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Evaluation of the Performance of Two Australian Waste-Plastic-Modified Hot Mix Asphalts

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Abstract: The construction of hundreds of kilometres of roads around the world every year results in the consumption of large amounts of raw materials and the depletion of natural resources. In addition, technologically advanced countries such as Australia are currently facing a major issue regarding the waste materials produced daily by their citizens. The disposal of these waste materials is a critical issue faced by municipalities in modern cities. Currently, using waste materials in civil and construction engineering is of great interest to researchers and industry. This study investigates the impact of using waste polyethylene terephthalate to modify asphalt mixtures following Australian design guidelines and criteria. Different types of asphalt are used to investigate and determine the mechanical properties of modified asphalt mixtures. The Marshall stability, Marshall flow, Marshall quotient, and wheel-tracking tests were tested. The Marshall stability, Marshall flow, and MQ of the Marshall test results exhibited significant improvements when using PET in modified SMA and AC mixtures. It can be seen that the 8% PET produced a mixture with the highest stability of 19.78 kN. The lowest rut depth was about 2.08 mm for samples modified with 8% PET.

Keywords: waste plastic; asphalt modification; stability; rutting

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1. Introduction

Complexity in the modelling of soil aggregates create motivation in carrying out research on the mechanical behaviour of materials [1,2]. Road pavements begin experiencing functional deterioration once they are open to heavy traffic or when groundwater freezes during the cold season. This deterioration can include rutting, fatigue cracking, shoving, and stripping. For instance, Figure 1 shows the cracking deformation at a road section in Perth, Australia. In cold regions, groundwater freezing beneath the surface layer can result in serious cracks in asphalt mixtures over even a single cold season [3,4]. One way to increase the service life of road surfaces is to use certain additives, such as polymers, to modify and improve the properties of the mix. It has been confirmed and reported in several studies that using virgin polymer is costly, and—as such—it is advisable to use waste polymer wherever possible [5–7].

Recycling materials produced by industrial plants and workshops, particularly in the field of civil engineering, have seen significant developments in recent decades. Some successful examples of these developments include silica fumes, furnace slag, and fly ash. The reuse of risky/hazardous waste has also been the subject of significant research over the years. This research is mainly centred on the impact of the residue on the properties of the building and construction materials, along with its effects on the environment. The most recent studies have concentrated on the possibilities of reusing waste materials in pavement construction, which has recently turned into a research hotspot. This has two main causes, namely, the lack or reduction in natural resources used for road construction and the existence of waste materials that can be reused in many construction projects in civil engineering [8–12].



Figure 1. Pavement deformation and cracking (photos by Nuha).

Finding a reliable, long-term, and cost-effective method to treat the issue of waste materials is a major concern in the fields of recycling, construction engineering, and pavement engineering and for local authorities. Their goal is to find an active solution that can save resources and protect the environment from the dumping of waste materials. Thus, efficient recycling is the main solution to manage this waste issue, which is important in industrial engineering and scientific research. According to earlier studies [13–18], recycling is a crucial method that has several advantages, including saving natural resources, protecting the environment, and being cost effective. Consequently, it is important to consider the recycling industry as a vital industry in the current era.

According to previous reports [19–22], using waste plastic for asphalt modification could help reduce environmental contamination and spare additional costs. Therefore, using waste plastic in asphalt is important, and could improve the temperature susceptibility and stiffness. Thus, waste-plastic-modified bitumen results in an enhancement in the rutting and fatigue resistance [23–25]. Modifying and advancing the properties of the bitumen and asphalt mix by using certain additives, such as plastic polymers, is one way of boosting the service life of road surfaces.

The application of waste materials as a replacement for new materials in road construction has a dual advantage. First is the substantial savings and reduced costs, and the second is reducing the quantity of waste that will be dumped in landfills. Thus, the use of waste plastic in the modification of asphalt should focus on enhancing the properties of the mixture [7,13–15,26–28].

The modification of bituminous mixes with waste plastics seems to have great potential for use in flexible pavements to enhance their active service life or minimise the layer thickness of its wearing course or base layer [13,15,29,30]. The application of waste plastic in asphalt modification increases the stability and service life of the pavement, in addition to improving its ability to tolerate high traffic loads, reducing its susceptibility to deformation, and imparting better ageing resistance. In addition, waste plastic asphalt can meet the requirement for design, coating, and construction, and seems to be a substantial, practical, and economical alternative to other commercial polymers [13–15]. Polymer-modified bituminous mixtures have a broad variety of applications worldwide [29,31]. Studies have been conducted to classify bitumen modifiers according to their composition, as follows: elastomeric polymers, plastomeric polymers, fibres, and crumb rubber. These additives vary considerably in their physical and chemical properties, which have a wide variety of influences on the performance of asphalt concrete.

The Australian recycling industry and researchers have worked to find an effective solution to manage this issue of waste production [32]. One significant proposal involved using Australian waste plastic in asphalt and pavement engineering. Waste plastic bags

in asphalt mixtures using the dry-mix method was investigated; however, these tests did not investigate the mechanical characteristics, rheological properties, durability, and engineering prospects of bitumen plastic modifiers using wet-mix methods [33]. Most current studies mentioned use the waste plastic either as an aggregate replacement [34,35] or as a base material for the dry-mix method, where it is used as a filler additive [3,14,19,21]. Therefore, it is important to investigate the use of waste plastics as a modifier using the wet-mix method. In the wet-mix method, the waste plastic is blended with heated bitumen using high shear mixing prior to being mixed with the aggregate; in the dry-mix method, the waste plastic is mixed directly with aggregate prior to adding the heated bitumen. Thus, dry mixing does not facilitate a deep physical–chemical reaction between the bitumen and plastic polymer. This study aims to investigate and select the optimum plastic modifier to be used in modifying asphalt mixtures following Australian standards. Different mixtures of dense-graded asphalt and stone mastic asphalt are used to investigate and determine the engineering properties of modified asphalt mixtures. To achieve this goal, the Marshall stability, Marshall flow, Marshall quotient, and wheel-tracking tests are used.

2. Materials and Methodology

2.1. Materials

In this study, C320 bitumen was used, provided by SAMI Bitumen Technologies, located in Perth, Western Australia. Table 1 shows the bitumen's properties.

Table 1. Bitumen properties.

Properties	Data	Unit	Methods
Penetration @ 25 °C	41	0.1 mm	AS 2341.12
Brookfield Viscosity @ 135 °C	0.50	Pa.s	AS 2341.2
Flashpoint	249	°C	AS 2341.14
Viscosity @ 60 °C	320	Pa.s	AS 2341.2

The PET plastics were collected from local communities in Perth, washed, and ground to a size of about 0.245 mm. The most common asphalt mixtures in use in pavement construction in Western Australia, WA, were used herein. The conventional 10 mm SMA and 14 mm dense-graded asphalt for course surfacing were employed. This type of aggregate is identified as the most widespread natural aggregate in Western Australia. Tables 2 and 3 show the particle-size distribution of asphalt mixtures used in this study.

Table 2. Particle-size distribution of dense graded asphalt.

Sieve Size (mm)	Lower Limit	Upper Limit	Selected Gradation
19	100	100	100
13.2	90	100	93
9.5	72	83	77
6.7	54	71	62.5
4.75	43	61	53.5
2.36	28	45	35.5
1.18	19	35	28.5
0.6	13	27	20.5
0.3	9	20	14
0.15	6	13	8.5
0.075	4	7	5

Table 3. Particle-size distribution of stone mastic asphalt.

Sieve Size (mm)	Lower Limit	Upper Limit	Selected Gradation
13.2	100	100	100
9.5	90	100	95
6.7	25	40	30
4.75	18	30	21.5
2.36	15	28	19.8
1.18	12	24	16.7
0.6	12	21	14.5
0.3	9	20	14
0.15	6	12	8
0.075	3	7	5

2.2. Sample Fabrication

The source of waste PET was local recycled water bottles, which were collected, washed, and ground to a size of 40–0.45 mm. As highlighted in Chapter three, the PET-modified binder used a high shear mixture at 4000 rpm and 180 °C for 40 min. Then, following wet mixing, the PET-modified bitumen was mixed with the aggregate to fabricate the PET-modified mixtures following the Marshall method. The optimum binder content was used in all samples of asphalt mixtures modified with waste plastic using various contents of 4%, 6%, and 8% by weight of the bitumen. The Marshall stability, Marshall flow, Marshall quotient, and wheel-tracking tests were used to investigate the influence of using waste plastic on the stability and strength properties of asphalt mixtures.

2.3. Marshall Tests

Usually, the Marshall method is used to design asphalt mixtures and verify the acceptable number of voids in them. Specimens were prepared in the laboratory using 50 or 75 blows per side from a Marshall hammer. The hammer blows impacted the cylinder sample, with a diameter of 101 mm and a height of 64.5 mm. The Marshall mixing method plays an important role in considering the air voids, strength performance, and durability properties of the mixture. It is worth noting that the Marshall mixing method has good results in designing both dense-graded asphalt and stone mastic asphalt. It is easier to achieve the compaction of the SMA/dense-graded mixture on the road and the desired density level in comparison to that required by conventional HMA. In the current study, the procedure included the heating, mixing, and compacting of the mixture of aggregates and bitumen, specified by the Marshall method [36]. The Marshall test machine is shown in Figure 2, and the main parameters tested were the stability of the flow and Marshall quotient (MQ).

2.4. Wheel-Tracking Test

This test has been conducted to evaluate and determine the resistance of the modified mixture to rutting. The Australian standard AGPT/T231 [37] has been used as a reference for the wheel-tracking test. The test parameters were a temperature of 60 °C and a vertical load of 700 N, applied to the top of the specimen using a wheel with a diameter of 200 mm. For every mix batch, three slabs were contacted using a copper roller compactor, following the Australian standard AGPT/T220. Each slab was attached to a moving table, with 42 passes/minute being the rate of the moving table. The test terminated automatically after reaching 10,000 passes. The mixture sample was kept in the box machine the entire previous night. The test only began when accurate and correct conditions were ensured, as shown in Figure 3.



Figure 2. Marshall tests at Curtin University.



Figure 3. Wheel-tracking sample and testing at Curtin University.

3. Results and Discussion

3.1. Marshall Test Results

Marshall tests were mainly used to determine and evaluate the ability of asphalt mixtures to resist collapse and permanent deformation, specifically rutting deformation. The results of the Marshall test, showing the Marshall stability and Marshall flow, are displayed in Figures 4–9 for different asphalt mixtures.

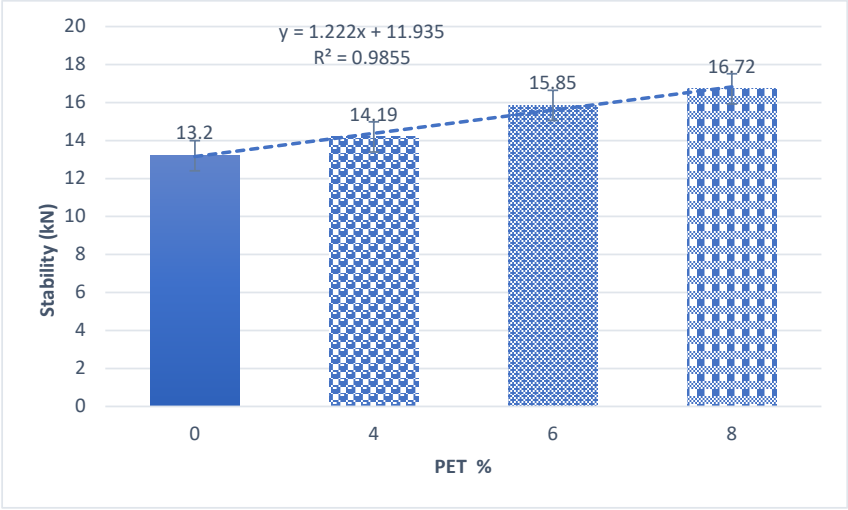


Figure 4. Marshall stability of the PET-modified AC asphalt mixtures.

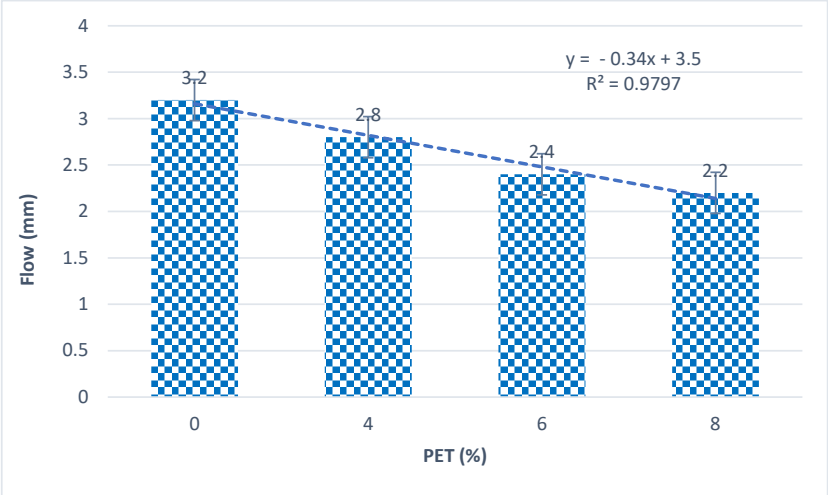


Figure 5. Flow results for the PET-modified AC asphalt mixtures.

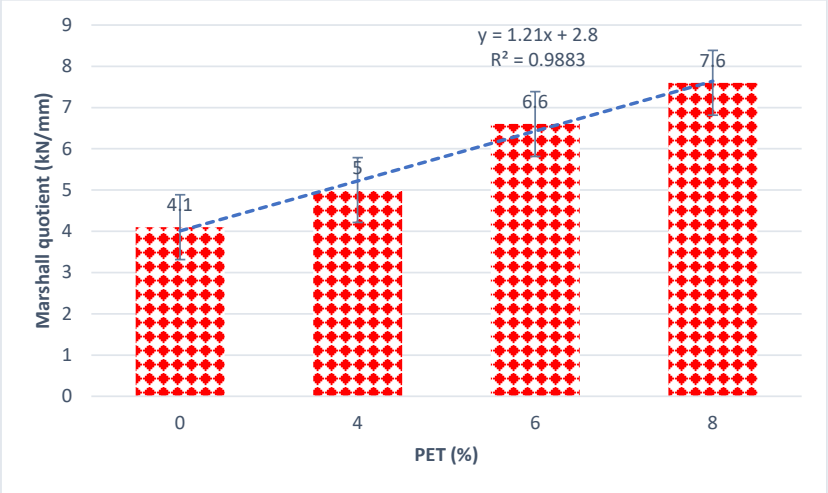


Figure 6. MQ results for the PET-modified AC asphalt mixtures.

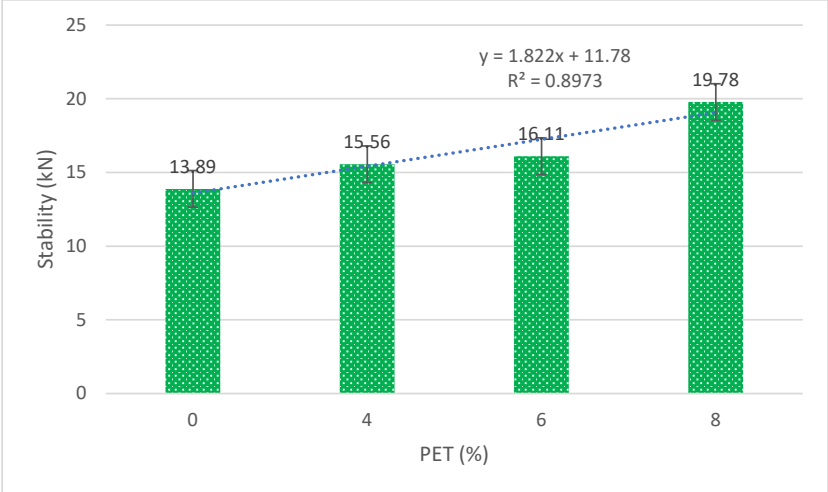


Figure 7. Stability of the PET-modified SMA asphalt mixtures.

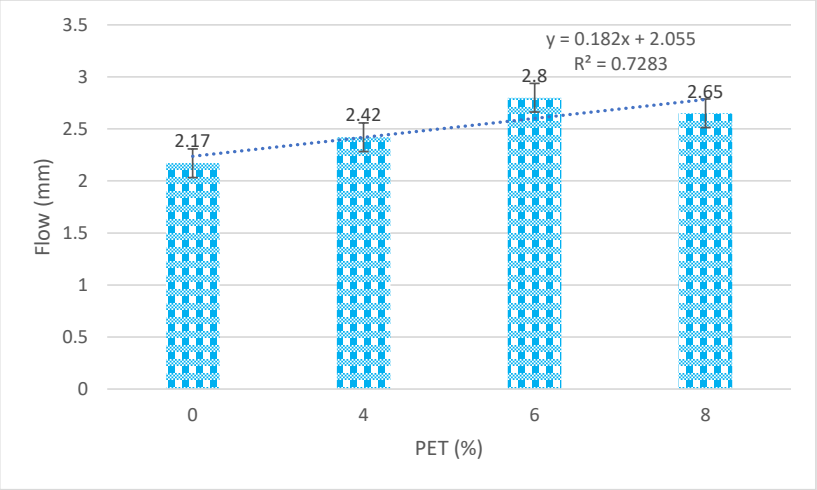


Figure 8. Flow of the PET-modified SMA asphalt mixtures.

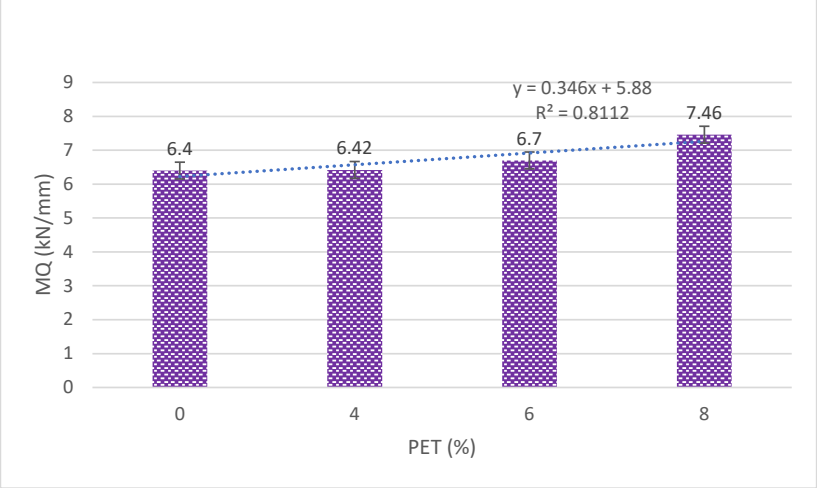


Figure 9. MQ results for the PET-modified SMA asphalt mixtures.

Results for the dense-graded asphalt samples are shown in Figure 4; the stability increases as the PET content increases from 4% to 6%, at 14.19 kN and 16.72 kN, respectively, in comparison to only 13.2 kN of the non-modified mixture (0% PET). On the other hand, Figure 5 shows the decrease in the Marshall flow, from 3.2 mm at 0% PET to 2.2 mm at 8% PET. As can be seen from the above results, the more PET content in the mixture, the higher the stability and the lower the flow; consequently, waste-plastic-modified asphalt exhibited improved stability in comparison to non-modified mixtures. The high stability indicates the excellent resistance to cracking, deformation, shear stress, and rutting deformation. The Marshall quotient (MQ) can be defined as the ratio of the Marshall stability to the Marshall flow, which is used as an indicator of the rutting resistance and mixtures' ability to withstand high shear stresses. The higher the waste PET content in the AC mixtures, the higher the MQ values, as shown in Figure 6. Therefore, the samples with waste plastic have a better ability to resist rutting and failure.

Further, Figure 7 shows the stability properties of the PET-modified SMA mixtures. It can be seen that the 8% PET produced a mixture with the highest stability of 19.78 kN. The use of 4% PET and 6% PET led to stabilities of 15.5 kN and 16.11 kN, respectively. Moreover, all PET samples had a significant effect on the Marshall stability in comparison to non-modified mixtures. The result of the Marshall flow supported the Marshall stability, as shown in Figure 8. The results show that 6% PET has the highest Marshall flow of 2.8 mm. This increase in the PET content results in a linear increase in the flow values, from 0%

to 6% PET; the flow value slightly decreases at 8% PET, to about 2.65 mm. The results for MQ were in line with the Marshall stability, exhibiting an increase with increasing plastic content, as can be seen in Figure 9.

3.2. Influence of Waste PET Content on Marshall Results

Figures 10 and 11 show the effect of different PET contents on the Marshall stability and Marshall flow of AC and SMA mixtures. In terms of stability, the PET-modified SMA mixtures have higher values than the PET-modified AC-14 dense mixtures. At 8% PET, the stability values were 19.78 kN and 16.72 kN for SMA and AC mixtures, respectively. All samples of PET-modified SMA mixtures had higher stabilities than PET-modified AC mixtures, even at 0% PET, which reflects the strong stone–stone structure of SMA. It can be seen that, at 0% and 4% PET, the flow of AC dense mixtures was about 3.2 mm and 2.8 mm, respectively. These results changed when more PET content was added to the asphalt mixture, resulting in 2.4 mm and 2.2 mm flows for 6% and 8% PET-modified SMA mixtures, respectively. Therefore, the PET content has an obvious impact on the stability, stiffness, and flow properties of SMA mixtures in comparison to the AC dense-graded mixtures. The reason for this could be the fact that SMA has more strength and durability than dense-graded mixtures [5,38].

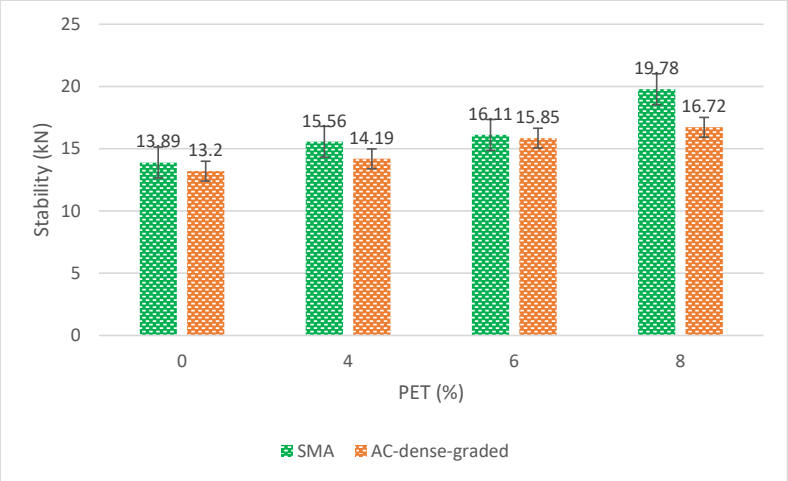


Figure 10. Effect of PET on the stability of modified asphalt mixtures.

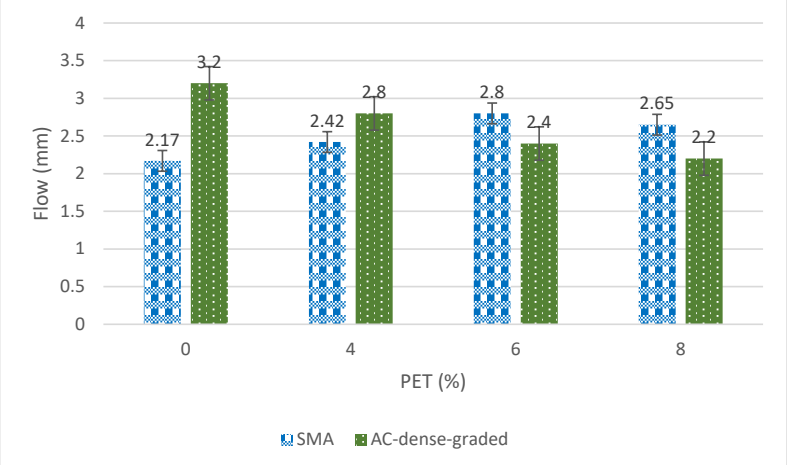


Figure 11. Effect of PET on the flow properties of asphalt mixtures.

SMA is characterised by a mixture of gap-graded aggregate, which minimises the fine- and medium-sized aggregates, resulting in a stable and structurally tough mixture. The

strength and stability of the SMA are because of the stone portion of the coarse aggregate skeleton, which results in an increase in the internal friction rate and the resistance of the mixture to shear, thereby enabling it to resist rutting and wear owing to repetitive studded tyre contact [3,16,30].

4. Rutting and Plastic-Modified Asphalt

Rutting is a type of permanent deformation of pavements that mostly occurs under the wheel path as a result of heavy traffic loads on the road. As mentioned in the literature review, the bitumen properties, modified binder properties, and asphalt aggregate mixture properties are factors that impact the asphalt mixtures' resistance to deformation. As such, it is highly important to investigate and determine the rutting resistance of the PET-modified mixtures. It has been reported that the rutting resistance is linked to the bitumen binder's susceptibility to temperature and stress [29]; therefore, it is important to examine the effect of the modified asphalt on increasing the rutting resistance.

Figures 12–14 show the rutting results of using PET as a modifier in different asphalt mixtures. Figure 12 shows that adding 4%, 6%, and 8% PET decreases the rutting depth to about 8.82 mm, 5.59 mm, and 3.25 mm, respectively, in comparison to 12.93 mm for non-modified AC mixtures. The improvement percentage in the rutting resistance of 8% PET-modified mixtures was about 25%. As a result, the PET-modified bitumen binders significantly enhance the stiffness of the modified asphalt mixtures, and this, in turn, improves the rutting resistance.

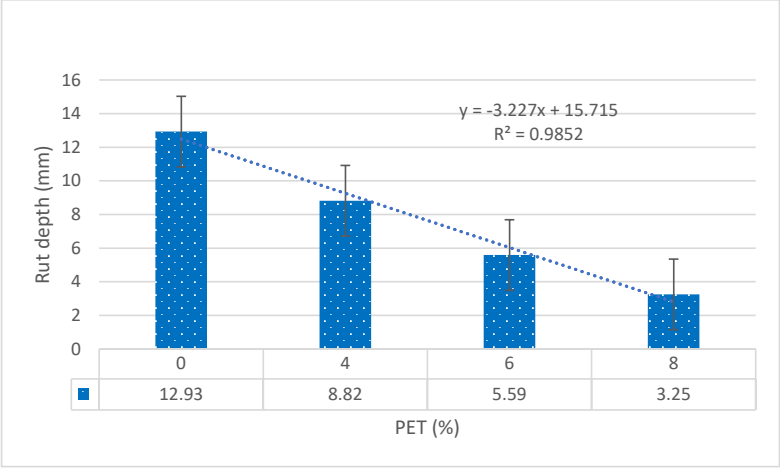


Figure 12. Rutting of PET-modified AC mixtures.

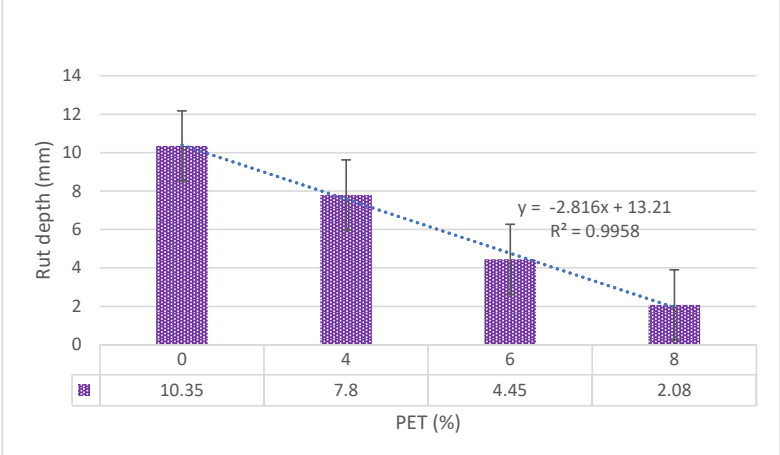


Figure 13. Rutting of PET-modified SMA mixtures.

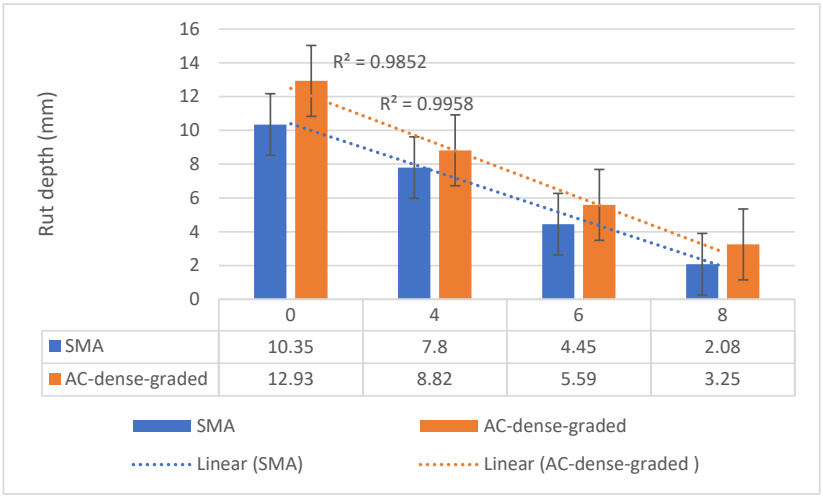


Figure 14. Rut depth of different asphalt mixtures modified with PET.

Figure 13 shows the rutting depth of the PET-modified SMA asphalt mixtures. It can be seen that the higher the level of plastic polymer in the mixture, the better the rutting resistance. The rut depth decreases from 10.35 mm for the non-modified mixtures to 7.8 mm when using 4% PET. For the 6% PET sample, the rut depth declined to 4.45 mm, with a 43% improvement in rutting resistance in comparison to the non-modified mixtures. The lowest rut depth was about 2.08 mm, for samples modified with 8% PET. The significant difference in using various PET contents was obvious, with a correlation coefficient of $R^2 = 0.9958$.

Figure 14 shows the effect of waste PET plastic content on the rutting resistance of SMA and AC dense mixtures at 60 °C. The waste-plastic-modified mixtures show better rutting performance of both types of mixtures. However, the rut depth of the PET-modified SMA mixtures was significantly higher than that of the AC14 mixtures. At high contents, such as 8% PET, the rut depth of SMA mixtures and AC dense mixtures were 2.08 mm and 3.25 mm, respectively. Therefore, the PET-modified bitumen could coat the aggregate and strengthen the bond structure of the SMA asphalt mixtures. The results show a linear decrease in the rutting depth with $R^2 = 0.9852$ and $R^2 = 0.9958$ for the AC dense mixtures and SMA mixtures, respectively. The findings are showing promising results and can be comparable to other findings of previous studies [20–22].

The particle shape of the aggregate determines the performance and workability of asphalt mixtures. When particles are angular rather than thin and flat, they exhibit better performance against stress; therefore, engineers recommend the application of angular particles to HMA. Particles with angular shapes, which is a typical property of crushed stones, have stronger interlocking and better performance than round ones, and, consequently, better resistance against the rutting brought about by heavy and repetitive loading [23–25].

As can be seen from Figures 15 and 16, the rutting deformations are more obvious at 8% PET-modified dense AC14 mixtures in comparison to the better rutting resistance of 8% PET-modified dense SMA mixtures. The use of 8% PET increases the rutting resistance by 74% and 79% for SMA mixtures and AC dense mixtures, individually. Another advantage of SMA is that it can increase the resistance of the mixture against plastic deformation, which is a common problem that results from heavy traffic loads, which exert severe stresses on the pavement. Moreover, its rough surface provides adequate friction, especially when the asphalt loses its surface cement film, which wears out through heavy and frequent vehicle traffic. However, other advantages of SMA make it the most preferred mixture for pavement construction projects around the globe, in comparison with other conventional HMA types. A few of these properties include its superior durability, high-level resistance to reflective cracking, and improved anti-ageing effects [19–22,35].



Figure 15. Rutting deformation for 0% PET (**left**) and 8% PET-modified SMA (**right**).

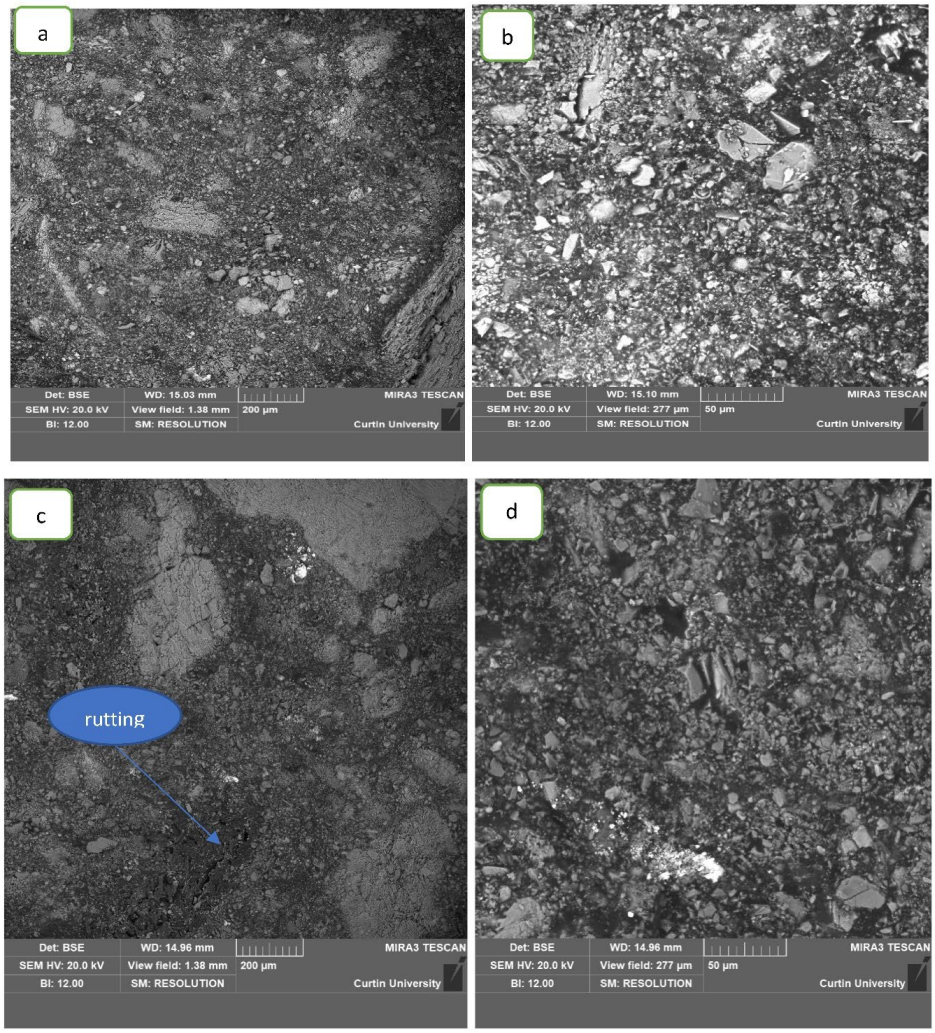


Figure 16. SEM structures of asphalt mixtures: (**a**) SMA modified with 8% PET at 200 µ magnification; (**b**) SMA modified with 8% PET at 50 µ magnification; (**c**) dense-graded asphalt modified with 8% PET at 200 µ magnification; and (**d**) dense-graded asphalt modified with 8% PET at 50 µ magnification.

The major reason for utilising fully crushed aggregate gap gradation (100%) is the enhancement of the degree of pavement stability caused by the interlocking resulting from stone-to-stone contact [39]. This interlocking provides the mix with a stronger stone-on-stone skeleton, which is stuck more stably together as a result of a strong composition of asphalt cement, fillers, and other additives [40]. SMA was initially used in asphalt mixes to enhance their resistance against studded tyre wear. Therefore, introducing waste plastic into asphalt enhances the temperature susceptibility and stiffness. Thus, waste-plastic-modified bitumen results in an enhancement in rutting and fatigue resistance [23–25,33,41–43]. Modifying and advancing the properties of bitumen and asphalt mixes by using certain additives, such as plastic polymers, is one way of boosting the service life of road surfaces.

5. Conclusions

The stability and engineering properties of asphalt mixtures modified with waste plastic are investigated and evaluated in this paper. Asphalt pavement is susceptible to deformation, cracking, and rutting with temperature variations: low–medium temperatures could lead to cracking and fatigue, and high temperatures could lead to rutting deformation. Therefore, modifying the bitumen composition could possibly improve the engineering properties of the asphalt mixtures. This improvement in engineering properties could be achieved through the introduction of different modifiers into the bitumen, which improves the bitumen–modifier phase during blending.

In this study, waste plastic has been used as a modifier to improve the engineering properties of different asphalt mixtures. The outcome of the paper has satisfied the objective as shown below:

1. The results highlighted the essential role of waste plastic in improving the stiffness and rutting resistance. The Marshall stability, Marshall flow, and MQ of Marshall tests exhibited good improvement by using PET in modified SMA and AC mixtures.
2. A similar trend was found as the PET-modified SMA and AC mixtures could resist the plastic deformation and shear stresses which, in turn, reduced the rut depth of the modified mixtures. Results show the lowest rut depth of 2.08 mm of 8% PET-modified stone mastic asphalt. However, the highest results of Marshall stability and rutting resistance were achieved for PET-modified SMA mixtures.
3. Based on the above results, it can be concluded that PET, as a recycled polymer, can significantly improve the engineering properties of the asphalt mixture. In addition, higher contents, of 6% and 8%, could make the SMA mixtures more stable and durable. As such, from the engineering point of view, this study showed that the use of waste plastic as a bitumen modifier is economical and environmentally friendly. Moreover, using waste plastic in asphalt modification could significantly reduce the rutting deformation.
4. The advance of utilising waste plastic as an ecological-environmentally friendly modifier in Australian's bitumen was performed and examined. The results show the possibility to use waste plastic in modifying asphalt mixtures.

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