Evaluation of permanent deformation characteristics of unmodified and Polyethylene Terephthalate modified asphalt mixtures using dynamic creep test

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**Abstract**

One of the major types of plastics that can be found in Municipal Solid Waste (MSW) is Polyethylene Terephthalate (PET) which is a non-biodegradable semi-crystalline thermoplastic polymer, and is considered as polyester material. Generating large amount of waste PET, mainly as bottles, would cause environmental hazards by disposing in landfills. This paper aims to evaluate effects of utilizing waste PET flakes as modifier in asphalt mixture as an alternative solution to overcome the potential risks arise from producing large amount of waste PET as well as evaluating the deformation characteristics of unmodified and PET modified asphalt mixtures. To achieve this aim, different percentages of PET were designated for this investigation, namely: 0%, 0.2%, 0.4%, 0.6%, 0.8% and 1% by weight of aggregate particles, and dynamic creep test was performed at different stress levels (300 kPa and 400 kPa) and temperatures (10°C, 25°C and 40°C). Consequently, Zhou three-stage model was developed. The results showed that permanent deformation characteristics of asphalt mixture were considerably improved by utilization of PET modification, when the permanent strain was remarkably decreased in PET modified mixture compared to the conventional mixture at all stress levels and temperatures. Besides, based on Zhou model, it was concluded that elastic and visco-elastic properties of asphalt mixture were improved by application of PET modification.

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**1. Introduction**

Plastics have prominent utilization worldwide. Polyethylene Terephthalate (PET) is one of the major types of plastics that can be found in the Municipal Solid Waste (MSW) [1]. MSW contains high proportion of thermoplastic polymers which has been increasing in value. PET is a semi-crystalline thermoplastic polymer, and is considered as polyester material [2]. Large amount of waste PET is being produced in the form of different products, for instance, bottles, fibers, molding and sheets are the products mostly manufactured in Europe by application of PET [3]. Utilization of PET is well-known in food industry because of superlative characteristics offered by PET as a packaging material, mainly as bottles [4].

During the last decades, number of vehicles on roads, especially heavy vehicle such as vans and trucks, has been increased, considerably. By rising the number and weight of vehicles, amount and cycles of applied loads to the asphalt mixture has increased significantly, thus service life of asphalt mixture was decreased. Moreover, performance of asphalt mixture is influenced by ambient temperature due to asphalt’s visco-elastic properties. Asphalt viscosity is highly affected by temperature when higher temperature results in softer and less viscose asphalt binder which can affect the permanent deformation performance of asphaltic concrete in negative manner.

To overcome these problems and make a better mixture providing longer service life, modifying asphalt mixture by utilizing additives such as fibers and polymers comes into popularity among road engineers and designers [5]. Among these additives, polymers (such as SBS, LDPE, and HDPE) have a prominent utilization [6–8]. In this case, many investigations have been conducted on effectiveness of using waste materials as additives in order to: (1) prevent from imposed additional charges by using additives and, (2) find a solution to reuse waste materials as secondary materials in such construction projects [9–12].

Hence, this study aims to assess effects of adding waste PET as an additive on permanent deformation characteristics of asphalt mixture.

**2. Background**

Progressive accumulation of permanent deformation is defined as rutting. Rutting, which is caused by repeated traffic loading, is sum of the total deformation accrues in each layer of pavement...
structure and, moreover, asphalt layer has shown a prominent magnitude in rutting [13]. The permanent deformation of asphalt mixture is greatly influenced by type of asphalt mixture and percentage of voids in mix [5]. In this case, it was reported that stone mastic asphalt (SMA) mixture has better performance in comparison with conventional dense graded mixture [14,15].

Different test methods can be used to evaluate permanent deformation of asphalt mixture such as static and dynamic creep tests as well as wheel tracking test among which static test was estimated that cannot be a true indicator of permanent deformation of modified mixture; however, dynamic creep test is considered as one of the best test procedure to assess the permanent deformation of asphalt mixture [16,17]. Concept of this method which is based on axial compression was developed in 1970 by Monismith et al.[18]. Further, it is reported that among all test procedures dynamic creep test is an appropriate laboratory method to investigate permanent deformation performance of modified and unmodified asphalt layers [19].

Several permanent deformation models were proposed since 1970s that include power-law model, VESYS model, Ohio State model, superpave and AASHTO 2002 models [18,20,21]. In past researches, Flow Number (FN) was a popular indicator to assess the permanent deformation of hot mix asphalt [22,23]. This value can be obtained as result of dynamic test by plotting cumulative plastic strain vs number of load cycles.

There are three phases of flow during the test namely: primary, secondary and tertiary stages. During the primary stage rate of strain decreases by load application. In secondary phase, rate of strain almost remains constant, and during tertiary phase the strain rate rises dramatically which is due to significant deformation of specimen under cyclic load application. In this criterion, the FN is defined as the load cycles when the tertiary stage is initiated. Although this method is one of the criteria to assess rutting performance of asphalt mixture, it has a disadvantage because it is observed that several minimum values from the strain rate were found [20].

In later investigation, in 2004, another model was developed by Zhou et al. [22]. Zhou proposed three-stage model with one model for each stage of creep curve namely: power-law model, linear model and exponential model each for primary, secondary and tertiary stages, respectively (Fig. 1). The models are presented at follows:

First stage : \( \varepsilon_p = AN^b, N \leq N_{PS} \)  

\[ (1) \]

Second stage : \( \varepsilon_p = \varepsilon_{PS} + c(N - N_{PS}), \quad N_{PS} \leq N \leq N_{ST} \)

\[ (2) \]

Third stage : \( \varepsilon_p = \varepsilon_{ST} + d(e^{(N - N_{ST})} - 1), \quad \varepsilon_{ST} = \varepsilon_{PS} + c(N_{ST} - N_{PS}), \quad N_{ST} \leq N \)

\[ (3) \]

where \( N_{PS} \) is the number of load cycle corresponding to the initiation of secondary stage. \( N_{ST} \) is number of load cycle corresponding to the initiation of tertiary stage. This value is also refers to FN. \( \varepsilon_{PS} \) is cumulative permanent strain at initiation of secondary stage. \( \varepsilon_{ST} \) is cumulative permanent strain at initiation of tertiary stage, and \( a, b, c, d \) and \( f \) are material constants.

Zhou model was seemed to have a better correlation with permanent deformation of asphalt mixture in field compared to other models. Further, this model outweighs the other models because each transition points in creep curve can be obtained by using this criterion. Thus, in other investigation Khodaii and Mehrara [13] used this model to evaluate permanent deformation of SBS modified asphalt mixture using dynamic creep test.

3. Objectives and experimental procedure

This study attempts to evaluate effects of using non-biodegradable PET as modifier on permanent deformation characteristics of Stone Mastic Asphalt (SMA) mixture. To achieve this aim different percentages of PET were designated for this investigation and dynamic creep test was conducted at two different stress levels (300 and 400 kPa). Moreover, to have a better understanding about PET modification, dynamic creep test was conducted at three different temperatures namely: 10, 25, and 40 °C. Consequently, Zhou three-stage model was designated for each stress levels and temperatures.

3.1. Materials

Granite-rich aggregate used in this study was prepared from Kajang Rock Quarry in Malaysia. Aggregate particle size distribution of selected gradation is presented in Fig. 2.

SMA mixtures have been prepared with fresh 80/100 penetration grade asphalt cement. No stabilizing additives were added to asphalt cement. In order to minimize complications, the asphalt and aggregate sources were kept the same during the study. Table 1 illustrates the properties of materials utilized in this research program.

3.2. Polyethylene Terephthalate (PET)

In this study, waste PET flakes were obtained from PET bottles. After collection of PET bottles, they were washed and cut to small
parts. These small parts were further crushed. The crushed PET particles were sieved, and those passed sieve 2.36 mm were chosen for this investigation. Different percentages of crushed PET were used in this study, namely: 0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1% by weight of aggregate particles. The particle size distribution and properties of waste PET are shown in Tables 2 and 3, respectively.

### 3.3. Sample preparation

Three identical samples were prepared for each percentage of PET and for each stress levels and temperatures. For preparing the entire samples 1100 g of mixed aggregate particles and filler was heated at the temperature of 160 °C for 3 h. Besides, asphalt cement was heated at the temperature of 130 °C before mixing with aggregate particles in order to achieve proper viscosity. PET particles were added directly to mixture as the method of dry process, and 50 blows of compaction effort was considered on each side of specimen. All conventional and modified samples were prepared at Optimum Asphalt Content (OAC) according to ASTM: D1559 [8,13,17], and the results are presented in Table 4.

### 3.4. Dynamic creep test

When a load is applied to the surface of asphalt pavement, it deforms although a majority of deformation recovers after the load is removed. This phenomenon was referred to the characteristics of asphalt which known as visco-elastic material. Nevertheless, a minute amount of irrecoverable viscous deformation would still remains in mixture. By applying millions of load cycles, the small amounts of deformation would be accumulated and eventually result in surface rutting. The amount of this deformation is greatly influenced by amount and number of cyclic loads as well as environmental temperature.

Hence, the uniaxial repeated-load creep test was designated to characterize rutting performance of control and PET modified asphalt mixtures. Universal Testing Machine (UTM) was utilized which is the most commonly used device to measure the permanent deformation of asphalt mixture (see Fig. 3) [7]. During the test cyclic load with repeating time of 1000 ms (pulse compressive load of 100 ms with rest period of 900 ms) was applied. Prior to conduct the test, all specimens were placed at controlled temperature chamber for 3 h to reach the uniform temperature.

During the test the vertical deformation of specimen was measured by Linear Variable Differential Transducers (LVDTs) which
were installed in vertical direction, and strain can be calculated by using the following equation:

\[ \varepsilon = \frac{h}{H_0} \]  \hspace{1cm} (4)

where \( \varepsilon \) is the accumulated strain, \( h \) is the axial deformation, mm; and \( H_0 \) is the initial specimen height, mm.

The test would be terminated until accumulative load cycles reach 20,000, or until a large deformation caused the LVDTs to go out of range [22].

4. Results and discussion

This section discusses about permanent deformation performance of control (unmodified) and PET modified asphalt mixtures.
Three types of strains, namely: perfectly recoverable elastic, visco-elastic and irrecoverable plastic strains may develop after applying a load to the asphalt mixture. At higher temperature or under slow-moving loads, asphalt mixture may have pure elastic or viscoelastic behavior; however, it might behave as an elastic brittle material at lower temperature or under fast-moving loads [27].

### 4.1. Permanent strain

Total permanent strain of control and PET modified SMA mixtures were calculated and compared with each other. The results are illustrated in Figs. 4–9. As can be seen in these figures, rutting resistance of PET modified mixture improved remarkably com-
pared to the control mixture, and, in all cases, total permanent strain decreases at higher PET contents and for a certain number of load application while adding 1% PET results in the lowest strain decreases at higher PET contents and for a certain number of load application while adding 1% PET results in the lowest

regards to the mixing temperature which is around 160 °C, and is over the glass transition temperature of PET (75 °C) the amorphous region of PET would be changed to liquid form; however, a crystalline region would still exist as solid part due to the high melting point of PET which is around 250 °C [28,29]. Hence, it is deemed that PET might improve asphalt mixture characteristics in two ways: first the molten and liquid part of PET strengthens the bonds between aggregate particles and asphalt binder, and second the so-

pared to the control mixture, and, in all cases, total permanent strain decreases at higher PET contents and for a certain number of load application while adding 1% PET results in the lowest amount of strain.

In previous research [9] which was conducted on evaluation of different polymer modified asphalt, because of high melting point of PET it was supposed that PET hinders the mixing, and was not suitable to be used in asphalt modification. Nevertheless, the result of this investigation shows that using PET as modifier can considerably improve permanent deformation characteristics of asphalt mixture. Improvement of permanent deformation characteristics of PET modified asphalt mixture can be referred to PET properties which is known as semi-crystalline material. That is to say, with regards to the mixing temperature which is around 160 °C, and is over the glass transition temperature of PET (75 °C) the amorphous region of PET would be changed to liquid form; however, a crystalline region would still exist as solid part due to the high melting point of PET which is around 250 °C [28,29]. Hence, it is deemed that PET might improve asphalt mixture characteristics in two ways: first the molten and liquid part of PET strengthens the bonds between aggregate particles and asphalt binder, and second the solid region of PET absorbs or distracts some amount of energy applied by cyclic load.

In previous study [30], the wheel tracking test was used to evaluate the effect of PET on rutting resistance of asphalt mixture, and it was shown that adding 4% of PET (by weight asphalt content) re-

Table 5
Three stage models and boundary points for control and PET modified mixtures at 300 kPa stress.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>PET (%)</th>
<th>Primary stage</th>
<th>Secondary stage</th>
<th>Tertiary stage</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td>Model</td>
<td>End point</td>
<td>Model</td>
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<tr>
<td>10</td>
<td>0</td>
<td>$c_0 = 9.2861N^{0.3755}$</td>
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<td>$c_0 = 8.5225N^{0.3527}$</td>
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<td>$c_0 = 20.7908N^{0.3253}$</td>
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<td>$c_0 = 95.0441N^{0.2036}$</td>
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<td>40</td>
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<td>0.4</td>
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<td>0.6</td>
<td>$c_0 = 141.9040N^{0.3809}$</td>
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<td>0.8</td>
<td>$c_0 = 54.0753N^{0.4802}$</td>
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<td>$c_0 = 59.9830N^{0.4815}$</td>
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</table>

Table 6
Three stage models and boundary points for control and PET modified mixtures at 400 kPa stress.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>PET (%)</th>
<th>Primary stage</th>
<th>Secondary stage</th>
<th>Tertiary stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Model</td>
<td>End point</td>
<td>Model</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>$c_0 = 210.913AN^{0.7072}$</td>
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<td>$c_0 = 72.2730N^{0.7173}$</td>
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<td></td>
<td>0.4</td>
<td>$c_0 = 19.5347N^{0.3478}$</td>
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<td>$c_0 = 63.4469N^{0.3522}$</td>
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<td>$c_0 = 9.3535N^{0.5167}$</td>
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<td>$c_0 = 19.4108N^{0.7261}$</td>
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<td>$c_0 = 42.6260N^{0.5911}$</td>
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<td>1</td>
<td>$c_0 = 10.2958N^{0.7317}$</td>
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</tbody>
</table>

$^a$ Not found at the end of 20,000 load cycle.
reinforcement can improve the fatigue life of PET modified mixture. In addition, a study on fatigue characteristics of SMA mixture at different environmental temperatures, dynamic creep test was conducted at temperatures of 10, 25 and 40 °C which are considered as relatively low, medium and high temperatures, respectively. Besides stress levels of 300 kPa and 400 kPa were designated for this study. In previous research, it was reported that lower stress level (e.g. 100 kPa) cannot properly manifest the rutting performance of modified asphalt mixtures [13].

Fig. 4 shows that the final amount of accumulated strain at 10 °C and 300 kPa stress for control mixture is very low when the amount of strain for control mixture is under 400 μs after 20,000 load application. Nevertheless, this value is much lower for the mixture reinforced by 1% PET which is below 100 μs. Total permanent strain increases at higher temperatures. For instance, at the same stress level, in case of control mixture when the temperature increases from 10 °C to 25 °C (Fig. 5) the strain value rises to nearly 2000 μs which is around 5 times higher in comparison with 10 °C. Moreover, at the same temperature, the strain value for the mixture modified by 1% PET reaches to nearly 800 μs after 20,000 load repetition which is nearly 8 times higher than the amount calculated for 10 °C. More importantly, as can be seen in Fig. 6 at 40 °C and after applying a number of cyclic load all amounts of strains reach to the 10,000 μs in which the LVDTs go out of range.

Further, by rising temperature the same trend was observed at 400 kPa stress level. The strain values increase by an increment in stress (from 300 kPa to 400 kPa) for both 10 °C and 25 °C temperatures (Figs. 7 and 8). It is good to note that in 400 kPa stress and temperature of 25 °C the control specimen fails after nearly 12,000 load cycle when the strain value reaches to 6000 μs. Besides, it can be illustrated from Fig. 9 at temperature of 40 °C number of cycles that LVDTs go out of range (around one third) compared to the same temperature at 300 kPa stress level.

4.2. Temperature and stress level

In order to have better understanding about rutting characteristics of SMA mixture at different environmental temperature, dynamic creep test was conducted at temperatures of 10, 25 and 40 °C which are considered as relatively low, medium and high temperatures, respectively. Besides stress levels of 300 kPa and 400 kPa were designated for this study. In previous research, it was reported that lower stress level (e.g. 100 kPa) cannot properly manifest the rutting performance of modified asphalt mixtures [13].

4.3. Zhou's three-stage model

In this study, to have better understanding about permanent deformation behavior of control and PET modified mixtures; Zhou three-stage model was proposed at different stress levels and temperatures. MATLAB software was utilized for modelling each stage in order for finding the parameters as well as transition points between each stage. Besides, the FN was also calculated.

The results are presented in Tables 5 and 6. Achieved results show at 300 kPa stress and lower temperatures (10 °C and 25 °C), the control and modified mixtures do not go through secondary stage; however, at 300 kPa stress and temperature of 40 °C all stages can be recognized. Hence, importance of temperature can apparently be recognized on permanent deformation behavior of asphalt mixture. In other words, road pavement is much more susceptible against rutting damage in hot climate condition compared to cold regions. More importantly, as can be seen in Table 6, at 400 kPa stress and 25 °C the control mixture passes through third stage after 10,065 loading cycles whereas the mixtures modified by 0.2%, 0.4% and 0.6% of PET just enter the second stage. Furthermore, it was concluded that the mixtures fabricated by SBS modified binder had remarkably lower permanent strain and the mixture contained 5% of SBS showed the best mechanical behavior when after 10,000 loading cycles the permanent strain decreased from 10,000 μs for 5%-SBS modified mixture to under 3000 μs for unmodified mixture at temperature of 40 °C and 200 kPa stress. Further, other investigation on mineral and cellulose fibers showed that although using these additives could improve the rutting performance of asphalt mixture, the effect did not seem to be significant in comparison with the SBS modification [7].

![Number of Load Cycles at First and Second Stages for Control and PET Modified Mixtures at 300 kPa and 400 kPa Stresses and Temperature of 40 °C](image)

![Flow Number (FN) vs PET Content at 40 °C](image)
the mixtures modified by 0.8% and 1% PET still remain at the first stage. Fig. 10 manifests number of load cycles at first and second stages at 40 °C for both 300 kPa and 400 kPa stress levels. From this figure it can be illustrated that lengths of first and second stages (elastic and viscoelastic stages) are increased in PET modified mixtures when the mixtures including higher PET content showed to have higher amount in length. At 300 kPa, for instance, length of first stage rises from 1117 to 2473 cycles for control and 1%-PET modified mixture which is almost two times longer, and length of second stage increases from 1520 to 2400. It should be noted that effect of PET modification can be more highlighted at higher stress level, while at 400 kPa stress for mixture modified by 1% PET first and second stages are 3.45 and 2.27 times longer respectively compared to control mixture.

In addition, as can be seen in Fig. 11, FN increased considerably by adding waste PET in asphalt mixture. For instance, for control and 1%-PET modified mixtures the FN rise from 2637 to 4873 and 819 to 2277 cycles for 300 kPa and 400 kPa stress, respectively.

5. Conclusions

In this investigation, permanent deformation characteristics of control and PET modified asphalt mixture were evaluated using dynamic creep test. Dynamic creep test was conducted at different temperatures and stress levels. Creep models were proposed, and the results are summarized as follows:

1. Waste PET showed to have great potential to be reused as modifier in asphalt mixture.
2. Permanent deformation characteristics of PET modified asphalt mixtures remarkably improved compared to the control mixture, and the mixture modified by higher amount of PET showed to have better resistance against permanent deformation.
3. At higher stress level and temperature, permanent deformation resistance of both control and PET modified mixture decreased.
4. Based on Zhou three-stage model, length of first (elastic) and second (viscoelastic) stage of creep curve increased considerably in PET modified mixture, and effect of PET modification was more highlighted at higher stress level (400 kPa).
5. At temperature of 40 °C and at both 300 kPa and 400 kPa stress level, Flow Number (FN) was considerably increased by application of PET modification.

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References