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Investigation of the fractionalized polyethylene terephthalate (PET) on the properties of stone mastic asphalt (SMA) mixture as aggregate replacement

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A R T I C L E I N F O

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A B S T R A C T

Polyethylene terephthalate (PET) is a widely used plastic that accounts for almost 18 % of global polymer production and is non-biodegradable, making it a major cause of environmental pollution. Innovative solutions are needed to address PET waste management and reduce its impact. This study aims to investigate the impact of adding PET, on the engineering characteristics of a Stone Mastic Asphalt (SMA-20) mixture. Laboratory tests were conducted to assess the volumetric and mechanical properties of asphalt mixes containing different proportions of PET as fine and filler (ranging from 0 % to 30 %) by volume of aggregates. The results show that the PET incorporation into the asphalt mixture has significantly improved the performance. The addition of PET (fine and filler) to asphalt mixtures significantly increases their resilient modulus (M_R). The mixtures containing 10 % PET as fine and filler are 20 % and 22 % higher in M_R than the control mixture. Moreover, the moisture assessment shows that the PET mixture has a higher tensile strength ratio (TSR) value of 85.9 % and 83.90 % for Fine-10 and Filler-20, thus meeting the AASHTO requirement of ≥80 %. The utilization of PET as aggregate replacement significantly improves the permanent deformation characteristics of asphalt mixtures by decreasing permanent strain. The Fine-20 and Filler-20 revealed promising results by reducing the strain to 0.92 % and 0.81 %. Also, the enhancement in the creep stiffness modulus with 216 and 244 MPa. Furthermore, the addition of PET up to a concentration of 20 % had a beneficial effect on the fatigue response of mixtures. For instance, the failure cycles of the Filler-20 and Fine-10 are 23,231 and 17,521 cycles at a load of 2250 N, whereas the control mixture only endures 8581 failure cycles. In conclusion, PET addition significantly improves SMA properties, promoting waste material utilization in the pavement industry.

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1. Introduction

Globally, the annual plastic waste generation has reached approximately 396 million tons with a 4 % annual growth rate [1,2]. The massive plastic waste generation has accentuated the need for immediate waste management policies. Beyond the high generation, the improper disposal of waste plastic has turned out to be a global challenge. It has changed the functioning of an ecosystem, by causing soil, aquatic life, and water bodies environmental pollution [3–5]. Likewise, plastic with a size <5 mm is causing microplastic pollution, and recently emerged as one of the top 10 environmental pollutants worldwide [6–8]. Polyethene terephthalate (PET) is one of the major types of plastic waste. It is semi-crystalline thermoplastic polyester and accounts for nearly 18 % of total global polymer production [9,10].

PET is the most abundant produced plastic in the last few decades, due to its high thermal stability, mechanical strength and the least cost and production relationship. The terephthalic acid and the ethylene glycol polymerization produce PET [2,11]. The terephthalic acid (crystalline solid) and ethylene glycol (colorless) are mainly obtained from the xylene and the ethylene respectively. The combined heating of both materials under the presence of the chemical catalysts results in the production of PET in the form of a viscous molten mass. The produced material can be turned into plastic. PET is commonly used for packing drinks and water because it's cheaper and safer than glass, which can easily break [12,13]. This broad usage leads to the main cause of environmental pollution due to its non-biodegradability [14]. The stronger and more stable backbone of the polymer, the hydrophobicity and the higher crystallinity ratio made the PET harder to be naturally degraded. Since the recycled amount of PET does not fully match the huge production rate, overcoming the problems associated with PET waste needs an innovative reusing avenue.

Recently, PET has been increasingly utilized in the construction industry, particularly in asphalt and concrete mixtures, because of its higher recycling potential [15–17]. Besides, the benefit of the reduction in PET waste accumulation. The major concern pertaining to waste PET utilization in asphalt mixtures is to control the usage of non-renewable resources i.e., natural aggregates and bitumen, and to stabilize the environment from hazardous pollutants. Also, it enhances the durability and overall performance of the flexible pavements. Concerning the problems associated with PET wastage previously numerous studies have been performed to assess the performance of the waste PET incorporated in asphalt mixture by contemplating the wet and dry methods [18,19]. While the forgoing research has revealed the potential of waste PET in asphalt mixture, various factor impedes its utilization. The modification of the bitumen by direct incorporation of the waste PET faces the phase change compatibility due to the higher melting point (about 250 °C) of the PET [20]. Likewise, the lower density and higher melting temperature cause the non-homogeneity and poor dispersion of PET within the bitumen matrix [21]. Conversely, the chemical pre-treatment of waste PET is a promising avenue for bitumen modification. However, this method needs several solvents and chemicals and results in many toxic by-products and involves some more amount of energy for chemical processing ending up with more cost and associated environmental concerns. Hence, PET is majorly incorporated as a mixture modifier or as an aggregate substitute.

Based on previous literature, PET has the potential to be employed as an asphalt binder, aggregate substitute or mixture modifier. Lugeiyamu et al. [22] studied the feasibility of using PET as a partial replacement for asphalt binder in SMA mixtures. The study demonstrated that incorporating 10 % PET by weight of the binder produced a mixture with high stability compared to the control mixture. In a similar approach, Hassani et al. [23], partially used a PET as a replacement with aggregate in the fraction of 4.75–2.36 mm. The Marshall stability of the asphalt mixture was improved by 5 % and decreased by using a high amount of PET. Quesada et al. [24] investigated the stiffness properties of an asphalt mixture modified with PET by dry method. The findings showed that using PET enhanced the stiffness of the mixture at low temperatures. It was observed that 14 % by weight of asphalt binder is the optimum proportion of PET. In another study, when PET granules were used to replace various portions of the virgin aggregates. The indirect tensile strength values were decreased with increasing content of the PET, and the tensile strength ratio values showed that PET to the SMA mixtures produced more resistance to moisture [9]. Similar findings were observed by Ameri and Nasr [25]. On the other hand, several studies have investigated the fatigue resistance of PET-modified asphalt mixtures and observed higher fatigue resistance [26,27]. Moghaddam et al. [26] concluded that the SMA mixtures containing a high PET content demonstrated lower stiffness. In a similar study, Modarres and Hamedi [28], adding PET to the mixture in the range of 2–10 % by weight of the asphalt binder would significantly affect the fatigue performance of the mixtures. In addition, several investigations were carried out on the impact of PET in terms of the rutting resistance of the asphalt mixture. The results showed that rutting behavior of SMA mixtures has been enhanced by adding PET [18,29]. Ziari et al. [30] observed that the addition of PET enhances mixture rutting resistance and decreases as PET particle size increases. As a result, it might be concluded that introducing a low amount of PET in asphalt mixtures can improve its mechanical properties. Nevertheless, adding a higher content of PET fractions could negatively affect the performance of asphalt mixtures [26,31].

In addition to the above-discussed studies, research for the evaluation of the waste PET is still scarce. In spite of numerous parameters investigated for the performance assessment of the PET-modified asphalt mixtures, extended research should be made available on the effect of the different sizes of waste PET and the combination of the sizes as a substitution of aggregates. In previous research, not much focus was given to how temperature and load affect the performance of asphalt mixtures, even though these factors play a significant role. Therefore, this study investigates the PET substitution as an aggregate portion of different sizes or the combination of the sizes (fine and filler) on the performance of stone mastic asphalt (SMA) mixture in terms of stiffness modulus, moisture susceptibility, permanent deformation, indirect tensile strength, and fatigue resistance.

2. Materials and experimental methods

2.1. Materials

2.1.1. Asphalt and aggregates

The asphalt binder used in this study is supplied by KR Premix Holdings Sdn Bhd with penetration grade 60/70, and it is mostly used in Malaysia due to its adaptability to climatic conditions. Table 1 shows the properties of the base 60/70 asphalt binder. In this study, crushed granite was sourced from the Kajang quarry (Near Kuala Lumpur, Malaysia) and limestone cement was used as a filler which was characterized based on the ASTM testing procedure to prepare the specimens. The physical tests were performed to ensure the quality and strength of the material in conformity with Malaysian standards for the public works department (JKR). Fig. 1 exhibits the selected aggregate gradation and the properties of employed granite aggregate are presented in Table 2.

2.1.2. Waste PET

In this study, the waste plastic bottle in crushed form was used and supplied by Glowmore Express Sdn Bhd, Malaysia. The crushed bottles were sieved to obtain the desired sizes. The obtained sizes were further categorized as fine aggregate (i.e., passing from sieve 4.75 mm and retained on sieve 0.075 mm) and as a filler (i.e., passing from sieve 0.075 mm and retained on a pan), as illustrated in Fig. 2. Aggregate gradation typically includes various sizes of coarse aggregate, fine aggregate, and filler, all of which have irregular shapes. The categorized fine and the filler of PET were used as a substitute for a specific portion of aggregates as the volumetric replacement aimed to have a consistent mixture. This innovative utilization of PET flakes in asphalt mixtures offers several benefits. The irregular shape of the flakes fosters better bonding between the materials in the mixture, potentially enhancing the performance and durability of the asphalt pavement. The physical properties of the PET were evaluated by applying the standard methods and summarized in Table 3.

2.2. Methods

2.2.1. Asphalt mixture preparation

The Marshall mix design method (ASTM D1559 and D6926) was employed in this study to produce an SMA mixture [32,33]. The seven asphalt mixture combinations including the control mixture were prepared. The three mixes were prepared with fine PET and the other three with filler as a replacement for aggregate.

Table 4 describes the mixture design details and the percentage of waste PET substitution by volume of aggregates. A total of 105 cylindrical specimens were prepared using the Marshall compactor with 15 specimens for each mix design at a varying content of asphalt (4.5 %, 5.0 %, 5.5 %, 6.0 %, and 6.5 %) by weight of the total mix. The dry method of mixing was followed to compact the triplicates of a specimen. The oven-heated aggregates at 180 °C and the asphalt were first blended and then the PET was added as a substitute of aggregates by volume replacement (10 %, 20 % and 30 %). The desired mixing and compacting temperatures were determined based on the viscosity-temperature relationship of the asphalt binder, which ranged from 0.17 ± 0.02 Pa s to 0.28 ± 0.03 Pa s as illustrated in Fig. 3. The asphalt mixture was mixed and compacted at a temperature of 157 °C and 143 °C respectively. The blended mixture was compacted using a Marshall compactor by applying 50 blows at each side of the specimen following the specifications outlined by JKR for road works [33].

The compacted cylindrical specimens were tested for Marshall stability, flow and density. Based on the parameters and the void analysis the optimum asphalt content (OAC) of the seven asphalt mix designs was determined and presented in Table 5. The obtained OAC and the volumetric parameters i.e., voids in the total mix (VTM) and voids in mineral aggregates (VMA) are satisfying all Marshall Mix requirements based on the Malaysian specifications stipulated by JKR [33]. Therefore, the determined OAC was used for the preparation of the triplicate specimens for each asphalt mixture for the mechanical performance of the control and the modified mixtures with PET. The compacted cylindrical specimens were prepared at 4 % ± 0.5 % air voids for the Marshall stability, flow, resilient modulus, dynamic creep, and indirect tensile fatigue test. However, the moisture susceptibility specimens were prepared at 7 % ± 0.5 % using the Superpave gyratory compactor as per the ASTM standard and Malaysian specifications.

Table 1
Properties of asphalt binder.

Test description	Test standard	Measured value
Specific gravity	ASTM D70–2021	1.03
Penetration at 25 °C	ASTM D5–2019	65.50
Softening Point, °C	ASTM D36–2008	51.5
Flash (°C)	ASTM D92–2018	280
Fire Point (°C)	ASTM D92–2018	310
Brookfield Viscosity @ 135 ℃ (Pa. s)	ASTM D4402–2000	0.462
Dynamic Shear Rheometer	ASTM D7175–2001	1.22
RTFO aged residue (Pa)	ASTM D2872–2001	2.25
PAV-aged residue (MPa)	ASTM D6521–2019	313.60

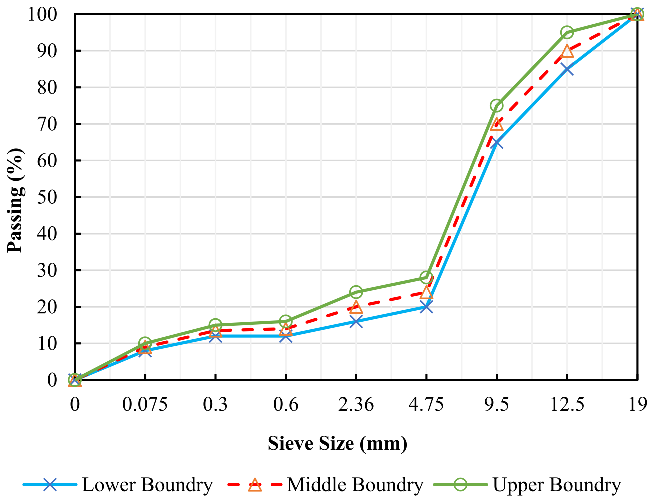

Fig. 1. Gradation curve for SMA with specification limits.

Table 2
Properties of granite aggregate.

Test Description	Test Standard	Result
Specific Gravity of fine aggregate	ASTM C128–2015	2.57
Specific Gravity of coarse aggregate	ASTM C127–2015	2.646
Specific Gravity of limestone	ASTM C128–2015	2.55
Water absorption of coarse aggregate (%)	ASTM C127–2015	0.60
Los Angles Abrasion (%)	ASTM C535–2009	20.66
Impact factor value (%)	ASTM D5874–2016	8.86
Soundness (%)	ASTM C88–2018	2.39
Flakiness index (%)	ASTM D4791–2019	17.75

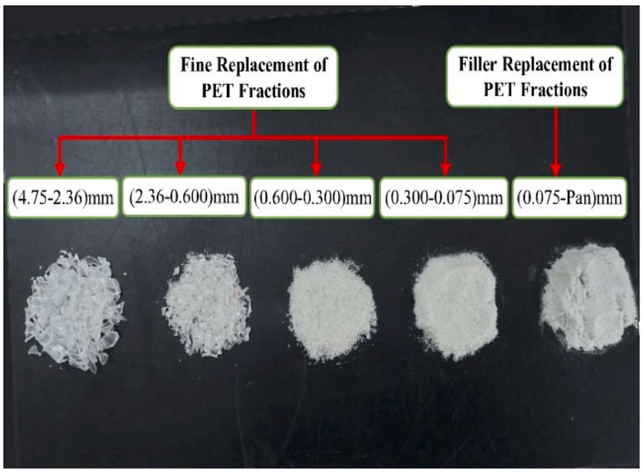

Fig. 2. Different sizes of recycled PET as fine and filler fractions used in asphalt mixture.

2.2.2. PET thermal analysis

The thermal analysis is a pre-requisite to evaluate the feasibility of the material used for the asphalt mixtures. It measures the rate of change of mass of the material under the range of temperatures in a well-controlled condition. The simultaneous thermal analyzer Mettler Toledo (TGA-DSC HT 3) was used to measure the PET thermal capability at a temperature range of 25 °C to 600 °C. The heating rate of the test was 20 °C/min and controlled under a nitrogen environment. The thermal decomposition and transition of the PET specimens were conducted under the test scheme of thermogravimetric analysis (TGA) and Differential Scanning Calorimetry (DSC) respectively.

Table 3
Physical and thermal properties of PET.

Properties	Specification	Measured value
Density (gm/cm^3)	ASTM D792–20	1.388
Soundness (%)	ASTM C88	0.052
Tensile strength (MPa)	ASTM D638	136.714
Melting point °C	(DSC)[a]	255
Boiling point °C	(DSC)[a]	350
Glass transition °C	(DSC)[a]	87

[a] Differential scanning calorimetry (DSC)

Table 4
Contents of the asphalt mixture blends.

Mix design	Aggregate replacement by volume		
	Coarse	Fine	Filler
Control	100 % granite	100 granite + 00 % PET	100 % limestone
PET-Fine-10	100 % granite	90 granite + 10 % PET	-
PET-Fine-20	100 % granite	80 granite + 20 % PET	-
PET-Fine-30	100 % granite	70 granite + 30 % PET	-
PET-Filler-10	100 % granite	-	90 limestone + 10 % PET
PET-Filler-20	100 % granite	-	80 limestone + 20 % PET
PET-Filler-30	100 % granite	-	70 limestone + 30 % PET

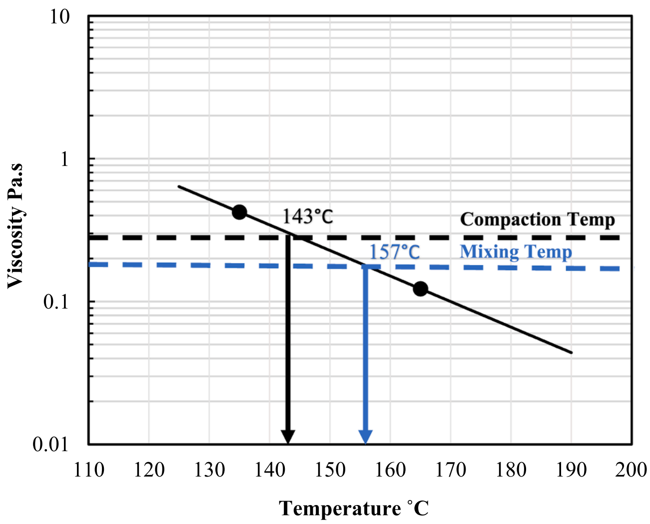

Fig. 3. Mixing and compaction temperatures of asphalt binder.

Table 5
Properties of mix design.

Mix design	O.A.C (%)	Density (g/cm3)	VTM (%)	VMA (%)	Stability (kN)	Resilient modulus (MPa)
Control	5.30	2.293	5.00	17.00	7.30	3680
PET-Fine-10	5.39	2.280	4.90	17.05	7.90	3240
PET-Fine-20	5.45	2.259	4.80	17.15	8.00	3180
PET-Fine-30	5.59	2.244	4.80	17.25	7.45	2900
PET-Filler-10	5.43	2.284	4.80	17.10	8.15	3280
PET-Filler-20	5.50	2.272	4.70	17.20	8.40	2960
PET-Filler-30	5.61	2.260	4.60	17.30	8.35	2840

2.2.3. PET tensile properties analysis

The tensile strength of the waste PET was evaluated using the Universal tester (Instron). The PET strip was prepared from the waste bottles following the ASTM D638 and supplied by Glowmore Express Sdn Bhd, Malaysia. The four different types of waste bottles were utilized to evaluate the amount of force required to break the PET strips. The average dimensions of the specimens were (130×10×0.17 mm) with minor variations in the thickness. The triplicate of each type of PET strip was tested by placing it in the Universal tester grips and pulled out at a speed of 5 mm/min up to the failure to measure the tensile strength. All specimens were tested for tensile strength at room temperature.

2.2.4. Marshall stability and flow

The compacted cylindrical specimens for the seven mixture designs at the desired OAC were tested for Marshall stability and flow. The test reflects the performance of the control and the PET-modified mixtures. A total of 21 compacted cylindrical specimens at 4 % air voids were tested for stability and flow following the ASTM D6927 [34]. The resistance related to the maximum load sustained by the specimen along the vertical axis at a strain rate of 50.8 mm/min at a temperature of 60 °C is the stability of the specimen.

2.2.5. Resilient modulus test

The stiffness and the quality of the PET-modified SMA mixtures were evaluated by performing a resilient modulus (M_R) test. The M_R is a fundamental material property used to assess the stiffness and deformation characteristics of asphalt mixture under different temperatures and loading conditions. A total of 42 cylindrical specimens were tested in this study and divided into two subsets of 21 specimens. A triplicate of specimens was tested for each asphalt mixture at a temperature of 25 ℃ and 40 ℃. The repetitive compressive load of 1000 N was applied in a haversine waveform along the vertical plane of the specimens using the universal material testing apparatus (MATTA). The horizontal and vertical deformations were measured by installed LVDTs along the diameter of a specimen after the application of 5 pulses to each asphalt mixture SMA specimen. The M_R is determined assuming the material Poisson ratio of 0.35 as specified in the ASTM and JKR specifications [33,35]. The stiffness modulus is determined using the following equation:

$$M_R = \frac{L(\nu + 0.27)}{D\ t} \tag{1}$$

where M_R is the resilient of modulus (MPa), L is the largest value of applied vertical load (N), D is the value of horizontal deformation (mm), t is the thickness of test specimen (mm) and v is Poisson's number (a value of 0.35 is normally used).

2.2.6. Moisture susceptibility

The degree of susceptibility to moisture damage is determined by preparing a laboratory-compacted specimen at air voids of 7 % using the gyratory compactor following the ASTM D4867 [36]. The 42 specimens were prepared and divided into dry and moisture-conditioned groups. The latter was partially saturated with distilled water and soaked at 60 °C for 24 h, followed by soaking in water at 25 °C for 1 h. The dry group was soaked in water at 25 °C for 20 min. Tensile strength was measured using the tensile splitting test, and the potential for moisture damage was determined using the tensile strength ratio (TSR). TSR was calculated by dividing the mean ITS values of wet specimens by those of dry specimens. The TSR test is the comparison to the tensile strength of the

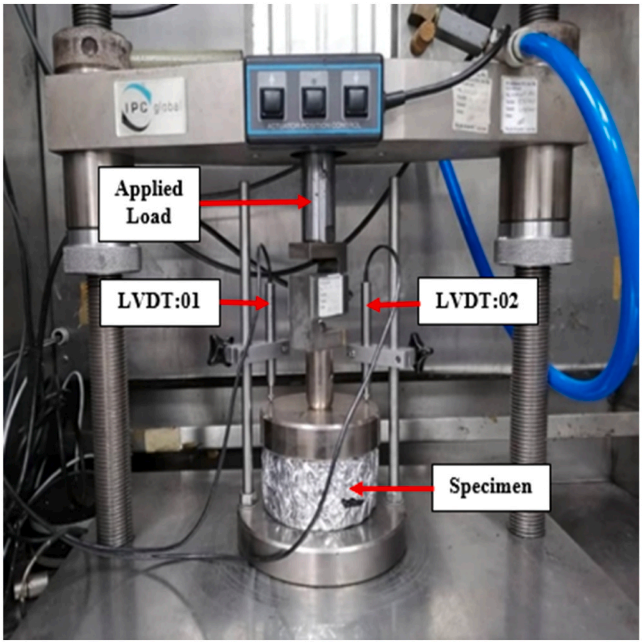

Fig. 4. Dynamic creep test setup of trimmed cylindrical specimen.

conditioned subset and the unconditioned subset used to evaluate the moisture susceptibility of asphalt mixture and can be determined by the following equation:

$$TSR = \frac{TS\ condioned}{TS\ unconditoned} \times 100 \tag{2}$$

2.2.7. Dynamic creep test

The dynamic creep test evaluated the permanent deformation resistance of the asphalt mixtures under the cyclic compression loading system. A total of 21 Marshall specimens for 7 asphalt mixtures were compacted at 4 % voids. However, prior to performing the actual test, each compacted specimen was trimmed using the diamond blade cutter to achieve the minimum of 50 mm thickness as specified in EN-12697–25 [37]. The cutting of the specimens aims to smoothen the surface of the specimens to avoid any friction between the loading plate and the specimen. The trimmed surface was further smoothened by applying sandpaper and coating the graphite powder on both sides of the specimen. Lastly, the specimen was carefully wrapped with an aluminum sheet to further provide a smoother surface for the testing conditions. The prepared specimens were conditioned for at least 3 hours at 40 °C before the application of the loading condition. The testing applied loads and the temperatures were selected as per the recommendation of the specifications of JKR [33]. The total deformation of the specimens was measured by two attached LVDTs from 0 to 3600 cycles. Fig. 4 shows a cylindrical specimen of the dynamic creep test. The cumulative axial strain (ε_n) after the applied (n) load cycle was determined by the following equation.

$$\varepsilon_n = 100\left(\frac{h_o - h_n}{h_o}\right) \tag{3}$$

Where ε_n is the cumulative axial strain (%), n is the number of load cycles, h_0 corresponds to the height of the average specimen in (mm), h_n represents the average height after the number load cycle (mm).

Whereas, the creep modulus (E_n) after the applied (n) load cycle in (MPa) can be determined by the following equation:

$$E_n = \frac{\sigma}{\varepsilon_n} \times 1000 \tag{4}$$

Where σ is the applied stress (kPa), and ε_n is the cumulative axial strain after the applied (n) load cycle (%).

2.2.8. Indirect tensile fatigue test

The indirect tensile fatigue test (ITFT) is a widely used method to evaluate the fatigue behavior of asphalt mixtures. The fatigue life of asphalt mixture denoted as (Nf), refers to the number of load cycles that a specimen can endure before failure occurs under repeated loading conditions. Moreover, it's influenced by material properties, loading conditions, and environmental factors. In this test, a total of 21 cylindrical specimens were tested at three loading conditions of 2000 N, 2250 N and 2500 N using MATTA. The cylindrical specimens were compacted at 4 % air voids using the Superpave gyratory compactor. The test assembly of the ITFT is similar to the

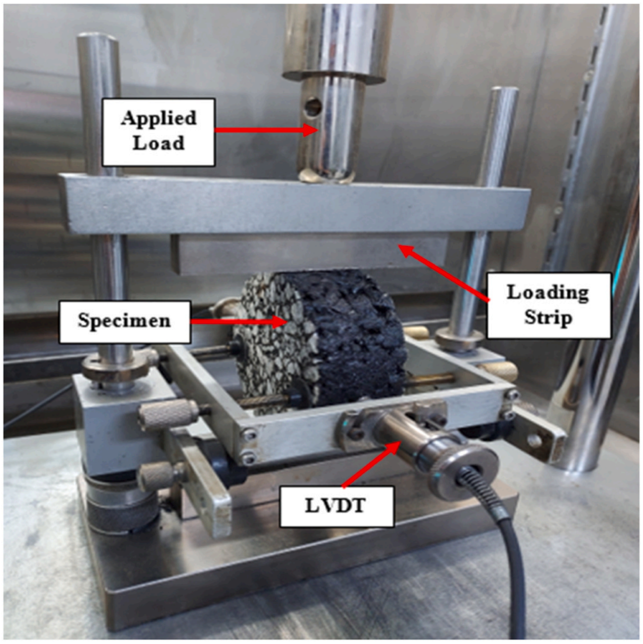

Fig. 5. Indirect tensile fatigue test setup of trimmed cylindrical specimen.

resilient modulus regardless of the specimen thickness which was trimmed to 40 mm following the standard specification EN-12697–24 [38]. The specimens were pre-conditioned for three hours at 20 °C to simulate the road fatigue environment. The haversine cyclic loading was applied to the testing specimen at a frequency of 2 Hz considering the high traffic volume roads while the rise time was selected as 100 ms to tackle the low-speed road operations. The cyclic loading was continued with 0.2 seconds of rise followed by the 0.3 s of rest period until the failure of the testing cylindrical specimens or at 9 mm of displacement. The vertical displacement and the horizontal deformation of the cylindrical specimen were assessed with attached LVDTs as shown in Fig. 5. The deformation for each specimen versus the loading cycle curve was plotted automatically by related software. The maximum tensile strain produced at the center of the specimen is calculated as:

$$\varepsilon_{xmax} = \frac{\sigma_{xmax}(1+3\nu)}{S_m} \times 1000 \quad (5)$$

Where ε_x is the tensile horizontal strain of the specimen in microstrain (με), σ_x is the maximum tensile stress of the specimen in kPa, ν is Poisson's ratio, and M_R is the stiffness modulus at σ_{xmax} in MPa. The maximum tensile of the specimen can be calculated as:

$$\sigma_{max} = \frac{2L}{\pi \times d \times t} \quad (6)$$

Where L is the vertical applied load (kN), d is the diameter of the specimen (mm), and t is the thickness of the specimen (mm).

The ITFT results were used to measure the fatigue life of the specimen by using the following equations:

$$N_f = k_1(\varepsilon_o)^{-k_2} \quad (6)$$

$$\log N_f = \log k_1 + \quad k_2 \quad \log_{\varepsilon 0} \quad (7)$$

Where N_f is fatigue life represented the number of cycles to failure, ε_0 is the initial tensile strain (microstrain), and k_1 and k_2 are associated with the material coefficients.

3. Results and discussions

3.1. Thermal and tensile analysis

The TGA and the DSC are the common methods to assess the thermal gradation of the materials. The physiochemical conditions of the PET during the process of mixing and the compaction and thermal behavior were determined following these methods.Fig. 6 depicts the TGA and DSC results of the waste PET in a range temperature of 25 °C to 600 °C. The three-stage downward curve trend of PET has been encountered as shown in Fig. 6. The first stage at 255 °C did not demonstrate any reduction in the weight of the specimen which mainly corresponds to the melting point of the waste PET and is in agreement with the earlier literature [39,40]. From this standpoint, it can be concluded that PET is feasible to be incorporated in asphalt mixtures, where the maximum process temperature is probably 200 °C. In the second stage, the waste PET underwent complete thermal degradation with major weight loss (76 %) at a temperature range of 355 °C to 470 °C. The thermal degradation of PET above 400 °C corresponds to its lower thermal conductivity and higher thermal stability in comparison to other types of waste plastics [41]. The PET degradation has adopted the stable behavior in stage three of the curve when the temperature reaches 505 °C with an overall 22.2 % remaining residue. Conversely, the exothermic

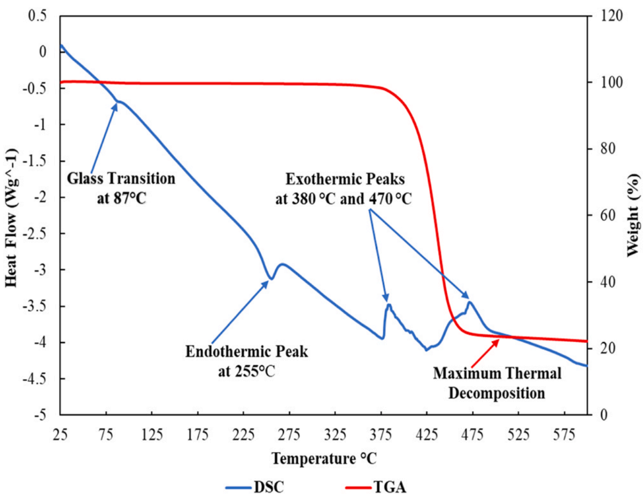

Fig. 6. TGA and DSC curves of recycled PET.

and the endothermic effects of the waste PET corresponding to increasing temperature (25 °C to 600 °C) were analysed using the DSC and the results are depicted in Fig. 6. The DSC curves show one minor and two major endothermic and exothermic curves respectively. The endothermic peak at 255 °C corresponds to the melting point of the PET while the peaks of exothermic at 380 °C and 470 °C relate to the PET pyrolysis temperatures. However, a minor endothermic peak has been observed for the glass transition region of PET (87 °C) and is in agreement with the earlier [2,42].

On the other hand, the tensile properties of the waste PET strips prepared from different types of bottles have been tested for their tensile properties. Fig. 7 illustrates the displacement to failure of plastic strips on increasing force under tensile loading. It is evident that all types of strips have demonstrated varied failure behavior which is possibly the difference in chemical composition, processing conditions, and particularly the difference in the thickness of the bottle types. The PET-Type 1 and type 2 have a minimum tensile strength of 112.17 MPa and 116.36 MPa with higher tensile strains of 10.68 % and 17.03 % respectively as displayed in Table 6. However, type 3 exhibited the higher tensile strength of 159.28 MPa among all other types of PET types which could be due to the overall density and the thickness of the plastic bottles. Furthermore, the tensile strain and the displacement at the maximum load for all types of PET have the same trend regardless of PET type 2 which has 23.43 mm displacement and 17.93 % tensile strain. The curves depicted in Fig. 7 show the different behavior of the PET plastic. The initial stage shows the elastic zone of the PET with an increase in the tensile force due to the unchanged modulus and stability of the PET structure. However, on the increasing elongation, the curves reached the yielding point and suddenly the force required for the displacement was reduced and PET entered the materials' hardening point. Whereas, the failure of the PET occurs suddenly when it reaches the allowable limit. The PET material is between the brittleness and the toughness with rigidity and certain flexibility as it chains composed of the aliphatic hydrocarbons, ester and phenyl groups. The average tensile strength of all types of PET is 136.71 MPa and previous studies have demonstrated this in the same vein [43].

3.2. Resilient modulus

The resilient modulus of PET-modified asphalt specimens is depicted in Fig. 8 and Fig. 9. It is a stiffness modulus of the asphalt mixture where the specimen deformation is fully recoverable under the elastic range loading. It can be observed that the M_R of the PET (fine and filler) modified specimens is significantly higher compared to the control asphalt mixture. The overall stiffness enhancement of PET as a fine replacement is comparatively lower than that of PET as a filler replacement. The M_R of the 10 % PET as fine is 3660 MPa which is 22 % higher than the control asphalt mixture (3155 MPa). However, the PET as filler at the same content demonstrated an M_R of 3988 MPa and was 26 % higher compared to the control mixture. Hence, the inclusion of PET into the asphalt mixture remarkably enhanced stiffness behavior. Similar outcomes were stated by Ghabchi et al. [13] and Esfandabad et al. [9]. It is evident in Fig. 9 that by increasing the temperature from 25 °C to 40 °C the M_R of the studied PET fine and the filler specimens was decreased twice. Nevertheless, the marginal difference in the fine and filler specimens was slightly increased as the filler specimens performed much better than the fine at higher temperatures. Similarly, the M_R of the 10 % PET at 40 °C as fine is 851 MPa which is 25 % higher than the control asphalt mixture (639 MPa). Moreover, the initial increment in the resilient modulus of PET asphalt mixture has been followed by a decreasing trend as the percentage incorporation of the PET is increased to 20 % as shown in Fig. 8 and Fig. 9. For instance, the incorporation of 30 % PET into the asphalt mixture causes a 15 % reduction in the stiffness modulus compared to 10 % PET, and a similar trend has been observed at a temperature of 40 °C. The higher presence of the PET in the asphalt mixture could reduce the tolerable loading condition and the resistance against the tensile stresses.

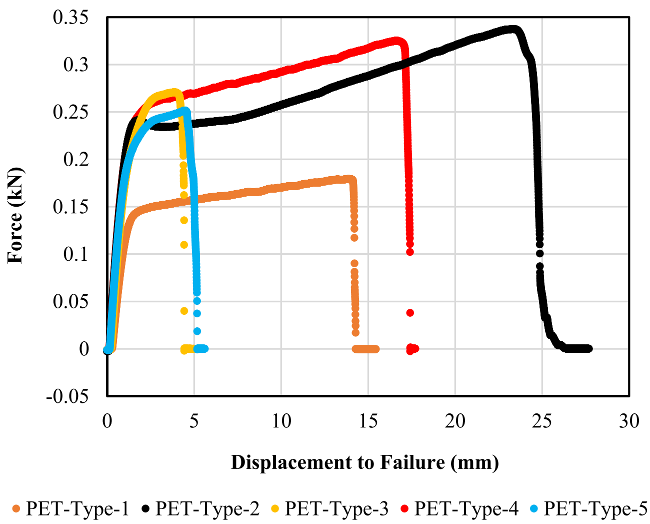

Fig. 7. Maximum load of PET strips to failure.

Table 6
Tensile strength properties of PET.

PET-Type	Specimen dimension (mm)	Tensile strength (MPa)	Tensile strain (%)	Force @ maximum load (kN)
PET-Type 1	130×10×0.16	112.17	10.68	0.179
PET-Type 2	130×10×0.29	116.36	17.93	0.337
PET-Type 3	130×10×0.17	159.28	2.95	0.271
PET-Type 4	130×10×0.22	147.84	12.79	0.325
PET-Type 5	130×10×0.17	147.92	3.46	0.251
Average		136.71	9.56	0.273

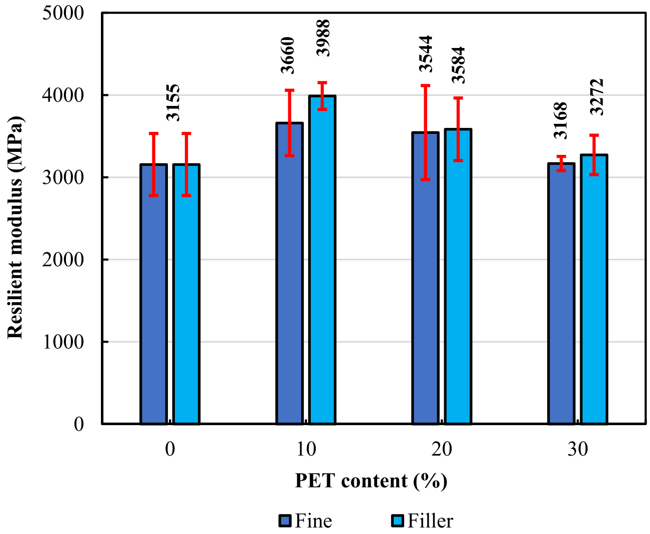

Fig. 8. Resilient modulus of PET asphalt mixtures at 25 °C.

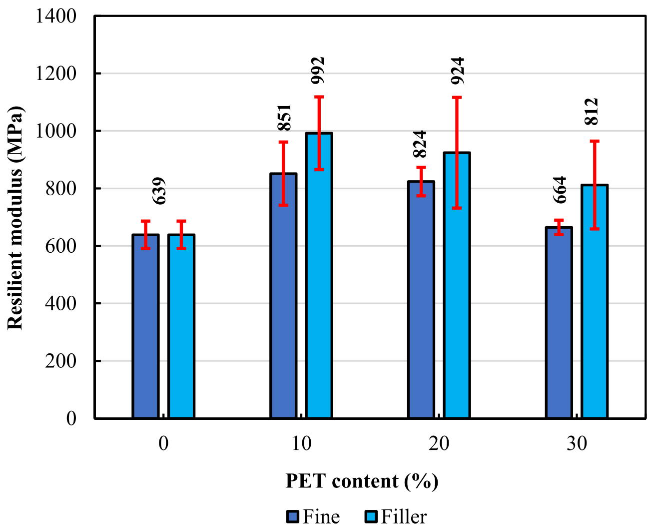

Fig. 9. Resilient modulus of PET asphalt mixture at 40 °C.

3.3. Moisture susceptibility

As described in the previous section there is a noteworthy difference in the M_R of the control and the PET-modified asphalt mixtures. This section further verifies the performance of the mixtures under the indirect tensile strength (ITS) and tensile strength ratio (TSR) evaluation. The outcomes of the dry and wet subsets of the ITS test and the calculated TSR are illustrated in Fig. 10. The overall ITS values of the wet subset are lower due to the conditioning of the specimens at 60 °C for 24 h thereby abating the cohesion

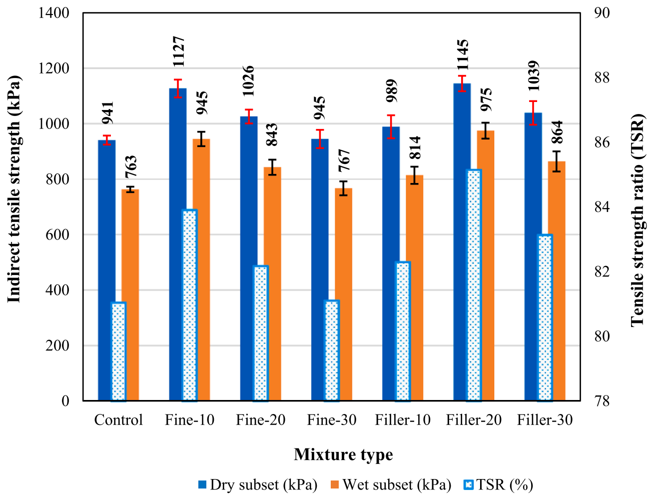

Fig. 10. Indirect tensile strength and tensile ratio of asphalt mixtures.

and the adhesion bond within the asphalt matrix. The percent incorporation of PET into the asphalt mixture is also evident as shown in Fig. 10. It is elucidated from the results that the asphalt mixture modification with the PET as the filler has higher ITS values at dry and wet conditions compared to the replacement of filler and these results are similar to the earlier discussed results of the $M_{R.}$ The Fine-10 asphalt mixture specimens have an indirect tensile strength of 1126.7 kPa in the dry condition and are 16 % higher than the control specimens (940 kPa). Similarly, the wet subsets of Fine-10 have demonstrated a 19 % improvement with ITS of 945.30 kPa to that of control specimens (762.57 kPa). On the contrary, it can be inferred from Fig. 10 that the filler incorporation has resulted in somehow similar performance regardless of the Filler-20 with 1145 kPa. However, it has a 1.6 % higher ITS compared to the dry subset of Fine-10.

Moreover, the Fine-10 and Filler-20 exhibited enhanced ITS values in dry and wet conditions compared to the control specimens. The further inclusion of the PET higher than the optimum caused the decrement in the ITS of the asphalt mixtures. This reduction is attributed to the accumulation of the asphalt binder film on the PET surface during the mixing process. This ultimately results in the reduction of asphalt film around the aggregates and causes the weakening of the adhesion of the aggregate-bitumen and eventually the ITS of the asphalt mixtures [27,44]. The detrimental damage caused by the moisture influx to the asphalt mixture is usually evaluated by the TSR as depicted in Fig. 10. A significant enhancement has been observed in the TSR outcomes due to the incorporation of the PET within the asphalt matrix as a replacement of fine and the filler at various contents. The Fine-10 has a TSR value of 83.90 % which is higher than the control specimens (81.04 %). It has been observed from the results that the Filler-20 had a higher TSR value of (85.14 %) among all modified mixtures and Fine-30 exhibited a lower TSR (81.10 %). The relatively reduced performance is ascribed to the increased PET content. However, the overall moisture susceptibility of the mixture is within the stipulated minimum TSR value of 80 % and is an indication of the improved moisture damage of asphalt mixtures [45].

3.4. Stability and flow

Fig. 11 and Fig. 12 depict the results of the stability and the flow of asphalt mixtures prepared at the optimum asphalt content. The trend of the stability results is coupled with the indirect tensile strength of the mixtures and justifies the outcomes. The stability of the asphalt mixture depends on the content of the PET. The values of the stability of fine and filler-modified mixtures increased to the optimum content and followed the decreasing trend. However, the Fine-10 has a stability value of 8.91 kN and is 12.35 % higher compared to the control mixture. Similarly, the further addition of the PET as fine reduces the resistance against compressive forces and Fine-30 demonstrated a significant reduction with the stability of 8.05 kN and is 3 % higher than the control mixture. Similar behavior of PET mixtures is encountered in the resilient and ITS outcomes Sections (3.2 and 3.3). Furthermore, the performance of the filler as a replacement in the asphalt mixture is higher compared to the fine replacement. As evident in Fig. 11 the Filler-20 has a stability value of 9.34 kN and is 16.02 % and 4.83 % higher than the control and Fine-10 respectively. Thus, the overall performance of the filler is higher at increased content of the PET. Comparable findings have been reported by Ahmadinia et al. [46] and Quesada et al. [24] where the increasing content of the PET leads to a reduction in the strength of the mixture. Alternatively, the results of the flow are depicted in Fig. 12. It can be seen the increasing content of PET causes the increase in the flow values. The Fine-10 demonstrated a flow of 5.67 mm which is higher than the control mixture (4.32 mm). The PET filler interestingly performs better in resisting the flow of the mixture and mainly due to the finer fractions which increase the viscosity of the binder and ultimately enhance the stiffness of the mixture. Despite the addition of higher content of filler PET, the flow values are not within the JKR specification (2–4 mm) [33]. Therefore, it can be deduced that PET as filler replacement has shown promising outcomes with higher stability and optimal flow values.

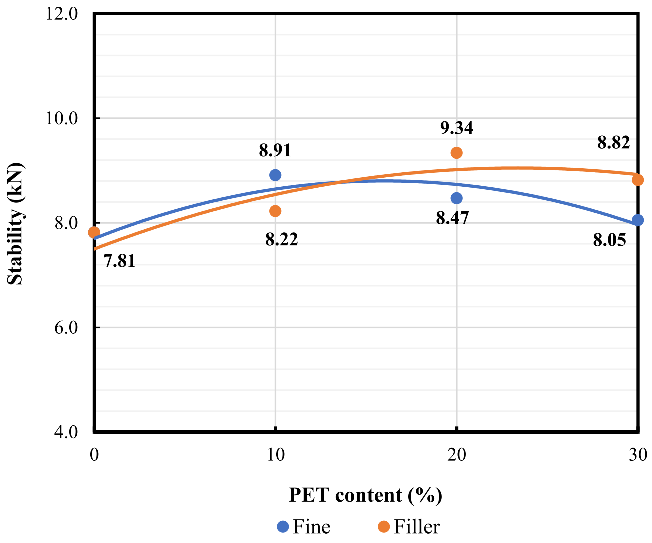

Fig. 11. Marshall stability for different percentages of PET replacements.

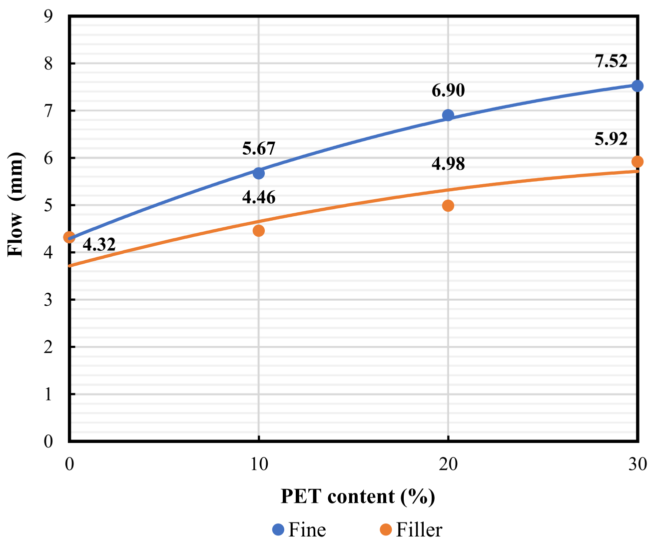

Fig. 12. Marshall flow for different percentages of PET replacements.

3.5. Dynamic creep test

Fig. 13 and Fig. 14 represent the total cumulative strain and creep stiffness modulus results, performed to determine the PET-modified asphalt mixture resistance to permanent deformation. Fig. 13 illustrates the increase in the permanent strain with the gradual increase of the stress cycles. The total strain (%) of the PET-modified asphalt mixtures is the lowest compared to the control SMA, an indication that the PET incorporation remarkably enhances the control mixture's permanent deformation. Despite the overall improvement in PET mixtures, the filler PET has displayed a higher resistance to deformation with minimum total permanent strain (%). The total cumulative strain at 3600 cycles decreased by 52 % with 20 % filler PET and by 45 % with 20 % PET as fine reinforcement compared to a neat mixture. The better performance of the filler PET is due to the smaller size which causes the mechanical interaction with the mastic and improves the adhesion to the asphalt binder. Also, provides better interlocking and more interparticle contact which led to stiffer mastic and then ultimately better mixture performance [13]. This outcome is further confirmed by the creep stiffness modulus of filler and fine PET with 20 % incorporation at 3600 cycles, where the creep modulus is 244 and 216 MPa respectively. The higher creep modulus of Filler-20 indicates that the mixture is least susceptible to rutting failure as shown in Fig. 14. Whereas, increasing the PET content to 30 % has suddenly influenced the creep stiffness modulus where lower stiffness resulted in higher permanent strain as stated in all PET-modified mixtures. The reason for the high strain can be attributed to the elevated content of PET, which exceeds the optimal PET content for achieving improved performance. The inclusion of a higher percentage of PET

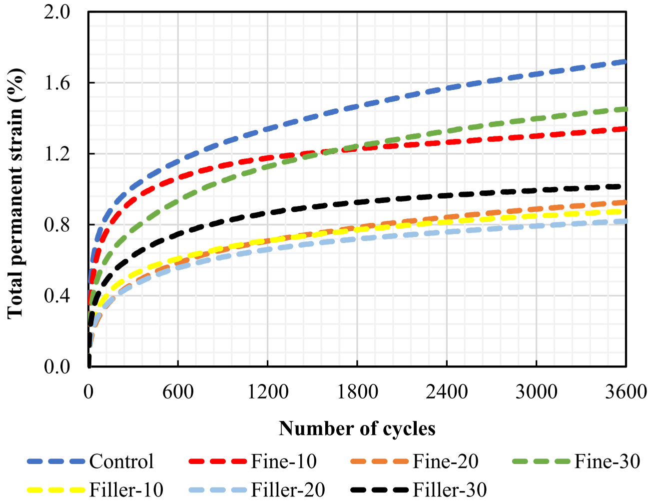

Fig. 13. Total permanent strain versus cycles of asphalt mixtures.

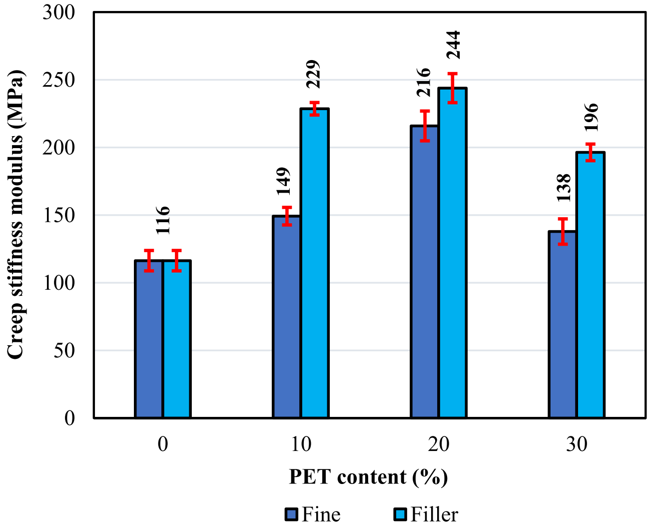

Fig. 14. Effect of PET on creep stiffness modulus of asphalt mixtures.

ultimately results in a reduction in the overall density of the asphalt mixture when compared to the original mixture that included only aggregates. The Filler-20 demonstrated higher resistance to permanent deformation with a strain of 0.81 %, while Fine-30 had the lowest resistance to deformation (1.4 %) compared to the control mixture with a strain of 1.72 %. In general, the asphalt mixture incorporated with the PET is more resistant to applied stress cycles and these outcomes are consistent with what was reported in the previous literature [9,18].

3.6. Indirect tensile fatigue test

The fatigue failure of the seven asphalt mixtures at different loading is depicted in Table 7, Fig. 15 and Fig. 16. The results show that

Table 7
Number of cycles to failure at different loading.

Load (N)	Number cycles to failure						
	Control	**Fine-10**	**Fine-20**	**Fine-30**	**Filler-10**	**Filler-20**	**Filler-30**
2000	11,261	32,331	27,441	16,461	33,901	41,331	20,611
2250	8581	17,521	13,031	9991	13,771	23,231	11,381
2500	2401	11,151	8881	5641	6241	12,451	8401

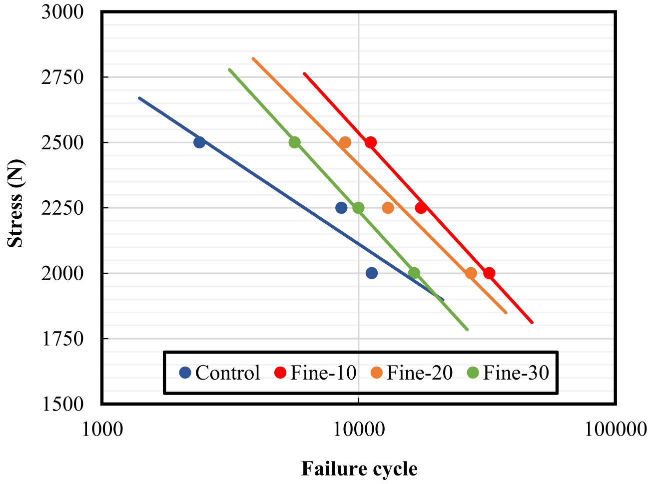

Fig. 15. Cycles to failure vs loading of PET fine mixtures.

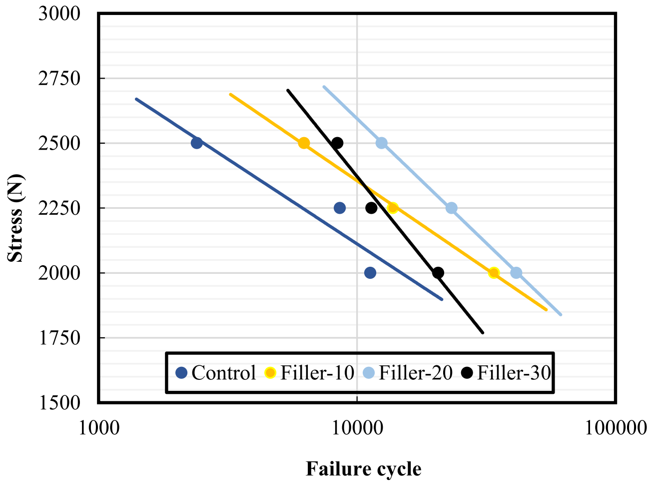

Fig. 16. Cycles to failure vs loading of PET filler mixtures.

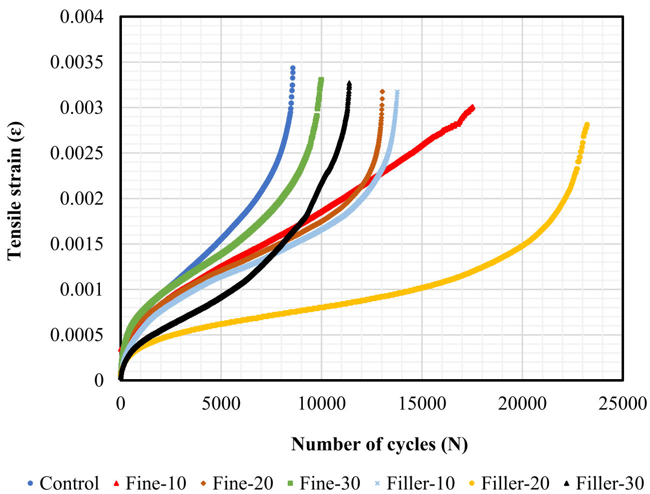

Fig. 18. Tensile strain versus loading cycles of asphalt mixtures at the load of 2250 N.

increasing the content of PET prolonged fatigue life and improved performance at a load level of 2000 N. However, further increases in PET content beyond 10 % led to a decrease in fatigue life for fine PET as an aggregate replacement at load levels of 2000 N, 2250 N, and 2500 N. Additionally, the asphalt mixture with 20 % PET as filler demonstrated greater resistance to fatigue damage than the control mixture at the same load levels. Fig. 15 shows that the asphalt mixture with 10 % fine PET has a 65.17 % improvement in failure cycles (32,331) compared to the control mixture (11,261) at a load of 2000 N. The addition of PET as a filler also significantly enhances the fatigue resistance of asphalt mixtures. For instance, the mixture with 20 % PET as filler exhibits a 72.75 % improvement in failure cycles (41,331) compared to the control mixture (11,261) at a load of 2000 N as shown in Fig. 16. The inclusion of PET also leads to longer fatigue life, which may be due to the higher energy absorbency of the PET fractions and the resulting enhanced performance of the asphalt mixture under repeated loading conditions [9].

The indirect tensile fatigue test resulted in an important outcome i.e., tensile strain as depicted in Fig. 17 at the load of 2000 N. The tensile strain refers to the deformation that occurs in the asphalt mixtures under cyclic loading. Figs. 17–19 illustrates that the tensile strain can be divided into three parts. The first part covers the initial load cycles during which the rate of deformation increment is relatively high because of plastic deformation. In the second part, the rate of deformation stabilizes and the fatigue curve shows a linear trend. In the third part, microcracks that formed during the second stage will continue to propagate [47]. Fig. 17 compares the tensile strain curves of the PET-modified asphalt mixtures at varying content. It can be noted that the modified mixture displayed a low and constant slope of deformation at the secondary zone compared to the conventional SMA.

Likewise, the behavior of the high load of 2250 N and 2500 N was similar to that of the tensile strain at 2000 N. Fig. 18 and Fig. 19 demonstrate this in terms of the tensile strain at a load of 2250 N and 2500 N. The results indicate that as the loading levels increased, the tensile strain values increased for all mixtures. The Fine-10 and Filler-20 mixtures exhibited the lowest tensile strain values compared to the other mixtures, indicating a more stabilized linear deformation compared to the other PET or control mixtures. Similar outcomes were observed in ITS and resilient modulus analysis which further signifies the PET impact on the asphalt mixture. Due to the improved elastic property of asphalt mixtures, the PET material demonstrated good resilience at moderate temperatures of 20 °C and low loading of 2000 N. Moreover, the high content of PET in both types of mixtures weakened the asphalt mixture at high loading levels, and a significant effect was observed at low loading levels, showing a lower tensile strain. Similar results have concluded by Ansari et al. [48] and Eskandarsefat et al. [49] while utilizing the polymers in asphalt mixtures.

Fig. 20 and Fig. 21 show the developed fatigue curves for the tested asphalt mixtures. These curves present the relationship between the fatigue life (N_f) and initial microstrain (ε_t) and the failure cycles. The fatigue equations with their regression coefficient R^2 and coefficients k_1 and k_2 are presented in Table 8. The 100 microstrain for the determination of the fatigue life was chosen as normally fatigue failure occurs at a range of 0–200 microstrain [50]. The addition of the PET into asphalt mixtures has significantly increased the N_f of the mixture compared to the control mixture. The Fine-10 and the Filler-20 have shown promising resistance against fatigue damage with 2.05E+05 and 3.34E+05 cycles. However, increasing the content of the PET by more than 20 % caused a reduction in the fatigue failure cycles. The promising performances might be due to the PET particle's higher energy absorbency and this phenomenon ultimately postpones the propagation of the cracks in a mixture [16,45].

4. Conclusion

The experimental evaluation of recycled PET as a substitute in SMA20 produced promising outcomes. PET inclusion slightly increased OAC, and thermal analysis confirmed its suitability for asphalt mixtures, with melting and degradation temperatures at 255 °C and 470 °C, respectively. PET-modified mixtures significantly improved M_R, with a 10 % PET addition resulting in a 20–22 % increase, reaching values of 3660 and 3988 MPa. Moreover, PET-modified mixtures displayed enhanced resistance to moisture

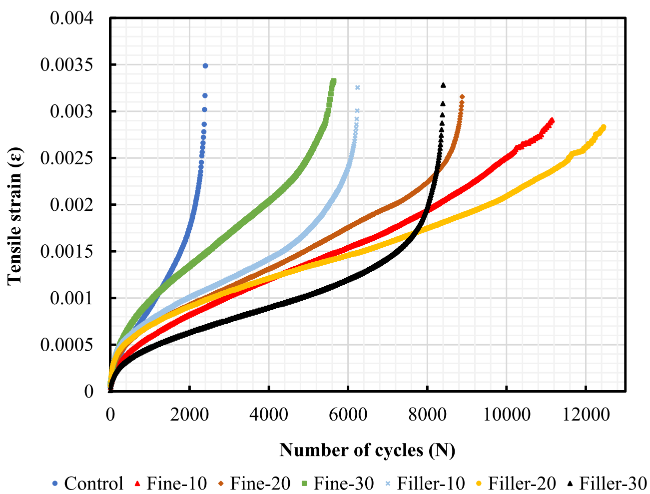

Fig. 19. Tensile strain versus loading cycles of asphalt mixtures at the load of 2500 N.

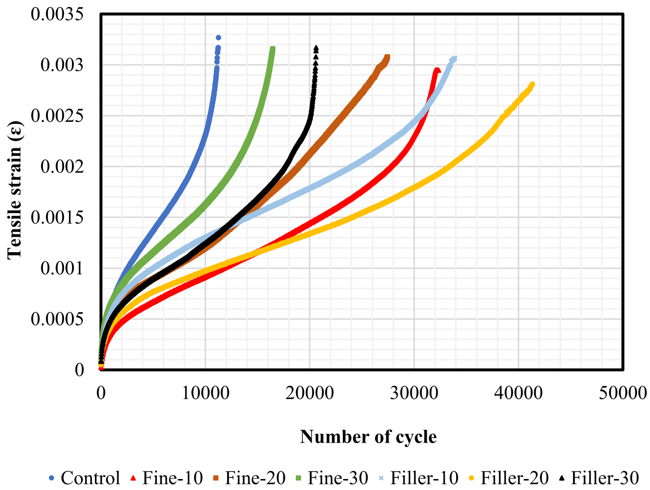

Fig. 17. Tensile strain versus loading cycles of asphalt mixtures at the load of 2000 N.

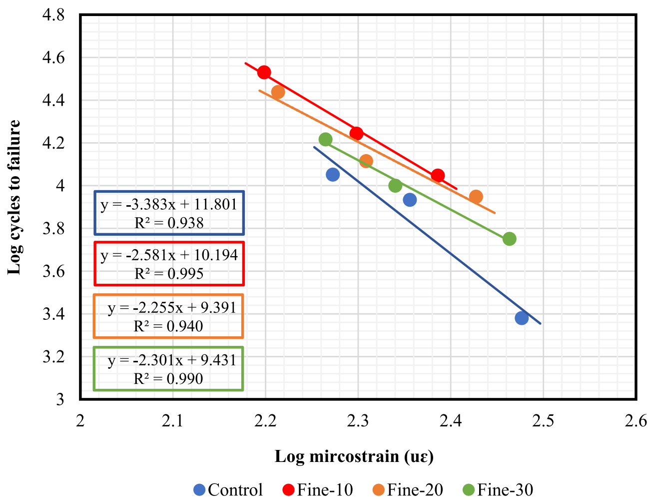

Fig. 20. Microstrain curves to cycles failure for fine PET of asphalt mixtures.

damage, with tensile strength ratios of 83.90 % and 85.14 % compared to 81.10 % for the control mixture. Additionally, PET reduced permanent deformation and enhanced creep stiffness modulus. These findings indicate PET's potential for improving mechanical properties and durability in asphalt mixtures while promoting sustainability.

5. Limitations and future prospects

The study on PET-modified asphalt mixtures has several limitations that may impact its findings. The recycled PET used was sourced solely from Glowmore Express Sdn Bhd in Malaysia, with only two PET gradations (Fine and Filler) and one asphalt binder type (grade 60/70) tested. The study employed the dry method for aggregate replacement using granite from a single source. These constraints limit the results' generalizability. Future research should investigate using PET as coarse aggregate in SMA mixtures, different aggregate gradations, and various asphalt binder types to better understand its effects. Additionally, applying the Superpave mix design and assessing performance at low temperatures and across varying temperatures would provide more comprehensive insights.

CRediT authorship contribution statement

Salihudin Hassim: Supervision, Methodology, Conceptualization. **Anwaar Hazoor Ansari:** Writing – review & editing, Formal analysis. **Zafreen Elahi:** Writing – review & editing, Formal analysis. **Mohamed Meftah Ben Zair:** Writing – original draft, Validation, Methodology, Formal analysis. **Mohamed Meftah Ben Zair:** Writing – original draft, Validation, Methodology, Formal analysis.

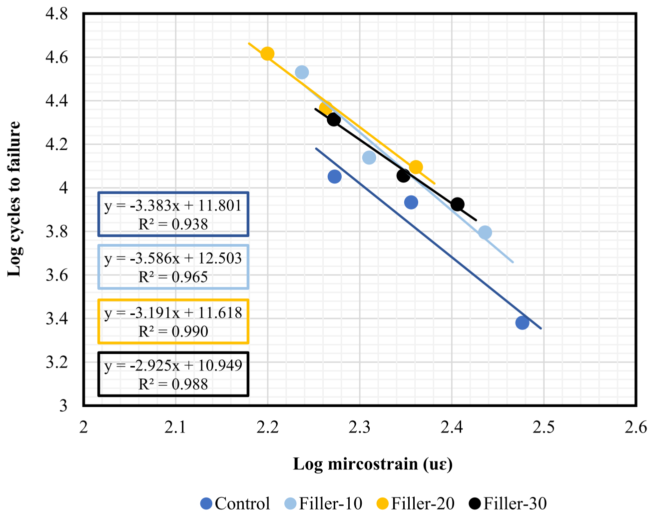

Fig. 21. Microstrain curves to cycles failure for PET filler of asphalt mixtures.

Table 8
Fatigue equations at 100 με for asphalt mixtures.

Mixture type	Fatigue equation $N_f = k_1(\varepsilon)^{k_2}$	k_1	k_2	R^2	Cycles at 100 micro strains
Control	$N_f = 3.11 \times 10^{11} \quad (\varepsilon)^{-3.383}$	$N_f = 3.11 \times 10^{11}$	-3.383	0.938	5.33E+04
Fine-10	$N_f = 2.98 \times 10^{10} (\varepsilon)^{-2.581}$	$N_f = 2.98 \times 10^{10}$	-2.581	0.995	2.05E+05
Fine-20	$N_f = 2.74 \times 10^{9} \quad (\varepsilon)^{-2.255}$	$N_f = 2.74 \times 10^{9}$	-2.255	0.940	8.48E+04
Fine-30	$N_f = 2.96 \times 10^{10} \quad (\varepsilon)^{-2.310}$	$N_f = 2.96 \times 10^{9}$	-2.310	0.990	7.12E+04
Filler-10	$N_f = 1.43 \times 10^{12} \quad (\varepsilon)^{-3.586}$	$N_f = 1.44 \times 10^{12}$	-3.586	0.965	9.66E+04
Filler-20	$N_f = 8.05 \times 10^{11} \quad (\varepsilon)^{-3.209}$	$N_f = 8.05 \times 10^{11}$	-3.191	0.990	3.34E+05
Filler-30	$N_f = 9.55 \times 10^{10} \quad (\varepsilon)^{-2.667}$	$N_f = 9.55 \times 10^{10}$	-2.925	0.988	1.35E+05

Fauzan Mohd Jakarni: Writing – review & editing, Supervision, Methodology, Conceptualization. **Ratnasamy Muniandy:** Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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