

Mechanical and hydraulic performance of porous asphalt concrete containing recycled PET plastic granule for permeable pavements

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Abstract

This research examines the mechanical and hydraulic properties of porous asphalt concrete (PAC) modified with recycled polyethylene terephthalate granules (G-PET) to enhance the performance of permeable pavement materials. Marshall specimens of the mixture containing various percentages of G-PET of 0%, 5%, 10%, 15%, 20%, and 40% (by weight of asphalt binder) were subjected to Marshall stability, indirect tensile strength, ultrasonic pulse velocity, Cantabro loss, draindown, moisture damage, and permeability tests. The experimental results show that adding G-PET improves pore uniformity, thereby increasing permeability. However, excessive G-PET addition led to higher porosity and reduced stiffness due to particle agglomeration and weak interfacial bonding of the mixture. Quantitative results showed that the 10% G-PET mixture provided the most favorable balance, meeting volumetric, mechanical, and permeability criteria within functional specifications for permeable pavements. This finding fills a gap in sustainable pavement design by developing an experimentally validated method to incorporate recycled plastics into porous asphalt mixes, thereby supporting circular-economy goals for infrastructure materials.

Keywords: Porous asphalt concrete, Granule polyethylene terephthalate, Permeable pavement, Stiffness, Permeability

1. Introduction

The increasing amount of plastic waste is considered one of the most significant environmental issues of the 21st century. It is a global challenge to manage waste sustainably and conserve resources. Polyethylene terephthalate (PET), widely used in packaging and consumer products, accounts for a significant share of non-biodegradable waste. The accumulation of PET in landfills and natural environments has prompted researchers and policymakers to seek new avenues to repurpose it in sustainable engineering projects. Recycling of waste plastic is a practical approach to reduce contamination and enhance materials used in civil infrastructure, particularly pavement engineering [1, 2]. Utilizing recycled plastic in asphalt mixes helps achieve circular-economy targets and provides longer-lasting, more sustainable infrastructure that aligns with international efforts to create greener infrastructure.

Mechanical recycling is the most important and practical pathway for plastic waste treatment, which includes initial physical processes (sorting, shredding, washing, and drying), followed by separation based on chemical composition, and then transformation into usable granules or pellets. These polymeric granules, including PE, PP, and PET, are attractive for asphalt modification because they behave like thermoplastic materials, are cost-efficient, and are compatible with conventional bituminous materials [3]. In a dry process, they are finely granulated, then evenly mixed with preheated aggregates and melted to improve the polymer coating of aggregate particles, interfacial bonding properties, and carrying capacity. The use of this incorporation technique for granulated plastic provides a sustainable and robust alternative to virgin polymer modification, resulting in pavements that are more durable, resilient, and stable under environmental and mechanical loads [4].

Porous asphalt concrete (PAC) or permeable asphalt pavement are responsive pavement technologies receiving growing attention due to their environmental benefits. With interconnected voids, its infiltration performance can be outstanding, reducing surface runoff and playing a hydraulic safety role for roads, as less water on the road surface lowers the risk of hydroplaning [5, 6]. Nevertheless, PAC has some limitations in mechanical properties, including easy raveling, poor binder drainage, and lower tensile strength. These deficiencies are likely to affect the long-term performance and mechanical properties of permeable pavement subjected to traffic loading and climatic exposure. It is indispensable to achieve sustainability to overcome these deficiencies through modification methods, thereby prolonging service life and enhancing the mechanical durability of PAC without compromising pore permeability [7, 8].

Previous studies show that polymer modification is possible, improving the performance of porous asphalt. Al-Busaltan et al. [9] and Saady et al. [10] reported that open-graded asphalt blended with sustainable polymers can significantly enhance durability, resilience, and water resistance. Similarly, the recent studies indicate that PET-modified asphalt mixtures increase stiffness and resistance to tension and abrasion [11-15]. Elmagarhe et al. [16] and Franesqui et al. [17] revealed that the addition of recycled plastic can enhance the properties and sustainability of porous asphalt without limiting its permeability. A field test has investigated the

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application of recycled-plastic-modified porous asphalt pavements. Hao et al. [18] conducted a field trial of three distinct types of plastic-modified PAC pavement on an urban expressway in Singapore. This investigation shows that after 10 months of field performance, the pavement exhibited International Roughness Index (IRI) and rut depth values below the threshold, with no visible cracking. The plastic-modified porous asphalt also achieved sustained tire-pavement noise reduction. These findings demonstrate its durability and effectiveness, confirming that recycled plastic incorporation supports long-term functional performance under real-world conditions. Recently, a full-scale field test of a polymer-based modified-PAC pavement overlay was conducted on a bridge deck on a motorway in Thailand over 6 years [19]. The field test results show that the mixture provides higher skid resistance and permeability than conventional materials used in current road construction, highlighting the importance of PAC pavements in improving road safety and performance under the region's harsh climatic conditions.

However, these studies collectively confirm the mechanical and ecological benefits of polymer modification; most focused on binder-based polymer mixing or dense-graded mix specimens. The mechanical and hydraulic impacts of using recycled PET plastic granules (G-PET) as an additive in porous asphalt mixtures were not adequately addressed, particularly regarding pore connectivity, binder retention, and structural stiffness. This gap in the literature underscores the need for an overall study of the mechanical-hydraulic interaction in G-PET-modified porous asphalt mixtures. Only a few studies examine the optimal quantity of PET granules to achieve an ideal trade-off between mechanical strength and hydraulic properties, similar to the functioning of permeable pavements [20, 21]. Furthermore, the use of advanced characterization tools, such as ultrasonic pulse velocity (UPV), to correlate the internal microstructure of PET-modified PAC with its macroscopic mechanical properties has received less attention. Knowledge of these interconnected effects is essential to optimizing mix design, field durability, and the sustainable use of plastic waste in paving materials.

To address these drawbacks, this paper explores the mechanical and hydraulic properties of granule PET-plastic-modified porous asphalt concrete suitable for permeable pavements. Using a polymer-modified asphalt (PMA) binder and varying G-PET contents, this research systematically investigates the effects of G-PET on volumetric properties, Marshall stability, indirect tensile strength, dynamic modulus, raveling resistance, and permeability. Performance trends are evaluated using both mechanical testing and hydraulic characterization methods. The findings are then utilized to determine the optimum G-PET dose that provides an ideal compromise between strength and permeability. The results shed important light on the mechanisms of polymer-aggregate interactions in porous asphalt and can help guide design for the introduction of recycled PET into permeable pavement technologies. In the end, this study contributes to sustainable, environmentally friendly, advanced-performance pavement materials that align with global sustainability and a circular economy.

2. Materials and methods

2.1 Materials characterization

2.1.1 Aggregates

The crushed limestone was used as aggregate in this study (Figure 1a). The coarse and fine aggregates were prepared for design as a PAC wearing course with a nominal size of 19.0 mm. Three different trails were selected for testing within the gradation, corresponding to its upper and lower limit values. The test results for the aggregate's physical properties are shown in Table 1.

Table 1 Aggregate characterization

Test	Standard	Specification	Results
<i>Gradation</i>	AASHTO T27		
Sieve size (mm)			
25.40		100	100
19.00		85 - 100	96.41
12.50		65 - 85	75.59
4.75		10 - 31	26.78
2.36		10 - 20	15.16
0.075		3 - 7	3.24
<i>Physical properties</i>			
Bulk specific gravity of coarse aggregate	ASTM C127	-	2.676
Bulk specific gravity of fine aggregate	ASTM C128	-	2.627
Water absorption of coarse aggregate (%)	ASTM C127	< 2	0.24
Water absorption of fine aggregate (%)	ASTM C128	< 2	0.79
Los Angeles abrasion (%)	ASTM C131	< 30	26.14
Flakiness index (%)	BS 812	< 25	22
Elongation index (%)	BS 812	< 25	24
Chemical soundness (%)	ASTM C88	< 5	0.70
Sand equivalent (%)	ASTM D2419	> 60	68
Aggregate impact value (%)	BS 812-112	< 25	17

2.1.2 Asphalt binder

A polymer-modified asphalt (PMA) was used for all mixtures in this study. The PMA had the following properties: penetration value of 57, softening point of 77 °C, ductility of 88 cm, elastic recovery of 98%, toughness of 20.6 N · m, density of 1.046 g/cm³, and dynamic shear of 1.32 kPa.

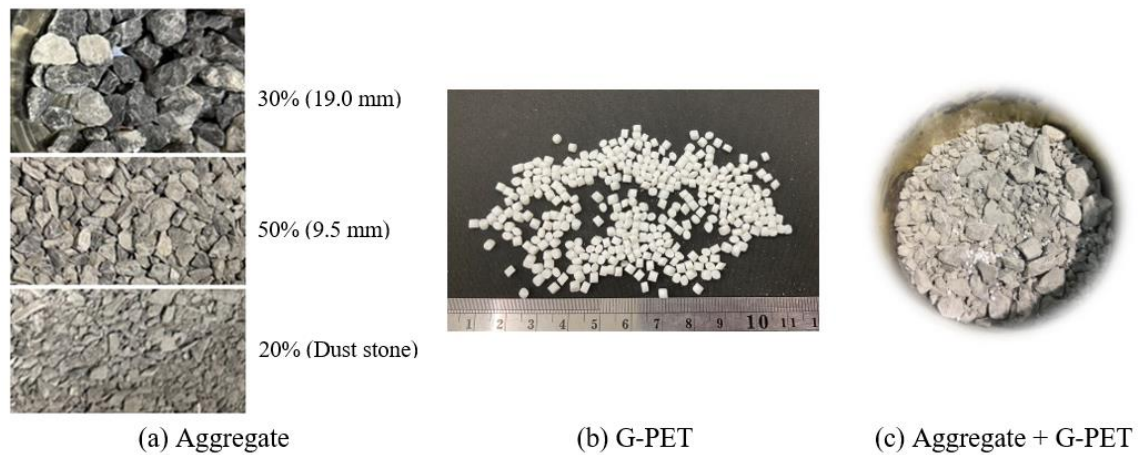


Figure 1 Materials used in this study

2.1.3 PET granule

Commercially available recycled polyethylene terephthalate (PET) plastic granules were procured from Global PCR & PIR Plastic 168 Co., Ltd., and used as an additive in the PAC mixtures. The G-PET consisted of cylinder-shaped particles with a size of 2 – 3 mm (Figure 1b) with a specific gravity of 1.32 and a melting point of 246 °C. Their angular morphology and lightweight nature were expected to influence both the mechanical and hydraulic behavior of the mixtures.

2.2 Mix design and specimen preparation

The PAC mixture design was conducted in accordance with ASTM D7064. To determine the optimum asphalt content (OAC), the varying PMA percentage in the Marshall specimens was 4.0, 4.5, 5.0, 5.5, and 6.0% by weight of aggregate. The Marshall test results showed that the OAC of the PAC mixture is 5%. Thus, the PMA content was fixed at 5% to produce all G-PET-modified PAC mixtures. The G-PET was blended with the combined aggregate during drying at G-PET contents of 0, 5, 10, 15, 20, and 40% by weight of the asphalt binder. Marshall compaction with 50 blows per side was employed for specimen preparation, ensuring consistent compaction while preserving adequate void structure. For each type of mixture, cylindrical samples with a diameter of 101.6 mm and a height of 63.5 mm were prepared using a Marshall compactor. Samples were prepared for mechanical and permeability tests.

2.3 Testing program

2.3.1 Air voids and porosity

The air voids (V_a) were calculated using the procedure given in ASTM D7063 after measuring the bulk specific gravity, as per ASTM D2726, as shown in Eq. (1). The maximum theoretical density was determined in accordance with ASTM D2041 for loose asphalt mix samples. The effective porosity (P_e) was calculated using Eq. (2) [7].

$$V_a(\%) = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100 \quad (1)$$

$$P_e = \left(1 - \left(\frac{W_{dry} - W_{sub}}{\rho_w V_T}\right)\right) \times 100 \quad (2)$$

where G_{mb} is bulk specific gravity of compacted specimen, G_{mm} is maximum theoretical specific gravity, W_{dry} and W_{sub} are dry and submerged weight of compacted specimen, respectively, ρ_w is density of water, and V_T is total volume of compacted specimen.

The connected air void (V_{ca}) is measured by the weight-in-water method and is calculated as shown in Eqs. (3) and (4).

$$V_{ca}(\%) = \left(\frac{V_T - V_c}{V_T}\right) \times 100 \quad (3)$$

$$V_c = \left(\frac{W_{dry} - W_{sub}}{\rho_w}\right) \quad (4)$$

where V_c = the volume of closed air void.

2.3.2 Draindown

The draindown resistance of PAC mixtures was tested in accordance with ASTM D6390. This test was conducted to assess the potential for asphalt binder drainage from the PAC matrix, an important consideration for coating thickness in high-void mixtures and long-term performance. To prevent binder segregation from molecular criteria, which would impair mixture homogeneity and durability in field applications, a draindown value lower than 0.3 % was defined as acceptable according to recognized specifications.

2.3.3 Raveling resistance test

The raveling resistance test is commonly used to assess the binding failure between the asphalt and aggregate particles of the PAC specimen. The Cantabro loss method outlined in ASTM D7064 was used to evaluate mix loss due to abrasion. Each sample was placed in a Los Angeles abrasion machine without steel balls and rotated for 300 cycles at 30–33 rpm. After each test, the specimens were weighed before and after abrasion to determine the percentage weight loss, which will be denoted as Cantabro loss.

2.3.4 Marshall stability and flow test

The mechanical characteristics of the PAC mixes were assessed using the Marshall stability and flow test, as per ASTM D6927. Cylindrical test specimens prepared in a water bath maintained at $60 \pm 1^\circ\text{C}$ for 30–40 min before testing were compressed at a constant rate of 50.8 mm/min using a Marshall testing machine (Figure 2a). The peak load at failure was defined as Marshall stability, which indicates resistance to plastic deformation under traffic loads. At the same time, vertical deformation at peak load was taken as the flow value. Additionally, the stability-to-flow ratio (Marshall quotient, MQ) was calculated to assess the PAC mixture's stiffness. A high MQ value indicates a mix with high stiffness, which has a greater ability to spread the applied load and resist rutting.

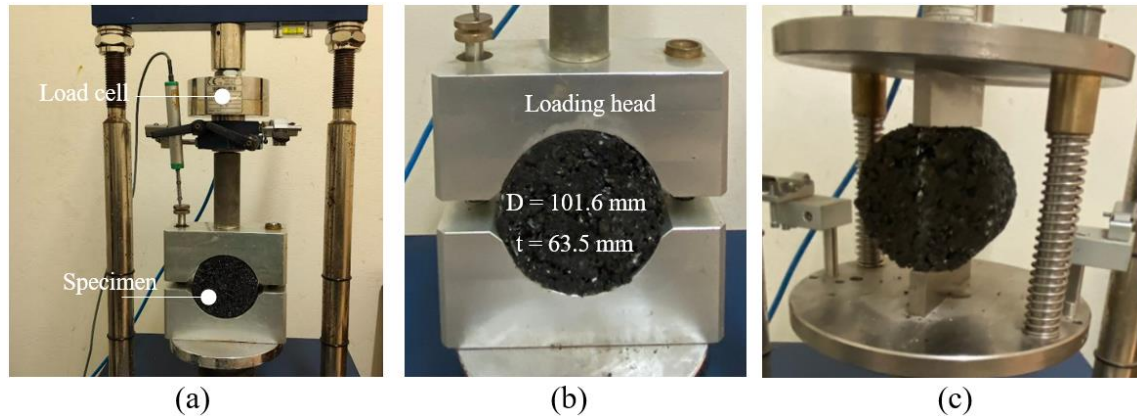


Figure 2 Marshall stability and ITS test (a) stability setup and placement, (b) Marshall specimen, (c) ITS specimens

2.3.5 Indirect tensile strength

The indirect tensile strength (ITS) of the PAC specimens (Figure 2c) was determined in accordance with ASTM D6931 to evaluate their resistance to tensile cracking. Cylindrical samples were conditioned to a target test temperature of $25 \pm 1^\circ\text{C}$ before testing. Each specimen was loaded diametrically along its vertical axis at a constant deformation rate of 50 mm/min using a Marshall testing machine until failure occurred. The maximum load at failure was recorded, and then the ITS value was obtained using Eq. (5).

$$\text{ITS} = \frac{2P}{\pi Dh} \quad (5)$$

where ITS = indirect tensile strength, P = maximum load, D = diameter of the specimen, and h = height of the specimen. The test results for three samples were averaged to obtain an accurate representative value for the variable.

2.3.6 Ultrasonic pulse velocity test

The PAC specimens were tested for ultrasonic pulse velocity (UPV) in accordance with ASTM C597. The speed of elastic ultrasonic waves transmitted through the sample is sensitive to the microstructural state and, hence, to void connectivity, density, or the presence of microcracks. Typically, the higher the UPV value, the denser and better connected the aggregate-binder skeleton [5], whereas contrasting results may indicate increased porosity, weak interfacial bonding, or internal defects. Cylindrical Marshall specimens were tested on a PUNDIT-UPV apparatus with 54 kHz transducers. An average of three measurements was taken to minimize variation, and that value was used for analysis. Ultimately, the dynamic modulus of PAC was calculated using Eq. (6) [22]. The UPV test is displayed in Figure 3.

$$E^* = \frac{V^2 \rho (1+\nu)(1-2\nu)}{(1-\nu)} \quad (6)$$

where V = pulse velocity of longitudinal stress waves (m/s); E^* = dynamic modulus (kPa); ρ = density of specimen (kg/m^3); and ν = Poisson's ratio.

2.3.7 Permeability test

The permeability test method assesses the vertical infiltration capacity of compacted PAC specimens using a falling-head apparatus, as illustrated in Figure 4. Cylindrical specimens were placed in a sealed chamber, and a predetermined volume of water was allowed to flow vertically through the specimen under gravity. Each testing sample was wrapped on one side only with plastic film to allow water to flow in a single direction. The upstream pipe was filled with water to saturate the specimen, with the water level approximately

450 mm above the top of the specimen. The time required for a known water level to drop from 300 mm to 75 mm above the specimen was recorded [23]. Three samples were used for the test, with five replications per sample. All tests were conducted at a controlled laboratory temperature (25 ± 2 °C). The hydraulic conductivity (k) was calculated using Darcy's law as shown in Eq. (7).

$$k = \frac{aL}{At} \ln \frac{h_1}{h_2} \quad (7)$$

where L is the specimen height (cm), a is the inner cross-sectional area of the standpipe (cm^2), A is the cross-sectional area (cm^2), t is the elapsed time (sec), h_1 and h_2 are the initial and final hydraulic head across the test specimen (cm).



Figure 3 Ultrasonic pulse velocity test

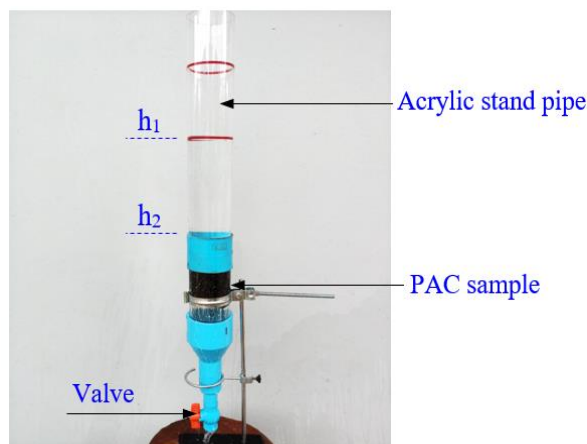


Figure 4 Physical pictures of the falling head permeability test

2.3.8 Moisture susceptibility

The tensile strength ratio (TSR) test was conducted in accordance with AASHTO T283 to evaluate the moisture susceptibility of the PAC mixtures. Cylindrical specimens were divided into two groups: unconditioned and conditioned. The conditioned group was subjected to vacuum saturation, followed by immersion in a 60 °C water bath for 24 hours. Both conditioned and unconditioned specimens were then tested for ITS at 25 ± 1 °C using a Marshall testing machine. The TSR was calculated as the ratio of the average ITS of the conditioned specimens (ITS-wet) to that of the unconditioned specimens (ITS-dry), expressed as a percentage. This procedure provides a quantitative measure of the PAC mixture's resistance to moisture-induced damage, which is critical for assessing the durability and long-term performance of G-PET-containing mixtures.

3. Results and discussions

3.1 Volumetric analysis

The volumetric properties of the PAC with different G-PET dosages showed significant variations in air void content (V_a) and effective porosity (P_e), as shown in Figure 5. The V_a values exceeded the minimum threshold of 20% [24, 25] for all mixtures. The control mix showed V_a of 20.74% and P_e of 15.14%. Incorporation of 5-10% G-PET resulted in a slight decrease in both V_a and P_e to about 20.68-20.71% and 13.48-15.13%, respectively, suggesting improved aggregate packing and a denser structure resulting from partial filling of intergranular voids by G-PET. This densification effect is indeed consistent with the views of Hao et al. [18], who reported a reduction in macro-voids upon incorporating plastic waste into porous mixes, without compromising the desired permeability through improved binder distribution and interface adhesion.

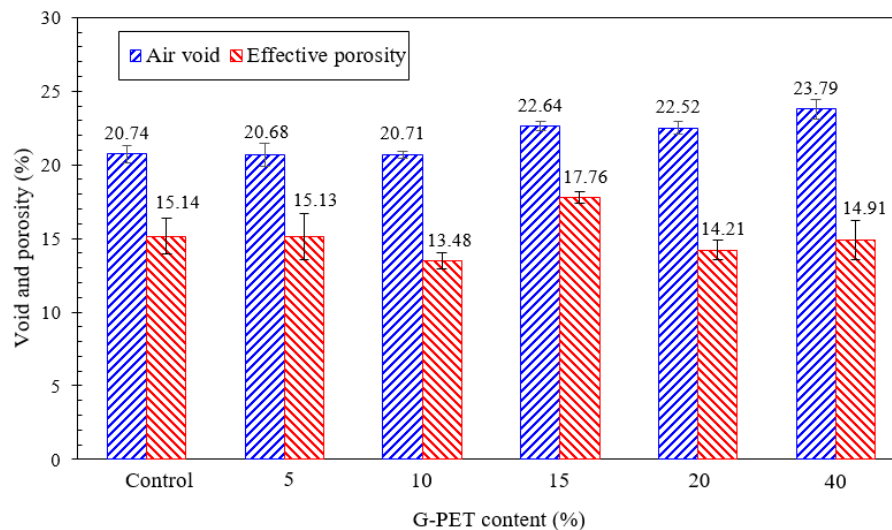


Figure 5 Volumetric characteristic of PAC mixtures

Beyond 15% G-PET, both V_a and P_e increase to 22.64% and 17.52% (at 15% PET), reaching their maximum values of 23.79% and 14.91% (at 40% PET). This tendency indicates that excessive G-PET content induced micro-void formation, resulting in poorer compaction and higher interconnected porosity. Kumar and Kumar [26] also reported similar results, stating that excessive plastic in the asphalt mixture led to non-uniformity and unsatisfactory pore connectivity, compromising mechanical integrity while allowing high permeability. For all blends, P_e ranged from about 13% to 18%, indicating that stormwater infiltration capacity was not significantly reduced. These findings are consistent with the research of Gundrathi et al. [20], who emphasized the importance of balancing connected and structurally stable voids in the modified PAC system to achieve satisfactory mechanical durability and appropriate drainage.

The fluorescent stereo microscope images in Figure 6 intuitively reveal the structural effect of adding G-PET on the internal morphology of PAC. The microstructure of the control mixture (Figure 6a) presents irregular and disconnected air voids bordered by the relatively thinner film asphalt binder, which agrees with the moderate volumetric air voids (20.74%). In contrast, the 10% G-PET modification (Figure 6b) shows a much better dispersed pore structure with relatively well-distributed G-PET particles, which are embedded within the binding phase. These polymer inclusions would fill the smaller voids and improve binder cohesion, consistent with the observed enhancements in total air void (20.71%) in the volumetric results (Figure 5). The well-connected, well-developed void network observed in the microscope image accounts for the high permeability but shows lower resistance to water infiltration in the hydraulic conductivity results. In contrast, a denser asphalt–aggregate interface indicates higher structural integrity. Overall, it is shown that when the G-PET fraction is moderate (5–15%), the uniformity of the pore network improves, and permeability can be maintained within a functional range.

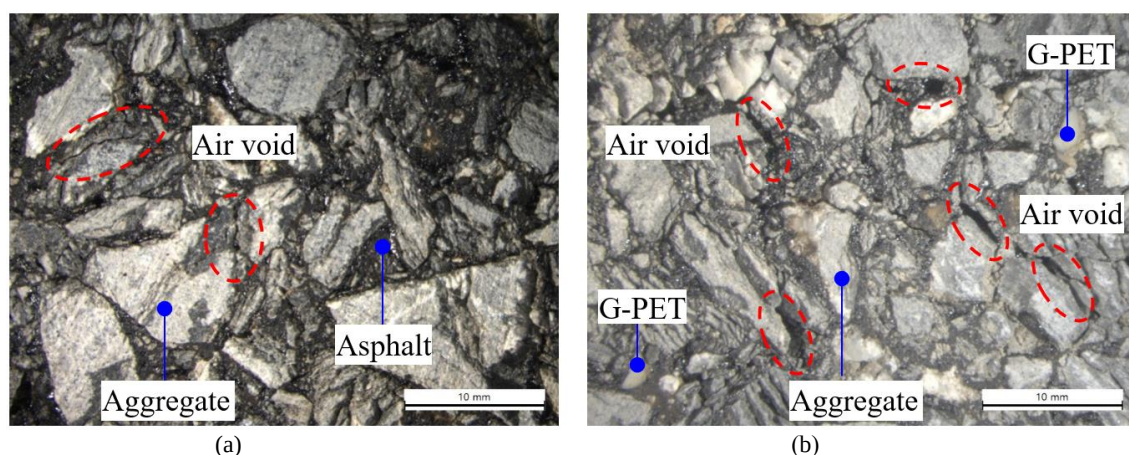


Figure 6 Fluorescent stereo microscope images of (a) control, and (b) 10% G-PET samples

3.2 Mechanical characterization

3.2.1 Marshall stability

Both the Marshall stability and flow of PAC modified with G-PET showed notable performance changes with increasing G-PET content, as depicted in Figure 7. The control mix showed a stability of 5.11 kN and a flow of 3.6 mm, above the acceptable limit of 3.55 kN [24]. The highest stability value (5.60 kN) was observed at 10% G-PET, indicating the effective range for improving interlocking and the mix's stiffness through polymeric supplementation between the G-PET particles and the asphalt binder. Beyond this dosage, the stability progressively declined to a minimum of 3.47 kN at 40% G-PET, indicating that excess addition decreases the cohesiveness of matrix-aggregate bonding.

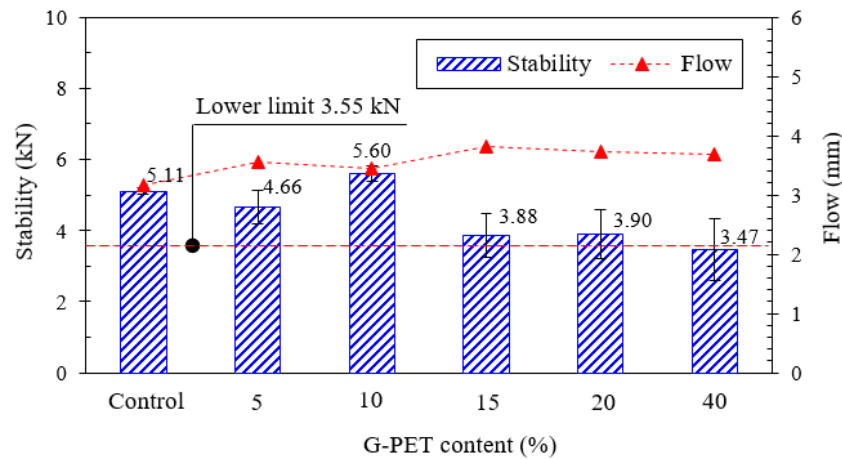


Figure 7 Marshall stability and flow result of PAC mixtures with different G-PET content

A similar pattern was also observed by Hassani et al. [27], who concluded that the optimal points for stiffness and Marshall stability occurred with a moderate addition of PET. However, higher contents led to increased brittleness and decreased strength, due to lower friction between G-PET. Additionally, the achieved flow values (3.1–3.8 mm) fell within the optimal deformation range (2–4 mm), in agreement with Baradaran et al. [21], who reported that an efficient mechanism for controlled flow was associated with improved elastic recovery and ductility in recycled PET polymers. The findings thus suggest that adding up to 10% G-PET optimally balances strength and flexibility, thereby improving the sustainability and mechanical endurance of a permeable asphalt pavement.

Figure 8 shows that the Marshall quotient (MQ) declined initially when 5% G-PET was introduced. It then reached a high of 1.62 kN/mm at a 10% G-PET mixture, indicating that an intermediate concentration of G-PET improves the binding strength and interlocking of the aggregates. As the G-PET content increased beyond this optimum, MQ decreased to 1.01–0.94 kN/mm at high G-PET content (15–40%). This decline may be due to large polymer agglomeration and increased connectivity of the voids, which weaken the aggregate-binder matrix and reduce the stiffness of the mixtures.

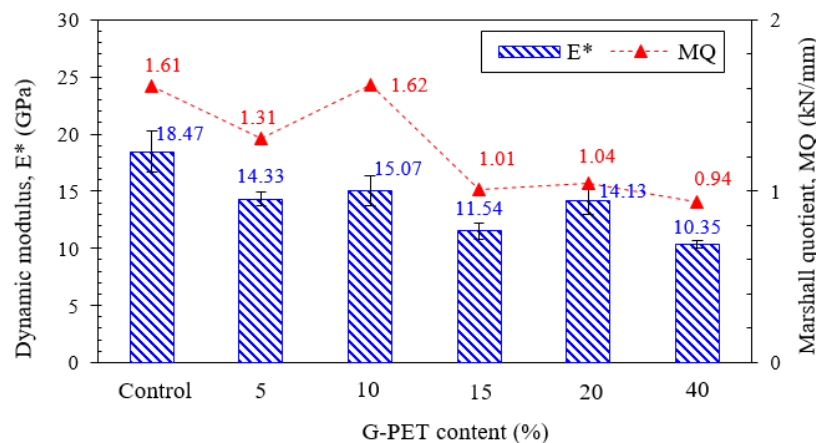


Figure 8 Dynamic modulus and Marshall quotient of PAC

3.2.2 Dynamic modulus

The dynamic modulus (E^*) of the PAC mixtures was calculated using Eq. (6), assuming a Poisson's ratio of 0.35 [28, 29]. The E^* values shown in Figure 8 exhibit a similar pattern to the MQ, as both are stiffness-dependent parameters governed by the exact internal mechanisms—aggregate interlock, binder cohesion, and pore structure continuity. Remarkably, 10% G-PET yielded a balanced response, regaining stiffness to 15.07 GPa and achieving the greatest MQ of 1.62 kN/mm, signifying enhanced load transfer and aggregate interlock despite the porous structure. As G-PET content increased, stiffness decreased once again (11.54 GPa at 15% and 10.35 GPa at 40%), with MQ reducing to 1.01–0.94 kN/mm, indicating enhanced void connection. Overall, the dynamic modulus derived from the UPV test was validated as reliable through theoretical consistency with elastic wave principles and consistent correlation with mechanical parameters such as MQ. The validations collectively indicate that the UPV method provides a reliable, non-destructive means of evaluating stiffness in G-PET-modified porous asphalt concrete.

3.2.3 Indirect tensile strength and moisture sensitivity

Figure 9 shows the results of ITS and TSR for PAC mixtures at varying G-PET percentages. The control blend produced ITS values of 0.55 MPa (dry) and 0.45 MPa (wet), serving as reference values for the tensile performance of the untreated PAC mix. Entirely consistent with that, when 5% G-PET was added, the ITS values remained similar at 0.55 MPa (dry) and 0.46 MPa (wet), indicating no significant change in the tensile response. The tensile strengths of the 10% G-PET compounds are significantly elevated, reaching 0.70 MPa (dry) and 0.58 MPa (wet), corresponding to a TSR of around 83%, indicating diminished moisture sensitivity and reduced

adhesive failure between the binder and aggregate. This enhancement indicates that a moderate amount of PET can facilitate the strengthening of the polymer in the binder matrix and improve tensile strength and interfacial adhesion. Nonetheless, further incorporation of G-PET above 10% led to a progressive reduction in ITS, indicating that excessive PET particles can disrupt the binder's continuity and weaken the matrix due to reduced dispersion and adhesion. This result is consistent with previous findings that excessive polymers can lead to heterogeneity and reduced overall strength [30, 31].

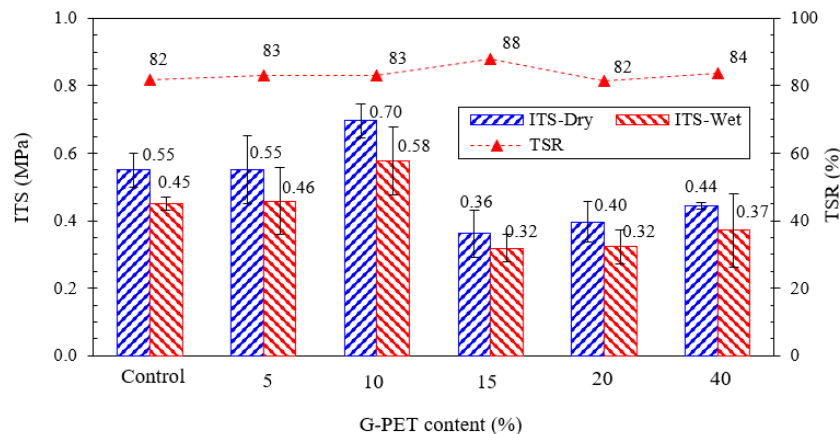


Figure 9 ITS and TSR results of PAC mixtures

The TSR values were consistently above the 80% threshold for all mixtures, indicating that moisture susceptibility was successfully mitigated and that the mixtures met the durability requirements for permeable pavements. The highest TSR (88%) was obtained at 15% G-PET, confirming superior moisture resistance at this level and also ranking the lowest TSR (82%) in control and high amount (20%) mixes. These findings are consistent with those in PET-modified dense asphalt, where similar enhancements were associated with increased binder-cohesion behaviour of SBS polymers [13, 32]. The TSR value of over 80% indicates that adding PET does not reduce resistance to water-induced stripping but may increase it, which is important for porous asphalt layers subjected to multiple wet-dry cycles. In summary, the addition of 10% G-PET yields an optimal dosage that enhances the mechanical performance (e.g., Marshall stability, MQ, E*) and durability (e.g., TSR) of porous asphalt concrete.

3.3 Draindown

As shown in Figure 10, the draindown results of the PAC with different G-PET contents are far below the 0.3% deviation from the upper limit for all mixtures, demonstrating good binder retention and mixture stability. The draindown value of the control was about 0.06% and increased slightly to 0.10% for the G-PET at 5% due to partial filling of mineral filler with hydrophobic G-PET. However, with increasing G-PET content, draindown steadily decreased to 0.08% at 10%, 0.07% at 15%, and then leveled off around 0.03% for mixtures containing 20–40% G-PET. This reduction trend implies that PET granules contribute to a high degree of binder stability through absorbent and physical anchoring of PMA within the aggregate skeleton [33], thereby reducing binder segregation during compaction and improving the durability in field application.

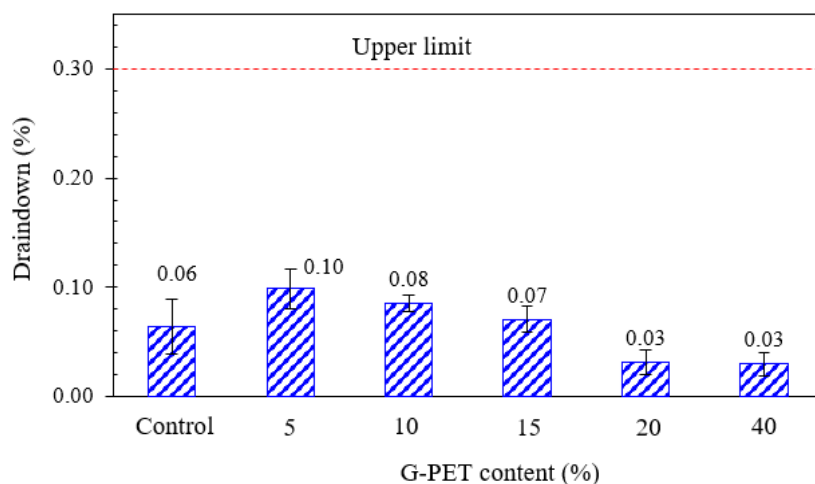


Figure 10 Draindown result

3.4 Raveling resistance

Figure 11 illustrates the Cantabro abrasion loss results for porous asphalt concrete mixtures with varying G-PET contents, showing that all mixtures experienced abrasion losses well below the allowable limit of 20%, confirming a strong ability to resist particle disintegration. The loss was 4.34% for the control mix, and the value rose slightly to 7.13% at 5% G-PET, possibly due to minor reductions in internal cohesion from the introduction of polymer granules. However, beyond this point, further gains in abrasion

resistance were observed, with losses of 4.27%, 3.79%, 3.97% and 2.57% at 10%, 15%, 20% and 40% G-PET, respectively. The increased durability at high G-PET fractions could be due to the polymer's flexible, energy-absorbing nature, which promotes interparticle adhesion on the one hand and suppresses raveling under repeated impacts on the other.

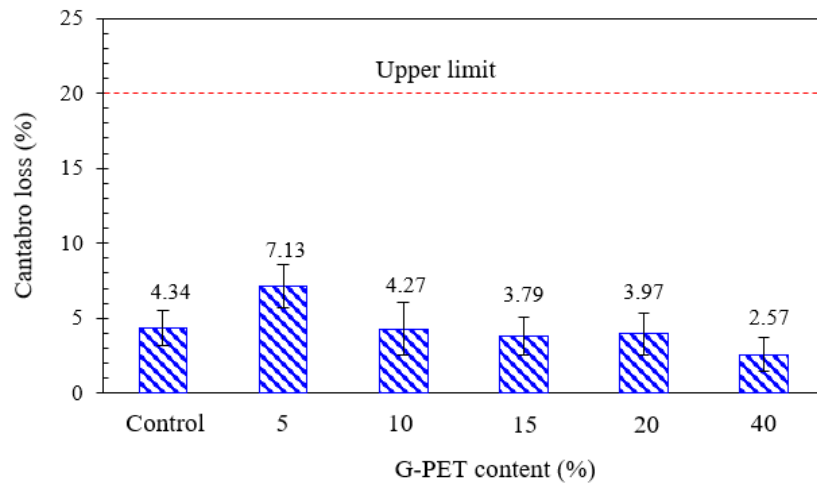


Figure 11 Cantabro abrasion loss result

In addition, the findings are consistent with those of Hao et al. [18], who found that the long-term abrasion resistance of porous asphalt mixtures modified with recycled plastic is similar to that of conventional polymer-modified binders. The demonstrated performance of G-PET enhances the structural robustness of porous asphalt without compromising failure limits by using PET as a stabilizing admixture. Overall, G-PET-modified mixtures showed the best abrasion resistance, with Cantabro losses below 8%—substantially below the 20% durability threshold for porous asphalt. These findings verify that G-PET improves mixture integrity and long-term stability, further validating it as an environmentally friendly modifier for permeable pavement systems, not only in terms of mechanical strength but also in terms of sustainability.

3.5 Permeability

The relationship between hydraulic conductivity (k) and connected air void (V_{ca}) in porous asphalt concrete with different G-PET contents is shown in Figure 12, which shows a positive correlation between pore continuity and permeability. The permeability of all G-PET-modified PAC mixtures exceeded 0.01 cm/s, thereby meeting the minimum permeability requirement specified in ASTM D7064. The control blend had the lowest k (0.05 cm/s) and V_{ca} of 13.03%, while increasing G-PET content to 10% led to anatomic changes in both parameters, with k reaching a maximum of 0.14 cm/s and V_{ca} of 17.75%. This improvement may be related to the development of reinforcing, interconnected void networks, driven by the hydrophobic and non-cohesive behavior of PET particles, which favors pore continuity. A moderate hydraulic conductivity reduction affected only G-PET content above 10%, following a trend of diminishing to 0.11–0.12 cm/s for 20–40% related content, along with a weakening of V_{ca} (16.58–17.57%). This decrease could be due to excess PET, which causes partial clogging and impairs optimal aggregate packing, thereby increasing tortuosity in the pore structure.

The above results are similar to those of Wang et al. [34], who showed that the hydraulic conductivity of porous asphalt mainly depends on the topology and connectivity of air voids rather than their total volume. The phenomenon is also consistent with that observed by Shan et al. [35], who found that pore structure improvement and the degree of void connection are affected to some extent by k value in pervious pavement, and that these factors directly impact permeability and anti-block performance. Furthermore, Pahsha et al. [36] confirm the results of this research regarding the improvement in hydraulic performance of PET in porous concrete compared to PAC, achieved by increasing pore connections and preventing binder blockage within the void system.

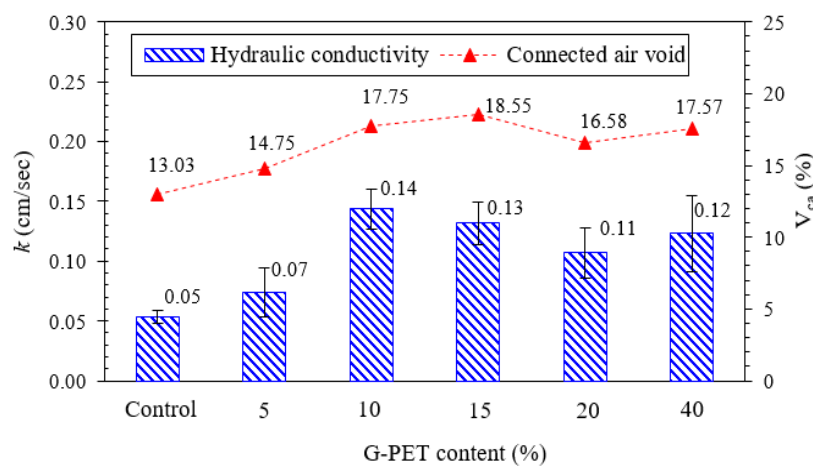


Figure 12 Permeability and connected air void of PAC

Figure 13 shows the correlation between k and V_{ca} of the PAC mixtures with G-PET. The result indicates a strong correlation with a power function ($R^2 = 0.97$). The exponential relationship indicates that even small increases in V_{ca} content result in disproportionately large increases in permeability. This characteristic can be due to the development of well-connected pore networks that allow continuous water flow in the mixture once it passes over its critical connectivity threshold. It confirmed that it is not just the total air voids but also their openness and interconnectivity that are the primary factors controlling PAC permeability, rather than the total amount of such air voids. These results are consistent with those reported by Wang et al. [37], who found a power-law correlation between permeability and connected porosity in PAC.

The overall conclusions indicate that an optimal G-PET content of 10–15% provides a compromise between hydraulic efficiency and mechanical strength. This optimal recycled plastic content is consistent with findings from a previous study [18], which indicated that porous mixtures containing 5% plastic generally demonstrate superior long-term performance compared to non-plastic mixtures, except for cracking resistance. However, excessive plastic content (15%) can adversely affect durability, resulting in significant deterioration in long-term pavement performance. The enhanced pore connectivity indicates that G-PET is a promising eco-efficient modifier for porous asphalt, strengthening permeability and service life. This work enhances the sustainable use of waste PET plastics as permeable pavement materials with potential circular-economy applications.

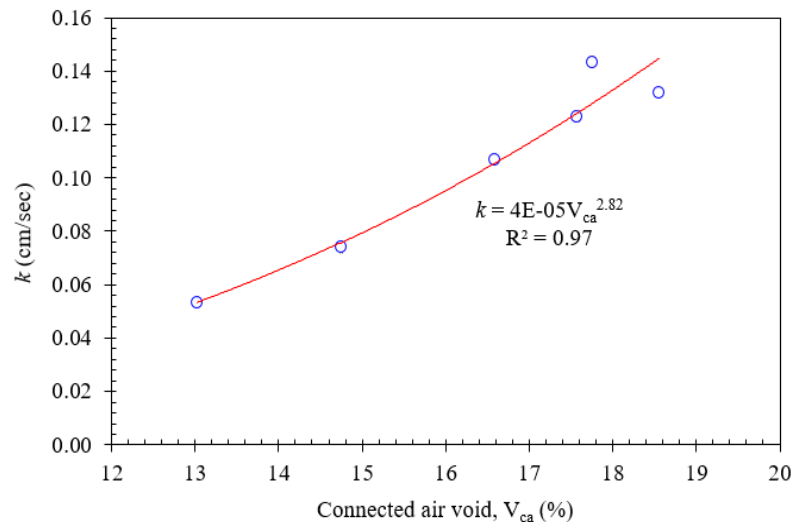


Figure 13 Relationship between V_{ca} and k of PAC mixtures

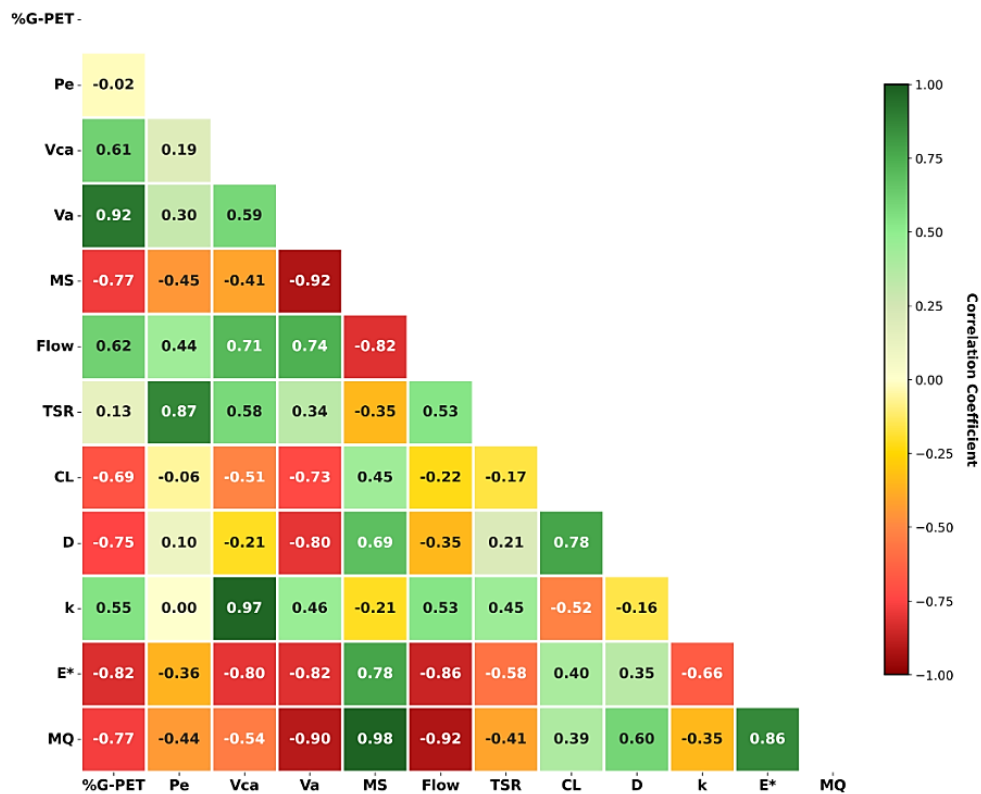
3.6 Statistical analysis of mixture performance

Based on Pearson correlation coefficient (r -value) analyses (Figure 14), it was clear that G-PET addition plays a crucial role in the volumetric and mechanical performance of the PAC mixture. The correlation analysis explains these trends: G-PET content was very strongly positively correlated ($r = 0.92$) with air voids (V_a) and negatively strongly correlated ($r < -0.7$) with Marshall stability (MS), draindown, dynamic modulus, and Marshall quotient (MQ). These are consistent with the relationships in which a higher dosage of G-PET can increase pore continuity but decrease stiffness and strength resistance.

The results in Figure 14 can be summarized as a correlation between PAC parameters—mechanical properties, void structure, permeability, and durability indicators. For mechanical performance, the MS and MQ are very strongly correlated ($r = 0.83$). Whereas air voids negatively impact both MS ($r = -0.92$) and MQ ($r = -0.90$), indicating that increased voids reduce mixture strength. Regarding stiffness behavior, the dynamic modulus (E^*) shows a robust correlation with MQ ($r = 0.86$), suggesting that both parameters are governed by mixture stiffness and deformation resistance. For void structure and permeability, hydraulic conductivity (k) and connected air voids (V_{ca}) are almost perfectly correlated ($r = 0.97$), confirming that V_{ca} is a primary factor controlling the permeable capacity of PAC. The statistical results for the Cantabro loss (CL), draindown (D), and TSR were used to describe the durability indicator. CL and D show a strong correlation ($r = 0.78$), which decreases with increasing G-PET content. However, TSR shows minimal correlation with G-PET ($r = 0.13$), indicating stable moisture resistance. Overall, these strong interrelationships confirm the effect of G-PET content on the mechanical and hydraulic properties of the PAC mixture.

3.7 Limitations and future work

Several limitations of the results presented in this paper regarding mechanical and hydraulic behavior should be considered in further research. The study was performed under laboratory conditions and may not be representative of field performance, particularly when subjected to varying temperature and traffic loads. However, the quantification of the impact of long-term aging, freeze–thaw cycling, and repeated wet–dry testing on the mechanical integrity and permeability of G-PET-modified PAC is lacking. In addition, the investigation primarily addressed the one-size/shape of the polymer; therefore, examination of these properties at the binder–aggregate interface (in combination with PET aggregate) remains to be done. Future research should extend to rheological characterization of the binder phase, fatigue and rutting resistance of mixtures, life-cycle cost analysis, and carbon footprint calculations to evaluate the overall beneficial effect from a sustainability perspective. Moreover, field tests and in-situ monitoring of G-PET pavement would be necessary to validate results obtained at the laboratory scale, on the one hand, and to help develop engineering design guidelines for large-scale use of recycled PET in porous pavement systems, on the other hand.



Note: P_e = effective porosity; V_{ca} = connected air void; V_a = air void; MS = Marshall stability; TSR = tensile strength ratio; CL = Cantabro loss; D = draindown; k = hydraulic conductivity; E^* = dynamic modulus; MQ = Marshall quotient

Figure 14 Correlation metric between G-PET content and performance parameters of PAC

4. Conclusions

From the results of this study, the following conclusion can be drawn:

- The study shows a promising approach of using waste G-PET plastic as an additive in the PAC mixture.
- Increasing G-PET content in the PAC mixture tends to decrease the strength and stiffness of the mix, possibly due to greater polymer agglomeration and increased connectivity of the voids. However, limiting the G-PET content to 20% provides acceptable performance.
- The incorporation of G-PET enhanced pore uniformity, binder cohesion, and moisture resistance while maintaining adequate permeability, confirming G-PET's dual functional role in strengthening the binder-aggregate matrix and improving drainage.
- Statistical analysis confirmed that increasing G-PET content significantly increases air void content and decreases the mix's stiffness.
- The finding reveals that the 10% G-PET mixture achieved the best performance among the mixtures.

In summary, the results presented in this paper provide a basic structure for the further application of G-PET-modified porous asphalt in the construction of a novel eco-efficient permeable pavement system.

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6. References

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