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ARTICLE

Viscoelastic Behavior, Fracture Resistance, and Fatigue Durability of Recycled Asphalt Concrete Incorporating Waste Plastic Aggregates

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ABSTRACT: With the increasing environmental pressure caused by waste plastic (WP), incorporating recycled plastics into asphalt concrete has become a promising strategy for sustainable pavement construction. In this study, waste polyethylene terephthalate (PET) was utilized to replace mineral aggregates through a dry process, and the effects of particle size and replacement level on the mechanical performance of asphalt concrete were systematically evaluated. High-temperature deformation resistance was assessed using wheel-tracking tests, followed by dynamic modulus measurements to examine the viscoelastic behavior and structural stiffness. Low-temperature cracking resistance was studied through fracture toughness and fracture energy tests, and fatigue performance was investigated using four-point bending fatigue tests. In addition, SCB (semi-circular bending) crack propagation observations and crack length analysis were conducted to clarify the influence of PET on crack development behavior. The research results indicated that coarse PET particles effectively participate in the load-bearing skeleton, significantly enhancing rutting resistance and high-frequency stiffness, whereas fine PET particles exhibit superior dispersion and void-filling capability, thereby improving low-temperature cracking resistance. An optimal PET replacement level was identified, as excessive substitution disrupts the mineral skeleton and leads to performance deterioration. PET increased crack tortuosity and final crack length, with a modest rise for fine PET but a larger, replacement-dependent increase for coarse PET due to stronger skeleton interference. Overall, moderate PET replacement provides balanced improvements in high-temperature stability, low-temperature cracking resistance, and fatigue durability, demonstrating the potential of waste PET as an effective aggregate substitute for sustainable asphalt pavement applications.

KEYWORDS: Asphalt concrete; PET; aggregate; fracture toughness; fatigue

1 Introduction

Plastics have become one of the most widely used engineering materials worldwide owing to their low cost, excellent durability, and outstanding processability. Projections indicate that global plastic production could exceed 1 billion tons per year by 2040, implying that the dependency of modern society on plastic products will continue to intensify [1–3]. However, the massive production and consumption of plastics, while significantly improving the quality of life and industrial productivity, have also led to serious environmental concerns. Most high-molecular-weight plastics are inherently resistant to degradation and possess long service lives [4,5]; when managed through conventional landfilling or uncontrolled dumping, large quantities of the waste plastic (WP) not only occupy scarce land resources for extended periods but may also impose a persistent environmental burden through microplastic generation and the release of additives. In parallel, the highway sector remains a major consumer of natural aggregates and energy. Against the backdrop of rapid expansion and frequent maintenance of transportation infrastructure, achieving material reduction and high-value recycling of solid wastes without compromising pavement performance has emerged as a critical challenge for developing green and low-carbon transportation systems [6].

The WP mainly includes polyethylene (PE) [7], polypropylene (PP) [8], and polyethylene terephthalate (PET) [9]. Incorporating different types of plastics into asphalt concrete can enhance their service performance, such as improving resistance to permanent deformation, durability, and structural stiffness [10–12]. In current practice, two main techniques are utilized to incorporate plastics into asphalt concrete: the wet process and the dry process. In the wet process, WP are blended with the asphalt binder at elevated temperatures and subjected to high-shear mixing to produce polymer-modified asphalt. Li et al. [13] investigated three types of waste-plastic-modified asphalts and clarified the underlying modification mechanisms using Fourier transform infrared spectroscopy (FTIR) and thermogravimetric analyses. Based on the rheological and thermal results, they optimized the preparation procedure and demonstrated that waste-plastic-modified asphalt exhibits markedly superior high-temperature performance compared with the base binder. Liu et al. [14] chemically modified PET and elucidated the aging mechanism of PET-modified asphalt at the nanoscale level. Yu et al. [15] showed through microstructural investigations that the melting of waste LDPE is essentially a physical process. Once melted, low-density polyethylene (LDPE) disperses within the asphalt matrix, constraining binder flow and thereby significantly improving the mixture's resistance to permanent deformation at high temperatures.

However, the wet process was relatively complex and time-consuming, and the resulting modified binders often suffer from storage stability issues such as phase separation and segregation. At the same time, intensive exploitation of natural aggregates for large-scale infrastructure has led to increasing depletion of these resources. In this context, utilizing WP as aggregate substitutes offers a promising alternative for large-volume recycling. In particular, PET, with its high melting point and favorable mechanical properties, can retain its particulate form at typical mixing temperatures, making it a suitable and effective replacement for mineral aggregates.

Ahmadinia et al. [16] discussed the effect of PET on the engineering characteristics of stone mastic asphalt (SMA) and reported that an optimum PET content of 6% by weight of asphalt yields the highest mixture stability. The PET particles effectively fill the internal voids of the asphalt concrete, thereby significantly improving its volumetric structure and mechanical performance. Esfandabad et al. [17] investigated asphalt concrete in which fine aggregates were partially replaced by PET particles and reported that increasing PET contents reduced indirect tensile strength and low-temperature fracture resistance, but improved moisture resistance and rutting characteristic by stiffening the mixtures. Baradaran et al. [18,19] introduced 1%–3% of the additives extracted from chemically treated PET together with different proportions (25% and 50%) of reclaimed asphalt pavement (RAP) into hot-mixed asphalt mixtures, and evaluated their low-temperature fracture performance using Edge Notch Disc Bend (ENDB) and SCB tests. Additionally, the cracking of asphalt mixtures under different fracture modes was analyzed. The results showed that the combination of 2% PET additive and 25% RAP had the best low-temperature crack resistance and the two test trends were consistent. Their results suggest a clear performance trade-off and indicate that the overall effect of PET was highly dependent on both dosage and temperature conditions.

However, the performance evolution of asphalt concrete incorporating WP through aggregate replacement has not been systematically clarified, and the underlying mechanisms associated with different PET particle sizes—particularly their distinct influences on engineering characteristics—remain insufficiently understood. Hence, this study aimed to systematically evaluate asphalt concrete in which waste PET was used as an aggregate substitute via the dry process, with two controlled particle-size fractions and multiple replacement levels. The performance was assessed comprehensively using rutting, dynamic modulus master curves, SCB fracture indices (fracture toughness/energy), four-point bending fatigue, and crack propagation/length measurements, to identify a rational replacement window and clarify the governing mechanisms. These comprehensive investigations aim to elucidate the structural mechanisms governing the effects of PET substitution on the high-temperature performance, viscoelastic behavior, low-temperature cracking resistance, and fatigue durability of asphalt concrete. The findings are expected to provide technical guidance for the large-scale valorization of waste PET and contribute to the development of sustainable and environmentally friendly pavement materials.

2 Materials and Methods

2.1 Materials

2.1.1 Asphalt

The asphalt (70 #) was utilized as the base material for this study, and its fundamental properties were characterized in accordance with the standard specification [18]. The results were presented in Table 1.

Table 1: Technical properties of asphalt.

Test Indicator		Standard	Results	Unit
25°C Needle penetration		60~80	71.6	mm
Softening point		≥46	53	°C
Ductility	10°C	≥20	61	cm
	5°C	≥100	≥110	cm
After RTFOT	Mass loss	−1~1	−0.19	%
	Needle penetration ratio	≥61	65.5	%
	Ductility	≥6	8	cm

2.1.2 Aggregates

The coarse and fine aggregates used in this study were basalts, along with limestone mineral powder, and their test indexes were shown in Table 2.

Table 2: Technical properties of aggregates.

Properties	Index	Results	Standard [19]
Coarse aggregate	Crush value (%)	15.7	≤26
	Wear value (%)	14.8	≤28
	Water absorption rate (%)	1.11	≤2.0
	Ruggedness (%)	7.8	≤12
Fine aggregate	Ruggedness (%)	8.9	≤12
	Angularity (s)	38.2	≥30
	Methylene blue number (g/kg)	4.6	≤25

(Continued)

Table 2 (continued)

Properties	Index		Results	Standard [19]
Mineral powder	Hydrophilic coefficient		0.4	<1
	Moisture content (%)		0.5	≤1
	Size range (%)	<0.6 mm	100	100
		<0.15 mm	95.5	90~100
		<0.075 mm	92.3	75~100

2.1.3 Polyethylene Terephthalate (PET)

This study substituted natural aggregates in asphalt concrete with waste PET. Compared to other plastics, PET offers advantages such as a relatively high melting point, high tensile strength, and good stiffness, making it an excellent candidate as an additive in asphalt concrete mixtures [3–6]. Considering the mixing temperature of 160°C–170°C in this study, PET was selected because it can maintain particle integrity during mixing/compaction and thus acts as a true aggregate substitute in the dry process, whereas some plastics (e.g., PE/PP) may soften significantly at such temperatures and behave more like binder modifiers. In addition, PET is one of the most widely used polymer materials worldwide, mainly originating from beverage bottles, packaging, and textile products, which results in a stable and abundant waste stream. Utilizing waste PET in asphalt concrete not only helps to alleviate environmental pressures associated with plastic disposal but also provides a potentially cost-effective alternative to conventional aggregates. Therefore, incorporating PET into asphalt mixtures presents considerable potential for future engineering applications. The properties of PET used in this study are summarized in Table 3. The PET was collected from a single supplier and then processed using the same crushing and sieving procedure. After mechanical crushing, the material was separated by sieving to obtain different particle-size. Therefore, the two PET samples differ only in particle size, while their material origin, chemical composition, and processing history are identical. The PET was sieved to obtain two particle-size fractions, namely 1.18–2.36 mm and 2.36–4.75 mm. The retained PET fractions were then used to replace the corresponding mineral aggregate size fractions in the asphalt mixture on an equal-mass basis.

Table 3: Technical properties of PET.

Material	Size of Particles	Shape	Color	Density	Melting Point
PET	1.18–2.36 mm	Cylinder	Light yellow	1.31 g/cm^3	250°C
	2.36–4.75 mm				

2.1.4 Gradation

This study selected the typical gradation of AC-13, using waste PET to replace the aggregates in the 1.18–2.36 mm (1 #) and 2.36–4.75 mm (2 #) ranges. Moreover, based on the mass of this particle size, the effects of three substitution rates (3%, 5%, 10%) were studied. PET was not added as an extra gradation component; instead, it was used to replace two specific sieve fractions of the mineral aggregate on an equal-mass basis. The gradation curve is shown in Fig. 1. The optimal asphalt-aggregate ratio was determined to be 4.7%.

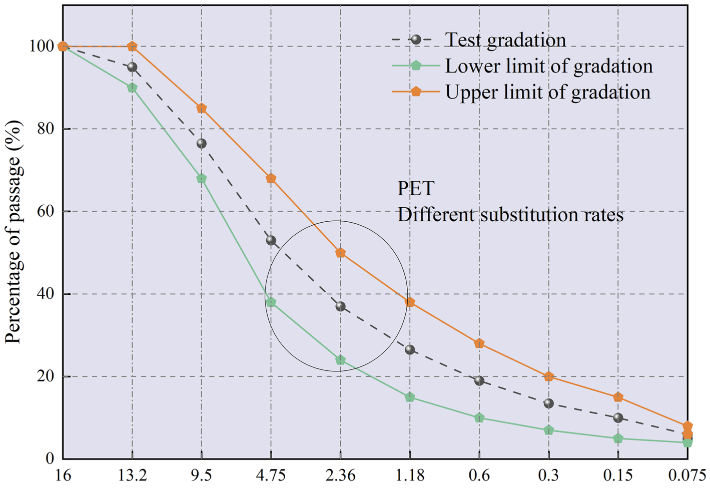


Figure 1: Aggregate gradation curves.

The PET mixtures were prepared using a staged dry-mixing procedure. First, the pre-heated mineral aggregates were mixed to obtain a uniform aggregate blend. Subsequently, PET particles were added into the aggregate blend and mixed separately to ensure homogeneous dispersion of PET and stable incorporation within the aggregate skeleton, prior to the addition of asphalt binder and other constituents.

2.2 Methods

2.2.1 High-Temperature Performance Test

The rutting test evaluated the permanent deformation resistance of asphalt concrete under high-temperature conditions by simulating repeated vehicular loading. The rutting test was conducted in accordance with relevant standards [20] at 60°C using slab specimens (300 mm × 300 mm × 50 mm) under a standard wheel contact pressure of 0.7 MPa, with rut depth continuously recorded during repeated wheel passes. A loading wheel then repeatedly passes over the specimen surface under specified load and speed. As the number of passes increases, a rut gradually forms, and the test apparatus continuously records the rut depth. The test proceeds until a predetermined number of wheel passes or rut depth is reached. The rate of rut development and the final rut depth are used to assess the high-temperature stability of the asphalt concrete, as shown in Fig. 2.

Figure 2: The rutting test process.

2.2.2 Dynamic Modulus Test

The dynamic modulus tests in this study were conducted using the AMPT apparatus at temperatures of −5°C, 10°C, 25°C, and 40°C. Cylindrical samples with a Φ (150 mm) and a *h* (170 mm) were formed using the SGC method. After curing for one day, the samples were cored to obtain cylindrical specimens with a diameter of 100 mm and a height of 150 mm. The samples with different substitutions of the PET were maintained at the set temperatures for over 4 h. Dynamic modulus and phase angle measurements were taken at different frequencies [21,22], enabling the evaluation of their viscoelastic changes at various substitution levels. The test process is shown in Fig. 3.

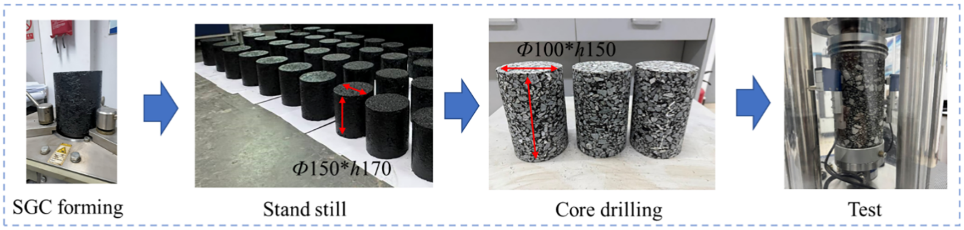


Figure 3: The preparation and testing process of sample with dynamic modulus.

2.2.3 Semi-Circular Bending (SCB) Test

Consistent with the sample preparation procedure for the dynamic modulus tests, the SCB specimens were first fabricated as cylindrical samples using the SGC compactor and then processed by coring and sawing to obtain semi-circular specimens (Φ150 mm and t 50 mm). Semi-circular bending (SCB) tests were performed to characterize the crack resistance and crack propagation behavior of the asphalt mixtures. Cylindrical specimens with a diameter of 150 mm were fabricated and then cut into semi-circular specimens with a thickness of 50 mm. A straight pre-notch was introduced at the flat edge along the specimen midline, with a notch depth of approximately 16.7 mm (≈1/3R) and a notch width of 1 mm. Prior to testing, all specimens were conditioned at the target test temperature for 4 h to ensure thermal equilibrium. During the SCB test, the specimen was placed on two supporting rollers positioned symmetrically 30 mm from the specimen centerline (i.e., *a* support span of 60 mm) and loaded at the midspan to achieve Mode-I fracture. The test was conducted under displacement-controlled mm/min of 5 mm/min until failure, while the crack development was recorded. The test process was shown in Fig. 4. The fracture toughness of asphalt concrete incorporating different PET replacement levels was calculated using the method shown in Eqs. (1) and (2) [23,24].

$$K_{IC} = Y_{I(0.8)} \frac{P}{2rt} \sqrt{\pi a} \tag{1}$$

$$Y_{IC} = 4.78 + 1.22\,m + 0.06^{7.05\,m} \tag{2}$$

where: K_{IC} represents fracture toughness; P is the peak load; r, t and a respectively represent the radius, thickness and preset crack of the specimen. m represents the ratio of a to r.

In addition, to more directly characterize crack propagation behavior, the post-fracture samples of different PETs were examined to measure both the absolute crack length and its ratio to the specimen radius. These indicators were used to quantify the effect of PET size and replacement level on crack propagation.

2.2.4 Fatigue Test

Fatigue cracking is one of the most prevalent and critical distress types affecting asphalt pavements. Under repeated traffic loading, the pavement structure undergoes cumulative damage, leading to stiffness degradation and eventual fatigue failure [18]. Fatigue life is therefore a key indicator governing the long-term performance and serviceability of asphalt pavements. In this study, a fatigue test was conducted to evaluate the fatigue cracking resistance of asphalt concrete incorporating PET of different particle sizes and replacement levels. Fatigue tests were performed using a four-point bending configuration under strain-controlled sinusoidal loading at a frequency of 10 Hz and 20°C [25]. All of these conditions were tested in 6 parallel groups to ensure the accuracy of the data. The flexural stiffness was continuously monitored, and the fatigue life N_f was defined as the number of cycles when the stiffness decreased to 50% of its initial value. Based on preliminary trials, strain amplitudes of 200, 400, and 600 μ_ε were selected to characterize the fatigue behavior across different strain levels, as shown in Fig. 5.

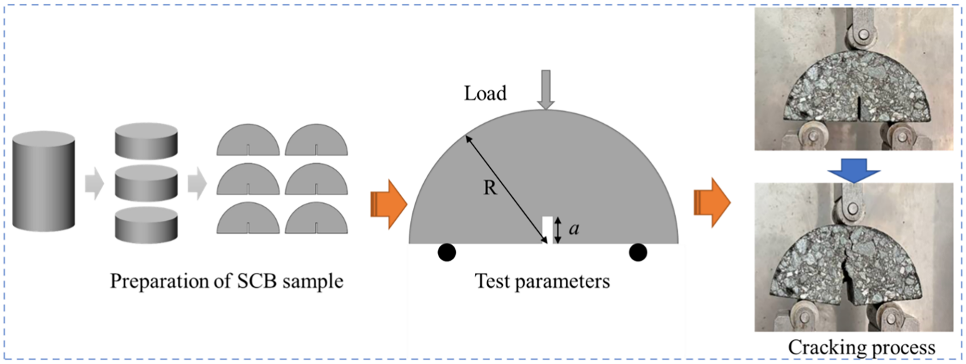


Figure 4: The preparation and testing process of sample.

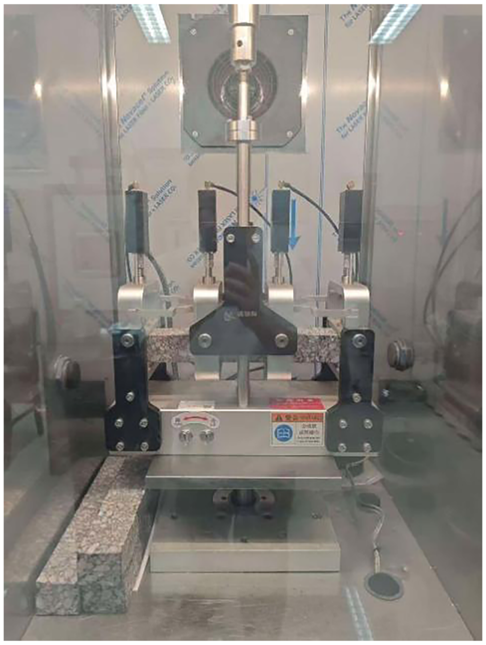


Figure 5: Four-point fatigue test.

3 Results and Discussion

3.1 Rutting Resistance Test

The relationship between rut depth and the number of wheel passes for asphalt concrete with different PET replacement levels is shown in Fig. 6. The numbering method is as follows: Samples numbered 1#—3% are represented as being replaced with 3% of 1 # PET.

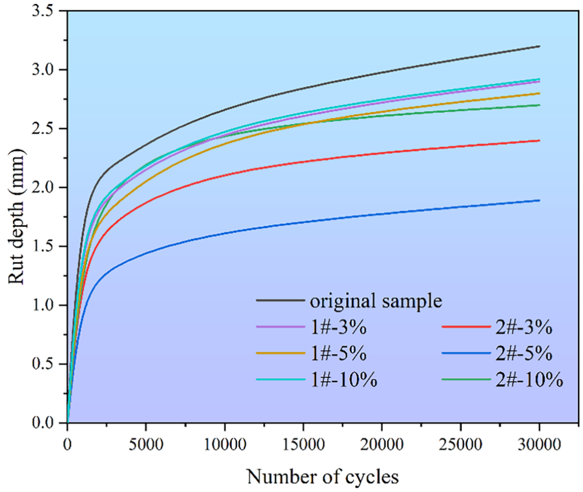


Figure 6: The curves of the number of rounds and depth under different substitution rates.

As shown in Fig. 6, at 2520-wheel passes [18], the control asphalt mixture exhibited the largest rut deformation, reaching 2.31 mm. In contrast, the mixtures incorporating PET as an aggregate substitute showed reduced deformation. These results indicate that PET enhanced the mixture's resistance to permanent deformation, and this improvement became more pronounced with increasing PET particle size. Across the investigated replacement levels, the rut deformation of the 1 # PET mixtures ranged from 1.71 to 1.85 mm. For the 2 # PET mixtures, the deformation varied more markedly with replacement level, with the minimum value reaching 1.62 mm. Moreover, all PET-substituted mixtures exhibited smaller rut depths than the original mixture, indicating that equal-mass replacement of a portion of the aggregate with PET effectively enhances the high-temperature deformation resistance of asphalt concrete. For the 2 # PET, the final rut depths at replacement levels of 3%, 5% and 10% are reduced by approximately 25%, 40.9% and 15.6%, respectively, relative to the original mixture, whereas the reductions for the 1 # PET are all within 10%. This suggests that the coarser 2 # PET particles are more capable of participating in the load-bearing skeleton, thereby increasing the overall stiffness and shear resistance of the mixture, while the finer 1 # PET particles are mainly distributed in the asphalt mastic, where they primarily act to enhance elasticity and improve adhesion.

For both particle sizes, the high-temperature performance of the mixtures first increased and then deteriorated with increasing PET content. When the replacement level is further increased to 10%, the equal-mass substitution leads to a marked increase in the volumetric fraction of PET, which weakens the rigid mineral skeleton and reduces the interfacial bonding and contact stiffness between aggregates. Consequently, an "over-dosage effect" occurs and the rutting resistance no longer increases with PET content. Overall, equal-mass replacement of part of the aggregate with waste PET can markedly enhance the high-temperature stability of asphalt concrete, with the best rutting performance obtained for the 2 # PET at a replacement level of about 5%. However, excessive replacement disrupts the aggregate skeleton and causes the rutting resistance to decrease or level off. Therefore, in practical applications, the PET particle size should preferably fall within the coarse-aggregate gradation range, and the replacement level should be controlled at a moderate value to balance environmental benefits and pavement performance.

3.2 Dynamic Modulus

The dynamic viscoelastic master curve incorporates the complete linear viscoelastic response of asphalt concrete over the range of in-service pavement temperatures and loading frequencies, and thus provides fundamental input parameters for material characterization and pavement mechanical analysis. In this study, based on the time-temperature superposition principle [21,22], the dynamic modulus data obtained at different temperatures were horizontally shifted and superposed along the frequency axis to construct the dynamic viscoelastic master curve at a reference temperature of 20°C, as illustrated in Fig. 7.

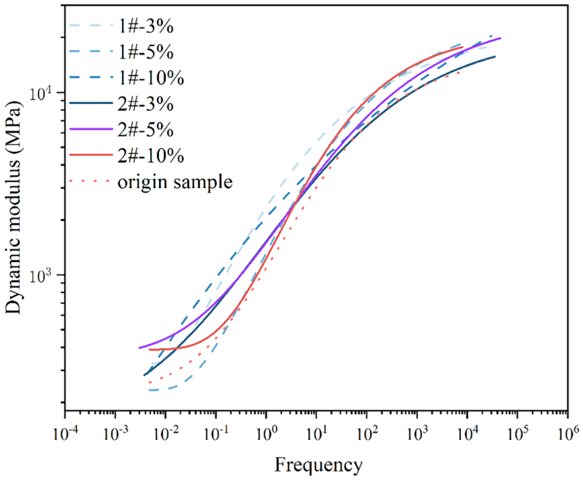


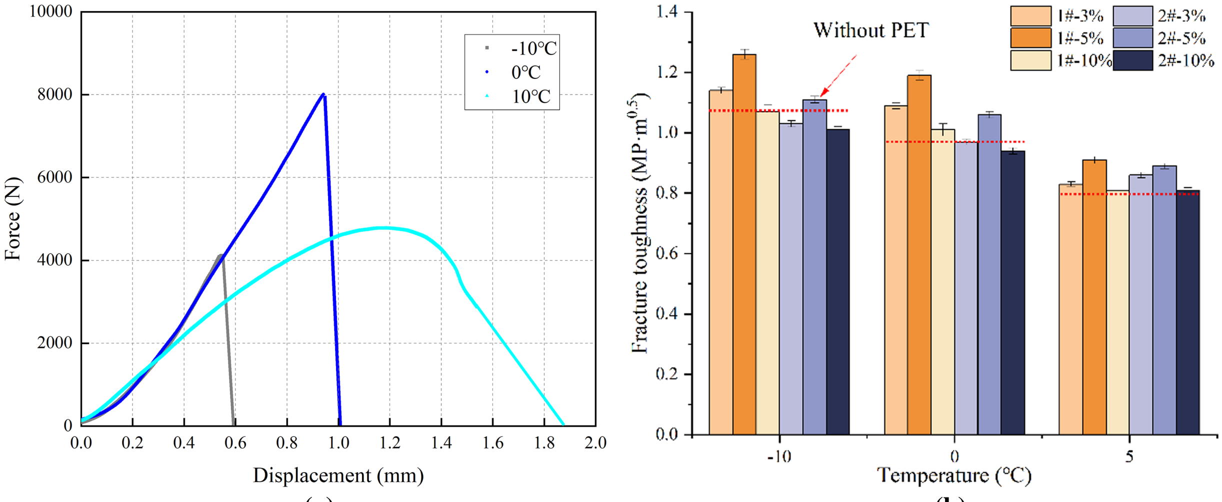
Figure 7: Dynamic modulus principal curves.

As illustrated in Fig. 7, the dynamic modulus of the mixture increases with frequency at all PET replacement rates, presenting an S-shaped characteristic. There is a gentle plateau area in the low-frequency region, a rapid increase in the medium-frequency region, and a gradual stabilization in the high-frequency region. As the loading frequency increases, the dynamic modulus significantly increases. According to the time-temperature equivalence principle, the low-frequency region can reflect the macroscopic mechanical properties of asphalt mixtures under high-temperature conditions, while the high-frequency region reflects the stiffness and elastic performance under low-temperature conditions. Overall, the dynamic modulus of the asphalt mixture containing PET is higher than that of the original sample. That is to say, the improvement in the anti-deformation ability observed in the high-temperature test is consistent with this. The dynamic modulus of the asphalt concrete with 2 # PET replacement is generally higher over the entire frequency range, suggesting that the larger PET particles contribute to a stiffer mixture. This enhancement is primarily attributed to a more pronounced skeleton effect: the coarser PET promotes more stable particle contacts and interlocking within the aggregate structure, thereby improving load transfer and mixture stability. In contrast, the dynamic modulus of the asphalt concrete with 1 # PET replacement was lower, indicating that smaller particles primarily disperse within the asphalt concrete and fill voids. Smaller particles may not provide sufficient framework support, resulting in lower stiffness, particularly at low frequencies where the mixture exhibits weaker elasticity and stronger viscous response.

3.3 Fracture Toughness

The fracture toughness values of asphalt concrete containing PET substitute aggregates under different temperature conditions (−10°C, 0°C, 5°C) and substitution levels (3%, 5%, 10%) were shown as Fig. 8.

As shown in Fig. 8a, the original samples were subjected to displacement loads at different temperatures, and the fracture toughness was calculated based on the peak loads. As shown in Fig. 8b, the fracture toughness was higher for the mixtures with 1 # PET compared to the 2 # PET (10°C), irrespective of the substitution levels. Compared with the original mixture (Without PET), the incorporation of PET leads to a size- and dosage-dependent change in fracture toughness, and an appropriate PET content can achieve comparable or slightly higher toughness than the control. This suggests that the smaller particle size of 1 # might improve the bonding between the aggregate and the binder, potentially increasing the concrete's resistance to cracking at low temperatures. As the substitution percentage increases from 3% to 10%, the fracture toughness decreases for both 1 # and 2 # PET, with the 1 # PET showing a more significant reduction. This could be due to the increasing proportion of the PW altering the physical properties of the mixture, such as its stiffness and cohesion.



(a) **(b)**

Figure 8: Displacement load curves and fracture toughness at different substitution ratios.

Under the other two temperature conditions, the trends remain similar. In terms of fracture toughness, 1 # PET was usually superior to 2 # PET. However, at 0°C, the difference between 1 # and 2 # PET becomes less pronounced, especially at higher substitution levels. This suggests that as the temperature increases, the differences in material behavior (due to particle size) start to diminish. At 5°C, the fracture toughness stabilizes, and the effect of PET substitution at higher percentages (especially 10%) becomes more noticeable, indicating that PET may influence the overall behavior of the asphalt mix under milder temperatures. Relative to the control mixture (without PET), high PET substitution tends to reduce fracture toughness more clearly at 5°C, indicating that excessive PET weakens crack resistance even under milder conditions. The influence of PET percentage on fracture toughness was clearly temperature- and size-dependent. At −10°C, 3% PET provided the most pronounced improvement, especially for 1 # PET, whereas increasing the content to 5% and 10% led to a progressive reduction, with 2 # PET showing a more obvious downward trend. At 0°C, the benefit of PET was mainly observed at 3% (again more evident for 1 #), while 5% was generally close to the control and 10%, particularly for 2 # PET, tended to drop below the control level. At 5°C, the overall differences among mixtures became smaller; 3%–5% PET produced only a slight increase or remained comparable to the control, while 10% showed little to no improvement. Overall, low PET contents (especially 3%) were more favorable for maintaining or enhancing low-temperature fracture toughness, whereas higher contents (toward 10%) tended to diminish the benefit, particularly for the coarser PET.

The increase in PET substitution (from 3% to 10%) generally leads to a decrease in fracture toughness, which is most evident in the 1 # group at −10°C. This might be due to the fact that higher amounts of plastic result in a less cohesive mixture, affecting its ability to resist crack propagation under low-temperature conditions. The 2 # PET, being larger in particle size, might experience a reduced impact from PET substitution, as the larger aggregates could provide more structural integrity, especially at higher temperatures. This is due to the fact that the PET particles, being polymeric, could influence the rheological properties of the asphalt. As the substitution level increases, the polymeric nature of PET may introduce greater brittleness, especially at low temperatures, reducing the mixture's fracture toughness. The differences observed between 1 # and 2 # PET could also be related to the interaction between the aggregate and binder: smaller aggregates might allow for better binder penetration and adhesion, while larger aggregates might lead to less effective binder-aggregate interaction, thus affecting crack resistance.

Moreover, smaller PET provides better fracture toughness than larger PET (2 #), particularly at lower substitution levels and lower temperatures. This can be attributed to the increased surface area of the smaller aggregates, which can form stronger bonds with the asphalt binder. In contrast, larger aggregates might lead to weaker interfacial bonding, as the surface area available for interaction with the binder is smaller. Overall, using the original sample as the baseline further confirms that PET can improve or maintain fracture toughness at low replacement levels, whereas excessive replacement leads to a noticeable deterioration in cracking resistance.

3.4 Fracture Energy (G_f)

The fracture energy (G_f) is an effective parameter for characterizing the cracking resistance of asphalt concrete and is one of the key factors in evaluating its performance. It refers to the amount of fracture work absorbed within the unit area of the toughness region. This value was obtained by calculating the area under the curve, as shown in Fig. 9 and Eq. (3) [26,27].

$$G_f = \frac{W_f}{(R - a) \times t} \tag{3}$$

where: W_f: The area under the load-displacement curve; a: Preset crack length; R: Radius of samples; t: Thickness of samples.

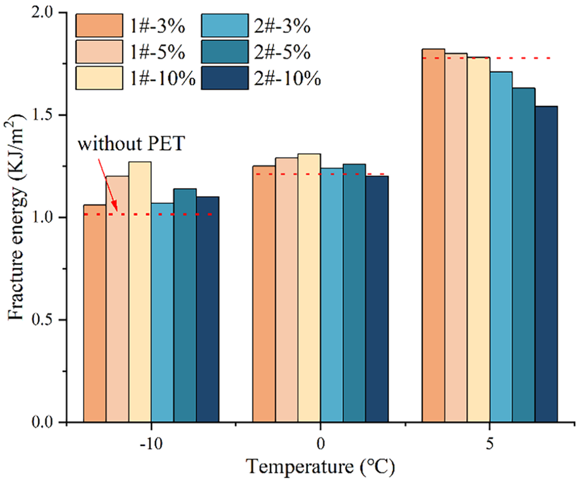


Figure 9: Fracture energy at different substitution ratios.

Based on the Fig. 9, it can be observed that at −10°C and 0°C, the fracture energy of the specimens with PET is higher than that of the conventional asphalt concrete. However, at 5°C, the fracture energy of the small particle size PET (1 #) is slightly higher than that of the control group, while the performance of the 2 # PET decreases. The addition of PET improved the cracking resistance, as it possesses good toughness, which helps alleviate cracks generated by the thermal shrinkage of the asphalt concrete at low temperatures. Moreover, regardless of temperature and PET content, the performance of 1 # PET in terms of low-temperature fracture energy is significantly better than that of 2 # PET. The G_f of the mixture with 1 # PET was generally higher, leading to a significant improvement in low-temperature cracking resistance. This was attributed to its better dispersion and bonding properties, which enhance the low-temperature cracking resistance and ductility of the asphalt concrete. The high specific surface area of 1 # PET helped fill voids, improving the density of the mixture and providing better cracking resistance at low temperatures.

The PET content also affects the cracking performance of the asphalt concrete. For example, at −10°C, the fracture energy of 1 # increased by 13.2% and 5.8% with 5% and 10% content, respectively, while 2 # showed an initial increase of 6.54% followed by a decrease of 3.51%. However, the overall cracking resistance was still higher than that of the mixture without PET. At 0°C, the increase in low-temperature cracking resistance due to PET addition was less pronounced. The increase for 1 # slowed down with higher content, and for 2 #, the increase slowed and when the content reached 10%, the performance became similar to the control group. At 5°C, the low-temperature performance of the asphalt concrete decreased as the PET content increased, with 2 # showing a greater decline than 1 #.

3.5 Fatigue Test

The fatigue characteristics of asphalt concretes with different PET substitution ratios are shown in Fig. 10.

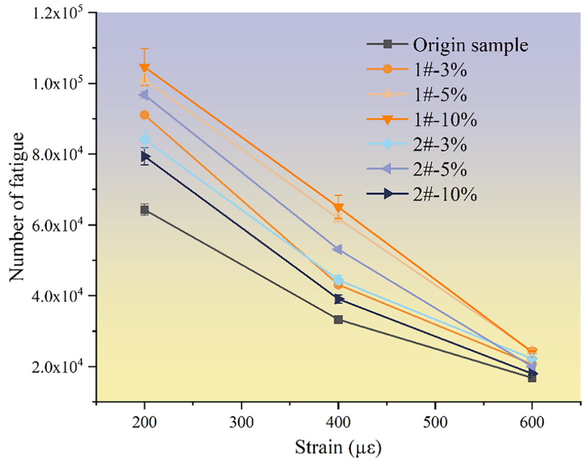


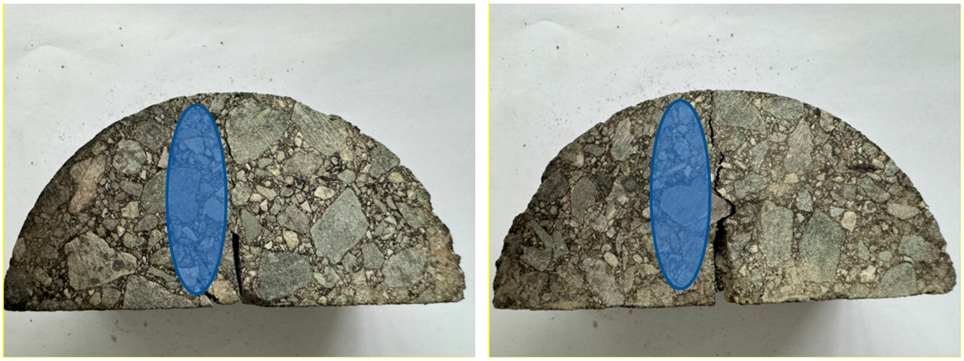
Figure 10: Fatigue characteristics of sample at different substitution ratios.

As shown in Fig. 10, the fatigue life of all concrete decreased significantly as the strain increased from 200 to 600 με, reflecting the typical strain-controlled fatigue behavior of asphalt concrete in which larger tensile deformation accelerates cumulative damage and shortens fatigue life. Compared with the original mixture, PET-modified mixtures exhibit consistently higher fatigue cycles at all strain levels, indicating that PET effectively delays the initiation and propagation of fatigue cracks. The 1 # PET (smaller particle size) shows the most pronounced improvement, particularly at the 3% and 5% replacement levels, where the fatigue life at 200 με was nearly twice that of the control mixture. This was attributed to the finer PET particles having better dispersion, larger specific surface area, and stronger interfacial adhesion with the asphalt mastic, which enhances the viscoelastic response of the binder and promotes more efficient stress dissipation during loading, thereby reducing stress concentration at crack tips and significantly extending fatigue life.

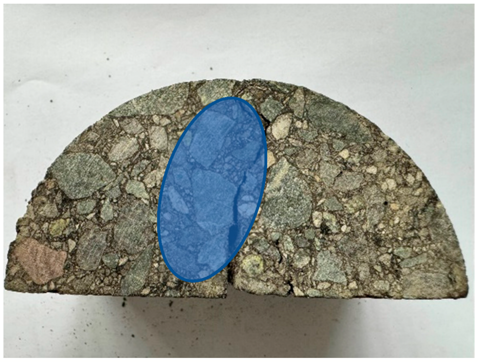
In contrast, the 2 # PET (larger particle size) contributes more to the load-bearing skeleton but exhibits weaker interfacial bonding with the asphalt matrix, resulting in a less noticeable improvement in fatigue performance. This is particularly evident at the higher replacement level of 10%, where a decline in fatigue life is observed. This degradation occurs because PET, as a rigid polymer, can disrupt the viscoelastic balance of the mixture when added in excessive amounts, making the internal structure more prone to microcrack coalescence and accelerating fatigue failure. Moreover, excessive PET weakens the mineral skeleton and disrupts the stress-transfer pathways, leading to localized stress concentrations and ultimately reducing fatigue resistance.

3.6 Crack Propagation and Proportion

This study clarified the effect of different substitution ratios on crack propagation and crack length, as shown in Figs. 11 and 12.



(a) without PET **(b)** 1 # PET



(c) 2 # PET

Figure 11: Crack propagation under different substitutions.

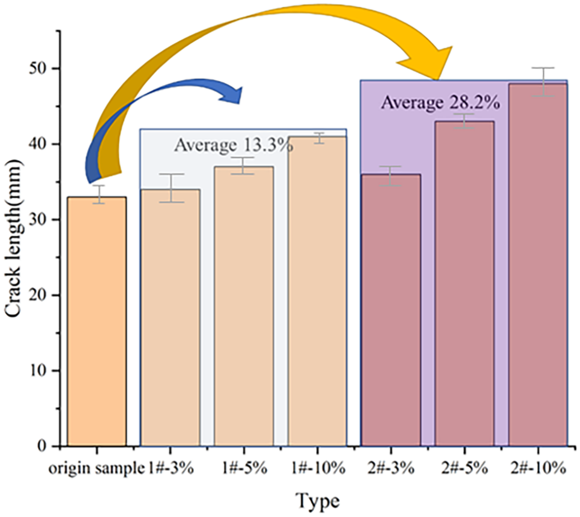


Figure 12: Crack length under different substitutions.

As illustrated in the Fig. 11, the cracks in all samples initiate from the pre-cut notch and propagate nearly vertically along the loading direction, indicating a typical Mode-I tensile fracture. The sample without PET exhibits a straight and rapidly penetrating crack path, reflecting severe stress concentration at the notch tip and relatively low fracture resistance. In contrast, the mixture containing 1 # PET shows slightly deflected and locally branched crack trajectories, suggesting that the finer PET particles introduce energy-dissipation sites and impede crack propagation [28,29]. The specimen with 2 # PET still presents a predominantly straight crack path, but the fracture surface appears rougher, indicating that the larger PET particles interrupt the crack front through skeleton interference. Overall, the incorporation of PET modifies the crack propagation behavior: fine PET promotes crack deflection through enhanced mastic toughness, while coarse PET increases surface roughness via aggregate-like blocking effects, although the principal crack direction remains vertically upward along the loading axis.

The cracking path of 2 # PET is more tortuous than that of 1 # PET, but the influence of the substitution amount is not significant. To further clarify the influence of PET on crack propagation behavior, the crack lengths of all fractured specimens were measured, and the results are presented in Fig. 12. Here, 1 #—3% denoted the asphalt mixture specimen incorporating 1 # PET at a replacement level of 3%.

As shown in the Fig. 12, the substitution of PET increased the crack length, indicating that the crack propagation process became more tortuous. However, the crack length under 1 # PET was not significantly affected by the substitution content. The crack length of 2 # PET increased significantly with the increase in the substitution content. This suggests that the particle size of PET and the substitution content jointly control the crack propagation behavior, and excessive 2 # PET has the most significant effect on the extension of the crack path. The incorporation of PET increased the final crack length, exhibiting only a moderate increase of approximately 13.3% on average compared with the original sample, with limited variation across the three replacement levels. This indicates that 1 # PET particles mainly enhanced the toughness of the asphalt mastic, causing the crack to deflect or locally branch and thereby slowing the progression of the main crack front [30,31]. As a result, the crack length increases only slightly under the same fracture energy input.

In contrast, the concrete with 2 # PET showed a pronounced increase in crack length, with an average growth of 28.2% and a clear upward trend with higher replacement levels. This behavior is attributed to the skeleton-interference effect of large PET particles. During crack propagation, these coarse particles act as rigid obstacles, forcing the crack to deviate around them and creating a more tortuous fracture path. Additionally, the weaker interfacial bonding around large PET particles provides preferential failure planes, facilitating more extensive crack penetration and contributing to longer final crack lengths.

4 Conclusions

In this study, waste polyethylene terephthalate (PET) was incorporated into asphalt concrete through aggregate substitution, and its effects on the high-temperature, low-temperature, and fatigue performance were comprehensively evaluated based on rutting tests, dynamic modulus measurements, fracture characterization, and four-point bending fatigue tests.

(1) Coarse PET particles (2 #) effectively participated in the load-bearing skeleton and significantly improved rutting resistance, with the optimum performance observed at a replacement level of approximately 5%. Excessive substitution increased the PET volume fraction and weakened the mineral skeleton, leading to reduced structural stability.
(2) Dynamic modulus master curves revealed that mixtures with 2 # PET exhibited higher stiffness across the frequency spectrum due to stronger particle interlocking and improved framework integrity. However, increasing PET content caused an overall reduction in modulus, indicating that the plastic phase weakened the mixture's elastic response, especially at low frequencies.
(3) 1 # PET exhibited superior low-temperature performance owing to better dispersion, higher surface area, and enhanced binder-particle adhesion. The fracture toughness and fracture energy of 1 # PET concrete were consistently higher than those of 2 #, particularly at −10°C. A moderate PET content provided the most pronounced improvement.
(4) PET incorporation improved stress dissipation capacity and delayed fatigue damage, particularly for 2 # PET at low replacement levels. However, excessive PET increased mixture viscosity and reduced structural cohesion, resulting in shorter fatigue life under high strain levels. The fatigue performance trends indicate that PET offers reinforcement benefits only within an optimal dosage window.
(5) PET addition increases crack tortuosity and final crack length, but the magnitude depends on particle size: fine PET induces slight crack deflection/branching with a modest crack-length increase, whereas coarse PET causes pronounced skeleton interference and a larger increase that rises with replacement level.

Overall, the results demonstrate that PET can serve as an effective aggregate substitute, achieving balanced improvements in rutting resistance, stiffness regulation, low-temperature cracking resistance, and fatigue durability when applied at suitable particle sizes and replacement levels. Coarse PET enhances structural skeleton integrity, while fine PET benefits low-temperature ductility. A replacement level of approximately 5% is recommended for practical engineering applications to achieve optimal performance without compromising mixture stability.

Future research should focus on long-term field validation, interaction mechanisms with different binder grades, and numerical modeling of PET mixture structure to further guide material design and large-scale implementation. The effects of using PET as an aggregate substitute on the moisture susceptibility of the asphalt mixture will be systematically investigated. Furthermore, the scope of research on substitution rates and different particle sizes will be further expanded, and the utilization rate of waste PET will be increased.

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