Performance evaluation of utilization of waste Polyethylene Terephthalate (PET) in stone mastic asphalt

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HIGHLIGHTS

- The role of waste PET was significant in the SMA and shows acceptable trends.
- The mixtures containing waste PET have much higher rutting resistance.
- The PET-mixtures have a higher resilient modulus.
- Utilizing PET in the SMA mixture improve its resistance against binder drain down.
- Utilizing PET in the SMA can have structural, environmental and economic benefits.

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ABSTRACT

In order to improve the properties of asphalt mixture and reduce the negative impact of the waste materials on nature and the environment, it seems to be logical to propose a means of re-using waste materials in engineering and industrial construction projects such as road pavement. The current paper presents an experimental research on the application of waste plastic bottles (Polyethylene Terephthalate (PET)) as an additive in stone mastic asphalt (SMA). Wheel tracking, moisture susceptibility, resilient modulus and drain down tests were carried out on the mixtures that included various percentages of waste PET as 0%, 2%, 4%, 6%, 8% and 10% by weight of bitumen content. By experimentation, the appropriate range for the amount of waste PET was determined to be 4–6% by weight of the bitumen content. The results show that the addition of waste PET into the mixture has a significant positive effect on the properties of SMA which could improve the mixture’s resistance against permanent deformation (rutting), increase the stiffness of the mix, provide lower binder drain down and promotion of re-use and recycling of waste materials in a more environmentally and economical way.

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1. Introduction

One of the major challenges that nearly all developing and developed countries have been facing over the past two decades is economic competitiveness and productivity. However, the economic competitiveness has not only led to an unprecedented increase in the production of goods, but also to the creation of the most efficient and safest transportation facilities used for the delivery of the products. As a result, manufacturers have turned to making larger vehicles and containers, with more axle load and higher tire pressure to maintain the economic competitiveness in delivery of the goods across the global market. Hence, the number of these heavy vehicles on the existing roads has drastically and substantially increased [1,2].

This unprecedented increase in the number and frequency of road traffic and axle loads has significantly contributed to the fast deterioration and decomposition of asphalt pavements sooner than the expected time [2–4]. To counteract this process, improvements in roadway design, the application of materials of higher and better qualities, use of modifiers and additives for the bitumen and asphalt mixture, and employment of more effective methods of road construction may be effective [3].

Increasing demand for pavements with higher qualities, and the poor performance of some bituminous mixtures have led researchers to render new methods and designs to improve the performance and effective service life of bituminous mixtures [4,5]. Stone mastic asphalt (SMA) is an approach to the improvement of asphalt pavement performance, and, based on many research reports [5,6], the application of SMA to the construction and coating of roads has been proved to increase the durability of the road surfaces [7].

The experiments [2,5] have proved that SMA has more resistance to rutting in comparison with dense graded mixes due to
the composition of its whole structure, which consists of a coarse aggregate skeleton and higher binder content while providing stone-on-stone contact among the coarse aggregate [2,8,9]. SMA is designed to have a high filler content, 3–4% air voids, high coarse aggregate, and a relatively high content of bitumen (normally 5.5–7%) [5]. Originally, SMA was used in asphalt mixes to enhance their resistance against studded tire wear. Another characteristic of SMA is its ability to provide the mixture with high resistance against deformation resulting from frequent and heavy traffic loads and high pressure created by vehicle tires [5,10]. Moreover, the rough surface of SMA provides sufficient friction between the asphalt mixture and tires. SMA has other features that make it the preferred mix compared to other kinds of conventional hot mix asphalt (HMA). Some of these properties include its enhanced durability, improvement against aging, high resistance to reflective cracking and its ability to minimize traffic noise [10,11]. However, the significant disadvantages of SMA are its higher initial expense and binder drainage. Since SMA has a gap-graded nature and high bitumen content, in order to prevent binder drain down, it needs stabilization to inhibit binder drain down, such as a polymer or fiber in the mixture [11,12].

The role of polymers in the asphalt industry is significantly increasing [13]. The application of polymers to bitumen has been proved to help enhance performance [14] and using polymeric materials such as styrene-butadiene-styrene (SBS) to the mixture has attracted the attention of both highway manufacturers and engineers to employ such materials as modifiers in asphalt mixtures [15,17]. In recent years, polymer modified asphalt binders have turned into the norm in designing pavements of high performance, especially in most of the developed and some of the developing countries [14].

The date of the first patent registration of asphalt modification processes with both natural and synthetic polymers goes back to 1843, while in the modern era, the first serious utilization of such polymers in fiber reinforcement was initiated in the early 1990s [16]. Polymer modified bituminous mixtures appear to possess the highest potential for successful application in the design of pavements to increase the durability and service length of the pavement or to reduce pavement layer thickness or its base thickness [15,17]. Some of the advantages of the application of polymer modified binders are their higher elasticity recovery, a greater softening point, higher ductility, and higher viscosity [14]. When polymers are applied to an asphalt mixture, they usually result in a higher degree of stiffness in the bitumen and an improvement in the temperature susceptibility of the mixture, and, as a result, increase the resistance of the mixture against rutting. In such cases, polymers allow the application of a softer base bitumen that can provide superior low temperature performance. Improved adhesion and degree of cohesion is one of the significant properties of polymer modified binders [18,19]. Another use of polymer is to create an aggregate coating material that is expected to increase the degree of the aggregate surface roughness and produces a superior asphalt mixture [18].

In effect, the behavior of the binder modified by different kinds of polymer can be very different even though they may possess the same grade of performance. As an example, natural rubber contributes to the improvement of the mixture’s rutting resistance and ductility; however, it is vulnerable to decomposition. The application of tire rubber as a modifier instead reduces reflective cracking and rutting, but in order to maintain its combination with the bitumen and prevent separation, special conditions are required. Styrene-Butadiene Rubber (SBR) is a synthetic rubber that is added to bitumen as a polymer to help improve the low-temperature ductility, viscosity, elastic recovery, and cohesive and adhesive properties of the mixture. SBS added binders show better performance at low temperatures in comparison to the neat binder [14].

Nowadays, polymer modified asphalt mixtures are relatively costly for paving roads [5,20]. Therefore, before the commercial utilization of polymer modifiers, it is vital to analyze the cost-benefits of the various ways to make the projects feasible and more economical. SBS, for instance, is usually employed to modify the asphalt mixture in road construction all over the world. However, despite the typical excellent properties of polymer modified mixtures, the high cost of SBS is considered as its main disadvantage, which limits its wide use for most road pavement construction. Therefore, because of the escalating cost of materials and energy, and the scarcity of natural resources, it is apparent that there is a necessity for the existence of a polymer modified mixture that can be conveniently prepared from a comparatively inexpensive polymer such a mixture would prove indispensable for high performance road construction [20]. The application of waste materials is one such alternative for polymer modified mixtures.

Recently, considerable research has been conducted to study the possibility of using solid waste materials in road construction projects and has quickly led to several hot issues [21]. Every day, miles of new roads are built in different countries around the world using millions of tons of raw materials and natural stocks. This huge consumption leads to impoverishment of these resources on a daily basis. At the same time, as a result of consumerism in modern societies, most of the developed and developing countries are seriously facing major problems arising from the disposal of waste material.

Waste re-cycling is especially vital in dealing with certain waste materials such as plastic bottles, which, due to their longer biodegradation period, are very harmful to the environment and ecosystem balance. The annual consumption of plastic containers around the world has risen dramatically in recent years. The annual consumption of plastic materials has soared from approximately 5000,000 tons in the 1950s to around 100,000,000 tons in 2001 [22]. Therefore, to reduce the negative impact of these plastic waste materials on nature and the environment, it seems to be logical to propose ways to re-use waste materials of this kind in engineering and industrial construction and production projects such as road pavement [23,24].

The current paper presents an experimental research on the application of waste plastic bottles (Polyethylene Terephthalate (PET)) as an additive in SMA. However, although there is not sufficient up-to-date information about the application of PET to hot mix asphalt (HMA), it is noteworthy to mention that none of the known studies previously conducted by other researchers have seriously focused on the application of waste PET as an additive to SMA. In the first part of the research [25], the possibility of using waste PET in the SMA mixture was checked and after attaining an acceptable trend and satisfying standard requirements, in the present paper, performance tests were applied on the SMA mixture. The main objective of this study, however, was to determine the impact of incorporating waste PET on the engineering properties of SMA with and without chopped PET. The performance tests including, wheel tracking test, moisture susceptibility test, resilient modulus test and drain down test were conducted on the mixtures.

2. Experimental details

2.1. Materials

This research has used various materials including aggregate, bitumen, Portland cement and waste PET for experiments on the mixtures. Crushed granite with SMA20 gradation that was obtained from Kajang quarry (a suburb near Kuala Lumpur, Malaysian Capital) was used as the aggregate material. The selected gradation and some properties of the employed aggregate are respectively presented in Fig. 1 and Table 1. The used bitumen was 80/100 penetration grade. Table 2 displays the physicochemical properties of the used bitumen. Portland cement was utilized as a
filler and the waste PET obtained from waste plastic bottle was used as an additive. The collected waste PET bottles were first washed, dried, cut into smaller parts, and crushed by a crushing machine as displayed in Fig. 2. The PET gradation and the specific gravity levels of the materials are respectively displayed in Tables 3 and 4. In order to minimize complications, the same material sources were used throughout the research.

2.2. Sample preparations

Two of the common methods that are usually employed to add the selected additive to the asphalt mixture are the wet and dry processes. In the first method, the wet process, the additive is mixed with the binder after adding the binder to the mixture. While in the latter method, the dry process, the additive is blended with the aggregate before adding the binder to the mixture [26]. In the present study, the dry process was employed with a novelty. In this research the waste PET was added into the mixture in the last part of the mixing process and after adding and blended the binder with the aggregate instead of mixing the additive with the aggregate before adding the binder.

To fabricate the samples, the stages to be followed are as follows:

Prior to adding the aggregate to the mixture, it was heated up to 200 °C for 2 h. The weight of aggregate for each sample was 1100 g. In addition, the bitumen was heated up to 150 °C for a period of 1 h before being blended with the aggregate. The bitumen, filler, and aggregate were mixed at 160 ± 5 °C for about 5 min. Then, PET was introduced into the combination and blended with it for nearly 2 min. The percentage of the added PET was between 0% and 10% (0%, 2%, 4%, 6%, 8%, 10%) by weight of bitumen. The Marshall compactor was then employed to compact the mixture with 50 blows from the top and bottom side of the mixture at 145 °C. A roller compactor was used to make slabs for the wheel tracking test.

2.3. Performance tests

The conventional mixture and mixtures containing waste PET were assessed and evaluated through the resilient modulus test, indirect tension strength test, wheel tracking, and drain down test. The experiments were carried out in the standard experiment conditions (BS 598-110) of wheel loads of 520 N ± 5 N, which moves back and forth in harmonic motion at 42 passes or 21 cycles per min for 45 min or as long as it takes for a 15 mm deformation to occur in the specimen, whichever comes first [30]. The rut depth was recorded every 5 min during the experiment.

2.3.2. Wheel tracking test

Resistance to rutting is one of the vital performance requirements for a bituminous mixture, especially in hot climates. In the literature, the typical tests used for testing and evaluating the rutting include the Marshall wheel test, wheel track test, static and dynamic creep tests, and indirect tensile test [24]. However, the wheel tracking test is the most recommended one because of its features, which allow better field simulation [29], particularly for the assessment of the performance of stone-skeleton mixtures or mixtures that include modified binders [17].

In the present study, wheel tracking test was used to evaluate the mixtures resistance against rutting. For this test, 18 specimens with 300 × 300 × 50 mm slab dimension were prepared. Test temperature was 45 °C and the slabs were kept 6 h at that temperature before the actual start of the test. The test was conducted under standard experiment conditions (BS 598-110) of wheel loads of 520 N ± 5 N, which moves back and forth in harmonic motion at 42 passes or 21 cycles per min for 45 min or as long as it takes for a 15 mm deformation to occur in the specimen, whichever comes first [30]. The rut depth was recorded every 5 min during the experiment.

2.3.3. Drain down test

SMA, like porous asphalt mixture, is subjected to binder drainage problems. Because SMA has a high optimal binder content, drainage problems may occur in the mixing, transporting and laying processes [4]. The drain down test using the wire basket method, as suggested in AASHTO T305, was carried out on all the evaluated mixtures. The loose mix prepared in the laboratory was placed into a forced draft oven for a period of about 1 h. After 1 h, the basket with the specimen along with the plate was removed from the oven to determine the mass of the plate. The increased weight of the plate shows the drain down amount of the mix. The drain down test was carried out at 170 °C.

2.3.4. Moisture susceptibility test

The moisture susceptibility of bituminous mixtures is defined as the vulnerability of the asphalt mixture to be damaged by water. When moisture collects within the bituminous mixture, it can cause damage to the bond between the aggregates and asphalt binder, which, in turn, accelerates the development of other kinds of distress such as cracking and potholing [13,31].

The moisture susceptibility test was carried out in accordance with the AASHTO T283 procedure on six SMA mixes, which were compacted to an average 7% air-void content. Three Marshall specimens for the dry group (unconditioned) and three specimens for the wet group (conditioned) were prepared. A tensile strength ratio (TSR) of the wet to dry group was calculated based on the outcomes of the indirect

<table>
<thead>
<tr>
<th>Test method</th>
<th>Value</th>
<th>Standard requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration</td>
<td>ASTM D 5-97</td>
<td>1/10 mm</td>
</tr>
<tr>
<td>Softening point</td>
<td>ASTM D-36</td>
<td>°C</td>
</tr>
<tr>
<td>Ductility (25 °C)</td>
<td>ASTM D-113</td>
<td>cm</td>
</tr>
<tr>
<td>Flash point</td>
<td>ASTM D-92</td>
<td>°C</td>
</tr>
<tr>
<td>Fire point</td>
<td>ASTM D-92</td>
<td>°C</td>
</tr>
</tbody>
</table>

2.3.1. Resilient modulus test

The resilient modulus (MR) test is the most popular test used to measure the elastic properties of the bituminous mixture, representing an applied stress ratio to the recoverable strain after removal of the applied stress [21]. The modulus of asphalt is a fundamental design parameter during the application of the elastic-layered system theory for designing the structure of asphalt pavements. The current performance of asphalt pavements in asphalt pavement projects also employ the modulus as a vital material parameter [27,28]. Therefore, it is desirable that the modulus of asphalt be predicted during the design stage of the asphalt mixture to improve the mixture design and for enhancement of the pavement performance prediction.

The MR was determined from tests on Marshall cylindrical specimens on both conventional and PET-mixtures in indirect tension mode. Three specimens were prepared for each PET content and the conventional mixture and were tested with a Universal Testing Machine (UTM). The test was carried out according to ASTM D4123 at 25 °C.

Table 2

<table>
<thead>
<tr>
<th>Test</th>
<th>Method</th>
<th>Unit</th>
<th>Value</th>
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</thead>
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</tr>
<tr>
<td>Softening point</td>
<td>ASTM D-36</td>
<td>°C</td>
<td>&gt;47.7</td>
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<tr>
<td>Ductility (25 °C)</td>
<td>ASTM D-113</td>
<td>cm</td>
<td>&gt;100%</td>
</tr>
<tr>
<td>Flash point</td>
<td>ASTM D-92</td>
<td>°C</td>
<td>&gt;301</td>
</tr>
<tr>
<td>Fire point</td>
<td>ASTM D-92</td>
<td>°C</td>
<td>&gt;319</td>
</tr>
</tbody>
</table>

Table 1

<table>
<thead>
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<th>Properties</th>
<th>Test method</th>
<th>Value</th>
<th>Standard requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>L.A. abrasion (%)</td>
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<td>Flakiness index (%)</td>
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<tr>
<td>Elongation index (%)</td>
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<td>12.1%</td>
<td>&lt;20%</td>
</tr>
<tr>
<td>Soundness (%)</td>
<td>BS812:part3</td>
<td>4.7%</td>
<td>&lt;12%</td>
</tr>
<tr>
<td>Impact value (%)</td>
<td>BS812:part3</td>
<td>13.6%</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>Polished stone value</td>
<td>BS812:part3</td>
<td>46.9%</td>
<td>&gt;40%</td>
</tr>
<tr>
<td>Aggregate crushing</td>
<td>BS812:part3</td>
<td>18.8%</td>
<td>&lt;30%</td>
</tr>
</tbody>
</table>
tensile strength test conducted at 25°C. It is noteworthy to mention here that the higher the TSR value the better the asphalt mixture resistance against moisture damage [32]; a 70% or more TSR value is required for normal SMA specification [27].

3. Results and discussion

3.1. Resilient modulus

Fig. 3 illustrates the MR value versus PET content. As the figure shows, after the addition of PET, the MR value increases until it reaches the maximum level, after which it starts to decrease. The MR values of mixtures containing PET were generally greater than the conventional mix (0% PET) and the achieved results indicate that the maximum value of MR was obtained by adding 6% PET, which showed that the MR had increased by 16% compared to the conventional mix.

To modify and improve the quality of the asphalt mixture, researchers and manufacturers have used many kinds of polymer. The enhancement and improvement of the performance of bituminous mixture containing polymers is, to a considerable extent, the result of the improvement in the rheological properties of the bitumen [33]. When a polymer is added to the mixture, it typically improves the mixture’s adhesion and cohesion properties [18,19,25,34]. However, PET has high a melting point (approximately 250°C) [35] while the maximum temperature for the mixing process and blend materials in the HMA is less than 180°C. Therefore, because of this high melting point researchers avoid using PET in the hot mix asphalt. Casey et al. [36] used different types of polymer as modifiers for the binder (PVC, LDPE, Isotactic PP, MDPE, and HDPE mulches, Isotactic PP powder, and ABS and PET chips) and in the case of PET, they concluded that its high melting point hindered the mixing, making it impractical to make any further attempts to incorporate it into the bitumen.

However, the main idea for applying PET to the asphalt mixture in this study was based on a different property. PET, in its natural state, is a semi-crystalline resin [37–39], and its glass transition temperature ($T_g$) is about 70°C [35,40,41]. After heating the PET, its properties gradually start to change, which finally alter it into a substance with less or more crystal properties, and, as illustrated in Fig. 3, its addition to the mixture makes a stiffer mixture with higher MR value. Therefore, the main cause of this result could be the PET remaining as a semi crystal material within the mixture, which results in a stiffer mixture.

As mentioned earlier (sample preparations section) in this study, the dry process was used with the PET introduced into the mixture in the final part of the mixing process. The main reason for this was to keep the PET in the mixture in its natural state, with minimal change to its shape and properties.

3.2. Wheel tracking

The effect of waste PET on rutting resistance for mixtures is displayed in Fig. 4. The results indicate that mixes containing waste PET have better permanent deformation resistance compared to the conventional mixture. Furthermore, Fig. 4 indicates that the rut depth increases sharply for the first 15 min after which the increase becomes slower and more gradual. The rut depth for mixtures with 0%, 2%, 4%, 6%, 8% and 10% PET content after 45 min is 1.78 mm, 1.50 mm, 1.26 mm, 1.35 mm, 1.62 mm and 1.56 mm, respectively, which indicate that the minimum rut depth obtained for the mix with 4% PET could reduce the rut depth by 29% compared to the conventional mix.

As discussed in the previous section, the results achieved can contribute to the formation of a stiffer mixture, which improves the rutting resistance of the mixture [18,42,43].

3.3. Drain down

The results of the drain down test for the mixtures are displayed in Fig. 5. Regardless of the content of the employed PET, the drain
down value of the PET-mixes was lower than the drain down value of the control mixture, and, furthermore, any increase in PET content into the mixture reduces the value of the drain down. The reduction of drain down value can be as a result of the chopped PET used in the mixture, which remains in crystal form, thereby increasing the surface area. The increased surface area, however, needs to be wetted with binder [44], which would finally lead to stabilizing and holding the binder on its surface and decrease the binder drain down.

3.4. Moisture susceptibility

The results of the tensile strength test of conventional mix and PET-mixes are displayed in Figs. 6 and 7. As the results illustrate, the tensile strength and TSR values of the mixtures decrease with the addition of PET. TSR values between 70% and 80% have been set as the minimum requirement by AASHTO T 283 and ASTM D 4867 standards. As Fig. 7 shows, all values of TSR are above 70% indicating that all mixes may have adequate resistance against damage induced by moisture [31,45]. However, the addition of waste PET does not improve the moisture susceptibility of the mixture. This result could be attributed to the crystal form of PET after mixing that holds the sticky binder on its surface and decreases the asphalt film thickness around the aggregate, which, in turn, results in a reduction to the resistance against damage induced by moisture.

4. Conclusion

This research focused on a laboratory evaluation of the performance of SMA using waste PET as an additive. The current section intends to summarize the overall conclusions achieved through this study. The significant findings of this study are presented as follows:

(1) The MR values of mixtures containing waste PET were generally higher than the conventional mix. The MR value of SMA mix increased by 16%, as compared to the conventional mix, using 6% PET which was the maximum value.

(2) The wheel tracking test results show that the mixture with waste PET has much higher rutting resistance compared to the conventional mixture. The lowest rut depth was obtained for the mix with 4% PET, which reduced the rut depth by 29% compared to the conventional mix.

(3) The role of waste PET was significant in reducing or preventing excessive SMA drain down. The drain down values of the mixtures containing waste PET were lower than that of the conventional mixture and reduced with any increase in PET content.
(4) The tensile strength and TSR value of the mixture decreases with the addition of waste PET, however, all values of TSR were above 70%, which indicates that all PET-mixes could achieve an acceptable level.

(5) The appropriate amount of PET was determined to be between 4% and 6% by weight of optimum bitumen content.

(6) Overall, the performance properties of the SMA mixtures containing waste PET show the acceptable trends and could satisfy the standard requirements.

References


