 mm. Therefore, proving that the optimum percentage of CR replacement for dense mixture is 18%. According to the previous research executed by the authors of [2] and [15], the value of the Marshall stability and stiffness should be enhanced as the percentage of crumb rubber replacement increases, however the result of this research shows a different outcome especially for the dense mixture. Nonetheless, the authors of [6] stated in the findings that the reduction in the value of Marshall stability and stiffness after the introduction of crumb rubber to the mixture may happen due to lack of adhesion between the aggregates. This may occur as with higher crumb rubber percentage, the binder would become more viscous and less workable. This can be proven based on the result of the penetration test shown in section 3.1. Thus, due to this, it is harder to coat all the aggregates properly and fully, which eventually leads to the occurrence of stripping and reduction of the overall strength of the sample. In observing the structure of the dense mixture itself, the typical structure arrangement inside the mixture is close and compact. As the crumb rubber was added in dense mixture, it contributed to the excessive stiffness that led to the high potential of cracking, thereby reducing the stability performance of dense mixture.

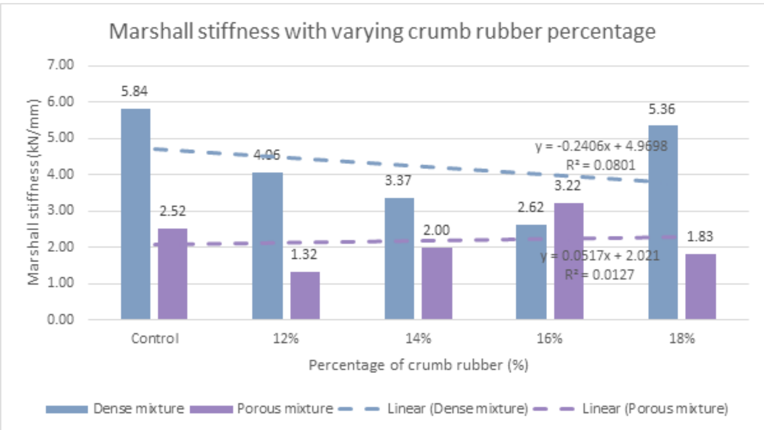

Fig. 7: Marshall stiffness for asphaltic binder utilizes to both dense mixture and porous mixture with percentage of crumb rubber varying from 0% to 18%.

4. CONCLUSION

The following conclusions were drawn to summarise the result obtained during the research work:

- For higher percentage of crumb rubber replacement, the binder would be stiffer as the value of penetration depth reduced progressively when the percentage increases. Other than that, from the result of softening point, it was also proven that the modification of asphalt binder with crumb rubber would cause the binder to be less susceptible towards temperature changes and the relationship between percentage of CR and softening point value shows a positive linear relationship, in which as the percentage of CR increases, the softening point rises as well.

- Marshall stability and Marshall flow test on the asphaltic mixture are conducted in identifying optimum percentage of crumb rubber replacement in the modified binder for dense asphalt mixture and porous asphalt mixture. From the analysis, it was acquired that for dense asphalt mixture, the optimum percentage of CR is 18% whereas for porous asphalt mixture, 16% gives the most optimum result.
- Based on the analysis executed, it was established that the utilization of CRMB for porous mixtures shows a more significant improvement compared to the utilization of CRMB for dense mixtures. This is proven as the coefficient of correlation obtained for Marshall stability in porous mixtures is higher than the coefficient of correlation obtained for Marshall stability in dense mixture, in which 0.924 is bigger than 0.367. Since the value of coefficient of correlation obtained for Marshall stability at porous mixtures is closer to 1, it shows that the relationship between the percentage of CR and Marshall stability for the porous mixture is very strongly significant.

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