The Addition of a High Dosage of Rubber to Asphalt Mixtures: The Effects on Rutting and Fatigue

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Abstract: Bitumen is subjected to cracks and damage during its service life. Adding a material with the potential to increase the durability of bitumen can expand its service life and reduce maintenance costs. Previous studies indicate that adding crumb rubber into asphalt has a positive effect on the performance of the mixture. Using crumb rubber may solve environmental problems due to vehicle tire waste disposal by reducing maintenance costs needed to increase asphalt’s strength. Some studies have investigated the effect of bitumen mixed with crumb rubber; however, it seems that the effect of different types of rubber mixtures used has been overlooked. Therefore, this study aims to better understand the effects of the increasing amount of rubber addition in various types of asphalt mixtures and determine the optimal mixture that could be used in road construction. A series of experiment was conducted, incorporating various tests (such as Marshall stability, rutting, and fatigue), to test various mixtures of asphalt in the form of dense-graded asphalt (DGA), fine gap-graded asphalt (FGG), gap-graded asphalt (Stone Mastic Asphalt, SMA), and open-graded asphalt.

The amount of added crumb rubber was 25% by weight of bitumen. All mixtures were classified as superior in rutting and fatigue resistance, since they all reached a maximum depth of rutting less than 15 mm and generated two times more failure cycles compared to the conventional asphalt. The most optimal performance asphalt mixture was showed by the SMA10 mixture, resulting in a minimum rut depth of less than 1.2 mm and producing 750% more fatigue cycles than conventional asphalt. The result indicates that the addition of 25% of the rubber particles in the binder can increase the properties and durability of asphalt mixtures.

Keywords: asphalt rubber; stone mastic asphalt; crumb rubber

1. Introduction

Crumb rubber is a recycled used tire, ranging from 4.75 mm to 0.075 mm in size, with a fiber content less than 0.5% and specific gravity of 1.15 ± 0.05 [1]. Crumb rubber could be incorporated into the asphalt mixture to prolong its service life [2]. Crumb rubber was first used in 1840 and, according to Thompson and Hoiberg [3], adding the rubber into bitumen can increase the technical properties of asphalt mixtures. Yildirim [4] stated that using rubber in the form of patches, joint sealers, and membranes started in the late 1930s. Hanson and Foo [5] said that used tires had been utilized as an asphalt hardener since 1950. Charlie Mac Donald [6] modified the bitumen binder using an additive in the form of tire rubber. The results indicate that the rubber particle size swells in high temperatures, potentially causing the volume increment. In the 1980s, Brule [7] stated that Europeans did a lot of research to develop a modified bituminous binder with a new additive polymer. Several years later, research has shown that asphalt performance can be improved by adding crumb rubber [8].
Asphalt is prone to cracks and damage after construction. The introduction of a mixture or binder into asphalt is required to increase asphalt’s life and reduce road maintenance costs [9]. Using crumb rubber in high quantities in asphalt mixtures may improve asphalt’s life, reducing environmental problems due to tire waste disposals [10]. Every year, the United States produces 300 million scrap tires, and 5.5% come from civil engineering applications [11]. Meanwhile, Australia generates 50 million waste tires [12]. Therefore, in infrastructure development, including the asphalt hardening process, it is expected to use the 3R principle (reclaim, recycle, reduce) for sustainability and reduce the amount of waste generated [13].

According to Venudharan and Biligiri [14], cost savings will also occur due to using used tires, while other bitumens, such as synthetic rubber-styrene-butadiene (SBR), styrene-butadiene-styrene (SBS), and natural rubber fiber, are classified as expensive polymers. Other polymers have been used for asphalt mixtures, adding waste Polyethylene Terephthalate (PET) plastic increased asphalt’s life and reduced costs. However, the use of PET plastic has not been tested in depth with various mixing conditions for application in the field [15]. Research on asphalt rubber has developed extensively. Wang and Dang [16] studied the effect of several factors on asphalt, such as the type of gradation on fatigue crack and a mixture of crumb rubber and asphalt. The results indicate that the gap-graded gradation has better fatigue test results than continuous grading. Further, Saha and Biligiri [17] evaluated the fracture damage of asphalt, mentioning that open-and gap-graded gradations have better asphalt performance than dense-graded gradations, which were previously used as in asphalt utilization. This can occur because the solid-graded aggregate does not have adequate storage space for the rubberised binder content.

However, in-depth research related to the effect of different types of rubber mixtures used to improve asphalt performance is limited, along with research on the amount of rubber that can be added to the asphalt. Therefore, this study aims to provide insight into the effect of increasing the amount of added rubber into various types of asphalt mixtures concerning asphalt performance while maintaining the technical properties of the mixture. A set of experimental tests were carried out to test the mixture of asphalt in the form of dense-graded asphalt (DGA), fine gap-graded asphalt (FGG), gap-graded asphalt (Stone Mastic Asphalt, SMA), and open-graded asphalt. The test consisted of particle size density (PSD), a density test, and void water, followed by Marshall stability and flow testing, rutting resistance testing and fatigue life testing. The test results were compared to the specifications in Standards [18] AS 2150–2005 to determine the optimum asphalt mix performance.

2. Material and Method

2.1. Material

The aggregate material was obtained from Curtin University’s laboratory stockpiles in the form of DG10 dense-graded 10 mm, SMA10 asphalt mastic stone 10 mm, SMA14 or asphalt mastic stone 14 mm, and FGG10 or fine gap-graded asphalt 10 mm. The filler was used as an aggregate void filler of the gap-graded asphalt to increase its stability [19]. The crumb rubber used in this study had a size of less than 0.3 mm to promote it to dissolve into bitumen. Another material used is the C320 bitumen binder which was produced at 260–380 Pa, and a temperature of 60 °C refers to the Standards [20] AS2891.1.3-2008.

Figure 1 presents the particle size distribution (PSD) test results, which was carried out according to Australia Standards [18]. The aggregate combination is shown in Table 1. The 14 mm aggregate is presented in SMA14-1 and SMA14-2, since they came from two different suppliers. Both were tested to acquire the most suitable material for production. The result indicated that DG10 had a smaller aggregate gap than the SMA, while SMA14-1 had finer particles than SMA14-2.
Figure 1. Particle size distribution test.

Table 1. Aggregate grading combinations.

| Combination | DG10 | SMA10 | SMA14-1 | SMA14-2 | FGG10 |
|-------------|------|-------|---------|---------|-------|
| 5 mm        | 12%  |       |         |         | 5%    |
| 10/7 mm     | 46%  | 30%   |         |         |       |
| 10 mm       | 50%  |       |         |         | 35%   |
| 14 mm (BGC) |      |       |         | 80%     |       |
| 14 MM (Boral) |  |      |         |         | 75%   |
| Dust        | 42%  | 12%   | 12%     | 12%     | 65%   |
| B.Dust      | 8%   | 8%    | 8%      | 8%      |       |

2.2. Sample Preparation

The amount of crumb rubber used was 25% by weight of bitumen. This percentage was chosen following Presti [1] as well as Venudharan and Biligiri [14], who suggested that the additive added to bitumen is 15–25% of the total bitumen weight. Therefore, 25% crumb rubber was added to DG10, SMA10, SMA14, and FGG10 to obtain the asphalt rubber mixture. Meanwhile, dense asphalt (DG10) served as a control mixture. The Marshall stability test was conducted at temperatures of 180 °C and 5000 RPM, and was found to be the most suitable conditions for the flow and stability for three-hour Marshall stability testing on the hotplate. All mixtures were cast on the asphalt plate using OBC. Following this, they were cut into three beam samples with an automatic saw and airdried for three days to obtain the fatigue value. The air space and slab weight were recorded. Each of the two square slabs of the asphalt mixture was cast and then compacted to be inserted into the wheel tracker mold to obtain the rutting resistance value.
2.3. Experimental Tests

2.3.1. Marshall Stability and Flow Test

The Marshall stability and flow tests were performed according to AS/NZS 2891.5:2015 Standards [21]. Samples were prepared by adding 110 g asphalt with 150 ± 3 °C into a cylindrical mold of 100 mm in diameter. The samples were then compacted using a mechanical hammer on all sides of the sample, then dried and extracted using a jack. The height and air void of the samples were measured by putting all the samples into a hot water bath at 60 °C for 30 min. All samples were then tested using a Marshall stability machine with a 51 ± 3 mm/minute shift rate.

2.3.2. Fatigue Cracking

The fatigue test sample was prepared according to AS/NZS 2891.1.2.1:2014 Standards [22]. The equipment used to measure fatigue is shown in Figure 2. Loads were applied to four points of each sample to instigate an asphalt block to bend and crack. The slab was cast and compacted with a segmental wheel compactor and then cut into three specimens of a rectangular beam (39 ± 5 mm long, 63.5 ± 5 mm horizontally wide and 50 ± 5 mm vertically deep). The blocks were tested three times and referred to Austroads [23,24] AG: PT/T233 to minimize errors.

Figure 2. Four-point bending beam fatigue apparatus.
2.3.3. Rutting Test

The rutting test refers to the Austroads [19] AG: PT/T231 testing method, with a temperature of 60 °C, representing extreme temperatures, and a 700 N vertical load, representing traffic conditions in reality. The sample used 10 mm and 14 mm thicknesses and nominal size of 50 ± 5 mm. The vertical load (N) 700 ± 20 N, air space content of 5 ± 0.5%, and the dimensions of the specimen measured as 300 mm × 300 mm. Table 2 shows the details of the asphalt mix performance criteria. The number of tests conducted for this research is presented in Table 3. Table 4 presents the number of tests in this study. The binder content of 3 is needed in sequential volumetric tests to obtain the optimal binder content for the asphalt rubber binder.

Table 2. Mixed Austroads performance criteria as per Ap-T100/08

| Performance   | <3.5 | 3.5–8 | 8–13     | >13    |
|---------------|------|-------|----------|--------|

Table 3. Experimental testing program.

| Mix Type | Wheel Tracking Test | Fatigue Test | Volumetric and Marshall Test |
|----------|---------------------|--------------|-----------------------------|
| DG10     | 2                   | 3            | 6                           |
| DG10 AR  | 2                   | 3            | 2                           |
| FGG10    | 6                   | 3            | 3                           |
| FGG10 AR | 2                   | 3            | 3                           |
| SMA10    | 6                   | -            | 6                           |
| SMA10 AR | 2                   | 3            | 2                           |
| SMA14    | 6                   | -            | 6                           |
| SMA14 AR | 2                   | 3            | 2                           |

Table 4. Comparison of asphalt mixtures specification as per standard and results of volumetric tests.

| Asphalt Mixture | Specifications | Results of Volumetric Tests |
|-----------------|----------------|-----------------------------|
|                 | Bitumen Content (%) | Air Voids (%) | VMA (%) | Bitumen Content (%) | Air Voids (%) | VMA (%) | Maximum Density (t/m³) |
| DG10            | 4.5–6.5          | 3–7             | 16      | 4.9–5.00           | 4.6–5.00     | 16.77   | 2.475                  |
| DG10 AR         | 4.5–6.5          | 3–7             | 16      | 6.3–6.15           | 6.3–6.15     | 20.87   | 2.407                  |
| SMA10           | 6.0–7.0          | 3–6             | 18      | 6.4–4.50           | 5.68–4.50    | 19.52   | 2.418                  |
| SMA10 AR        | 6.0–7.0          | 3–6             | 18      | 7.0–5.68           | 5.68–5.68    | 22.09   | 2.414                  |
| SMA14           | 6.0–6.8          | 3–6             | 18      | 6.3–4.5            | 4.5–4.5      | 19.82   | 2.504                  |
| SMA14 AR        | 5.8–6.3          | 3–6             | 18      | 6.8–4.39           | 4.5–4.39     | 20.72   | 2.473                  |
| FGG10           | 6.0–7.0          | 2–5             | -       | 6.0–2.4            | 2.4–2.4      | 16.48   | 2.417                  |
| FGG10 AR        | 6.0–7.0          | 2–5             | -       | 6.5–3.68           | 3.68–3.68    | 18.43   | 2.338                  |
3. Results and Discussion

2.4. Air Void and Density

The results of the volumetric test and AS2150-2005 Standards [18] specifications are shown in Table 4. The asphalt mixture had a water void value exceeding the virgin mixture and specifications in AS2150-2005, so it was necessary to add bitumen. The DG10 AR mixture had a bitumen content of 6.3% and a water void of 6.15%. This was similar to the results of the SMA10 AR, SMA14 AR, and FGG10 AR tests, which increased the bitumen content to reach the air void target. The bitumen content value increase was inversely proportional to the value of air void, which became smaller to reach the target. This is supported by the research of Mashaan and Karim [25]. They explained that the absorption of the binder by rubber particles occurs because the smaller binder acts as a cavity filler and an aggregate wrapper. Therefore, it can be concluded that the rubber particles in the binder material caused a decrease in the contact point between the aggregates, and the air cavity can increase in the asphalt rubber.

Table 4 shows a similar maximum density of SMA10 with SMA10 AR, and DG10 is similar with bitumen contents of DG10 AR. For the bitumen content value of the virgin mixture similar to the asphalt mixture, the maximum density value will also be similar. Therefore, there is no effect of the binder on the maximum density of the asphalt rubber mixture. For the mixture of DG10 AR and SMA10 AR, an increase in asphalt content caused a decrease in the maximum density due to an aggregate content reduction, which occurred when the aggregate density was higher than the bitumen density.

2.5. Marshall Stability and Flow

2.5.1. Marshall Stability

Marshall stability is obtained from the friction value from both internal and aggregation [26]. According to the Fattah and Hilal [27], the Marshall test is the right method to use to determine whether asphalt has good performance. The stability value is used as an indicator of strength in resisting external loads. Fadhil and Ibrahim [28] proposed that the Marshall test can be used to evaluate asphalt designs, especially HMA, for applications on highways. Its application has also been employed to design asphalt mixtures worldwide [29]. Therefore, it is very important to carry out this test, specifically to maintain the field application of different types of asphalt grading [30]. The Marshall stability values are presented in Table 5 and Figure 3, showing that all mixtures met or were above the specifications of AS2150-2005 Standards [18]. The asphalt mixture had a lower Marshall stability value than the virgin mixture, except for SMA14 AR with a value of 12.89 kN at odds with SMA14 by 0.11%. This statement is consistent with the research of Liu and Han [31] which showed that the stability value of the virgin gap Marshall is higher than the asphalt mixture’s stability. The increased SMA14 R value was classified as abnormal. This could be due to it being influenced by the water void and the aggregate framework of the asphalt mixture. If the value of the void water is low, the stability value increases, as indicated by the mixture of virgin FGG10, which had the lowest void water value and the highest stability. Figure 3 shows the stability values for mixes.

| Asphalt Mixture | Specifications | Results of the Marshall Test |
|-----------------|----------------|-----------------------------|
|                 | Bitumen Content (%) | Marshall Flow (mm) | Marshall Stability (kN) | Bitumen Content (%) | Marshall Stability (kN) | Marshall Flow (mm) |
|                 | Min | Max | Min | Max | Min | 4.9 | 16 | 2.5 |
| DG10 AR         | 4.5 | 6.5 | 2   | 4   | 6.5 | 6.3 | 14.38 | 3.48 |

Table 5. Comparison of asphalt mixtures specifications and results of the Marshall test.
Table 5. Cont.

| Asphalt Mixture | Specifications | Results of the Marshall Test |
|-----------------|----------------|-----------------------------|
|                 | Bitumen Content (%) | Marshall Flow (mm) | Marshall Stability (kN) | Bitumen Content (%) | Marshall Stability (kN) | Marshall Flow (mm) |
| SMA10           | 6.0 7.0          | 2 5                | 6.4 10.30               | 2.8               |
| SMA10 AR        | 6.0 7.0          | 2 5                | 7.0 10.21               | 3.77              |
| SMA14-2         | 5.8 6.8          | 2 5                | 6.3 7.1                 | 2.39              |
| SMA14-2 AR      | 5.8 6.8          | 2 5                | 6.8 12.89               | 3.55              |
| FGG10           | 6.0 7.0          | 2 5                | 4.5 17.85               | 2.76              |
| FGG10 AR        | 6.0 7.0          | 2 5                | 4.5 6.5                 | 3.52              |

Figure 3. Marshall Stability values for mixes.

2.5.2. Marshall Flow

Similar to the Marshall stability test results, Table 5 presents the Marshall flow values of all mixtures that fall into the range of values allowed, according to AS2150-2005 Standards [18]. The highest value was obtained from the SMA10 mixture, and all asphalt mixtures had a higher value than the virgin mixture. This aligns with Liu and Han’s [31] research, which stated that if the Marshall flow value of the rubber gap gradation asphalt is higher than the virgin mixture due to the larger air void during loading, the stress concentration will also be higher. An increase in the Marshall flow value in the asphalt mixture can occur due to the higher rubber content because the increased bitumen will cause the aggregate to float in the mixture. Figure 4 shows the flow values for mixes.
2.6. Rutting Resistance

The results of the rut depth test are shown in Table 6. Nwakaire and Yap [32] stated that this test aims to overcome the accumulation of traffic loads that cause permanent deformation. The test results of all mixtures were met or even above the specifications set by Austroads [19]. According to Table 6, no sample reached a depth of 15 mm of rutting. The SM10 AR mixture obtained the lowest rut depth, and the DG10 mixture showed the highest depth. The rutting value of DG10 AR was also lower than DG10. This indicates that the asphalt mixture had a better performance than the virgin mixture. These results are in accordance with the research of Chegenizadeh and Tokoni [33], which obtained results with the rutting resistance of a virgin SMA mixture being lower than SMA mixed with other components such as Ethylene-Vinyl Acetate (EVA). The research of Piromanski and Chegenizadeh [34] obtained similar results to the statement above, indicating that the rutting resistance of the asphalt mixture increases when other components are added such as waste HDPE polymer.

Table 6. Summary of rutting resistance results.

| Ranking | Mix Type   | Rut Depth (mm) |
|---------|------------|----------------|
| 1       | SMA10 AR   | 1.15           |
| 2       | SMA14 AR   | 1.40           |
| 3       | DG10 AR    | 1.50           |
| 4       | FGG10 AR   | 1.95           |
| 5       | DG10       | 2.40           |

Meanwhile, the SMA10 AR mixture was the best-performing mixture, consistent with the findings of Venudharan and Biligiri [14] as well as Kaloush [35]. Furthermore, the rut depth test of DG10 AR was deeper than SMA10 AR. An acceptable rationale is that SMA10 AR blends produce optimum stone contact blends and available voids that allow sufficient minerals to incorporate crumb rubber in the mixture. The FGG10 AR mixture is a fine gap-graded asphalt, which has a fine main material and causes stripping during rutting.
This phenomenon is presented in the wheel track result in Table 6, indicating a fluctuating result. Figure 5 presents the wheel tracking curves and Figure 6 present the comparison of rut values.

Figure 5. Results of the wheel track test.

Figure 6. Rut depth for wheel track tests.
2.7. Fatigue of Asphalt Rubber

2.7.1. Initial Flexural Stiffness of Asphalt Rubber

The results of flexural stiffness in Table 7 indicate that the control mixture DG10 had the highest value compared to the other rubber mixtures. Rubber particles cause stiffness and flexural properties to be reduced when loaded. This can occur because of rubber’s elastic nature. However, the bitumen content factor also has an effect when the bitumen is higher and the flexural strength of the asphalt rubber mixture is lower. FGG10 AR had the lowest aggregate stiffness, while SMA10 AR showed the opposite result. The reason for this might be that the higher the stone-on-stone contact is, the more resistant it is to deformation.

Table 7. Summary of the fatigue test.

| Mix Type       | Air Void (%) | Initial Flexural Stiffness | Number of Cycles |
|----------------|--------------|----------------------------|------------------|
| SMA10 AR       | 4.57         | 5179                       | 605,296          |
| FGG10 AR       | 3.7          | 4263                       | 587,986          |
| SMA14 AR       | 2.93         | 4447                       | 286,786          |
| DG10 AR        | 5.17         | 4691                       | 236,363          |
| DG10           | 5.13         | 7928                       | 80,843           |

2.7.2. Fatigue Cycle

Figure 7 shows that the SMA10 AR mixture had the highest fatigue value, while DG10 indicated the opposite result. Compared to the DG10 mixture, the SMA10 AR mixture experienced an increase in the fatigue cycle by 750%. The mix of SMA10 AR and DG10 AR also had a difference of 256%. This aligns with Witczak and Mamlouk’s [36] finding that the dense-graded asphalt rubber mixture has a lower fatigue life than the gap gradation. The SMA10 AR mixture in this study had higher test results than Mashaan and Ali’s [37] findings, which were 1.5 times the virgin asphalt mixture. However, the mixture of SMA14 AR had a low value and is very different to SMA10 AR.

![Figure 7. Result of average fatigue cycles of asphalt mixture.](image-url)
Fang and Guo [38] stated that vehicle loads and environmental factors cause repetitive asphalt pavement distress in the long term, which is called the fatigue phenomenon. Hence, it is important to conduct a fatigue test to evaluate the cycle of asphalt rubber from fatigue [37]. The fatigue resistance of this test is classified as superior because the results are two times greater than the number of failure cycles of conventional asphalt.

Flexural stiffness and the number of cycles have different relationships. Occasionally, they are directly proportional to the mixture of SMA10 AR, which has a high strength and fatigue life. It is also inversely proportional to the mixture of FGG10 AR, with the lowest stiffness value and the highest fatigue life. This shows that the aggregate framework plays an important role. Additionally, the flexural stiffness of asphalt rubber is relatively low with high fatigue compared to the control mixture DG10 due to the elastic properties of asphalt rubber.

3. Conclusions

This study aims to understand the increase in the amount of rubber in various types of asphalt mixtures, which is compatible with the performance of the asphalt while keeping its technical properties, and to determine the best asphalt mixture. Dense asphalt DG10 served as a control mixture, and the addition of 25% crumb rubber was conducted on DG10, SMA10, SMA14, and FGG10 to obtain the asphalt rubber mixture. The maximum density and void water test results showed that most of the results were valid according to the AS2150-2005 specifications. However, there were three invalid mixtures, namely DG10 AR, SMA10 AR, and SMA14. The asphalt mixture has a water void value exceeding the virgin mixture and the specifications in AS2150-2005. Therefore, adding bitumen is required. The increase in asphalt content causes a decrease in the maximum density value because the aggregate content is reduced. The Marshall stability and flow test results showed acceptable results according to the AS2150-200 specifications. The asphalt rubber mixture had a lower Marshall stability value than the virgin mixture due to the influence of void water and the aggregate framework. Meanwhile, the Marshall flow of the asphalt rubber mixture had a higher value than the virgin mixture. The results of the rut depth test indicated that all mixtures met or were above the specifications developed by Austroads [18]. The fatigue resistance results of AR added mixes were two times greater than the number of failure cycles of conventional asphalt, while the SMA10 AR mixture experienced an increase in fatigue cycles of 750%. SMA10 performed very well during the rutting and fatigue tests compared to the other mixtures. The result also suggests that 25% of the rubber particles in the binder can be accommodated in the aggregate framework.

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