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Original Article

Performance Evaluation of Hybrid Porous Asphalt Containing Recycled Waste Plastic

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Abstract

Plastic pollution represents a significant global environmental challenge, with millions of tons of plastic waste accumulated annually in landfills and natural ecosystems. The COVID-19 pandemic intensified this issue due to the widespread use of single-use personal protective equipment. As a response to this problem, this study examines the use of recycled polyethylene terephthalate and single-use face masks as additives in porous asphalt mixtures to improve the mixtures' properties and promote sustainability in pavement engineering. The research aimed to evaluate the combined effect of incorporating recycled polymers into a hybrid system, rather than separately modified mixtures of polyethylene terephthalate and single-use face mask fibers. Laboratory tests indicated that the hybrid mixture exhibited optimal performance, achieving a 34% increase in Marshall stability, a 19% decrease in flow, and a 20% reduction in air-void content. Additionally, permeability decreased by 36%, while remaining within the accepted limit, improving moisture susceptibility, and cantabro abrasion losses decreased by up to 11%, suggesting improvements in cohesion, structure, and durability. The findings demonstrate that hybrid polymer modification offers an environmentally sustainable and high-performance approach for future porous asphalt pavements.

Keywords: *Recycling, Open-Graded Asphalt Mixture, Plastic, Polymers, Personal Protective Equipment, PET.*

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1. Introduction

Plastic pollution is one of the most significant environmental challenges today. Annually, almost 400 million metric tons of plastic waste are generated globally. A considerable portion is disposed of in landfills or infiltrates terrestrial and aquatic ecosystems [1]. The COVID-19 pandemic exacerbated this global issue by significantly increasing the utilization of single-use personal protective equipment (PPE), such as face masks, gloves, and hospital gowns. Most of these goods are composed of polypropylene (PP), polyethylene (PE), or polyethylene terephthalate (PET). These plastics are non-biodegradable, and recycling rates remain low [2]. According to Prata et al. 2020, approximately 1,548 billion medical face masks and 780 billion disposable gloves were used worldwide annually during the global health crisis [3]. In Iraq, waste-management systems already under strain faced additional loads. The estimated amount of medical waste from face mask use during the COVID-19 pandemic in Iraq was about 478.99 tons per day [4]. A detailed report by the Japan International Cooperation Agency (JICA) and Yachiyo Engineering Company analyzed waste data in Iraq and found that in 2022, each person produced approximately 1.36 kilograms of waste per day. This amount is notably higher than the 0.74 kilograms per person per day world average [5]. These figures highlight the urgent need for engineering-based recycling pathways capable of absorbing large volumes of plastic waste, rather than continuing to rely on landfilling or open dumping, which exacerbate soil and water contamination. A sustainable method combines plastic waste with asphalt mixtures, solving both waste management problems and pavement performance issues. Incorporating polymeric elements into asphalt has been shown to extend its lifespan, increase stability, reduce the risk of rutting and cracking, and lower moisture absorption [6], [7], [8]. Among the various pavement types of hot asphalt mixtures, porous asphalt (PA) has attracted growing interest due to its unique environmental and functional advantages. A PA mixture is an open-graded mixture consisting of coarse and fine aggregates bound by asphalt binder. Still, it contains significantly less fine aggregate than conventional dense-graded asphalt with high air void content [9]. Because of these highly interconnected air voids, this open-graded structure provides rapid water drainage through the pavement's permeable surface layer, preventing surface ponding. An open-graded stone reservoir below the surface layer stores water (figure 1). This recharges groundwater and reduces flooding in cities [10]. The PA pavements are widely used in parking lots, recreational spaces, and low-volume roadways, offering additional benefits such as improved skid resistance, reduced tyre noise, and mitigation of the urban heat-island effect. In the context of Iraq, where the infrastructure often suffers from inadequate drainage and frequent waterlogging, the application of this type of pavement modified with plastic waste represents a promising solution [11]. Several studies have incorporated PET or other plastics into PA, often in combination with modified asphalt or Lawele granular asphalt, mainly to improve stability and raveling resistance. For example, Mabui et al. evaluated PA containing modified Buton asphalt and PET plastic waste, reporting improved strength and abrasion resistance[12] [13]. A previous study by Waisy Khalid et al. reported that incorporating PET as an alternative filler in asphalt mixtures notably enhanced their performance. The addition of PET reduced permeability, drain-down, and Cantabro loss by 22.64%, 29.27%, and 16.33%, respectively, while improving Marshall stability by over 15.5%[14]. In line with earlier research trends, the incorporation of 5% to 15% PET with cellulose fiber observed a steady reduction in air voids, voids in mineral aggregate, and tensile strength ratio. Although stability and density slightly declined at higher PET levels, Marshall stability remained above 10 kN. Moreover, the Cantabro abrasion loss remained below 4% for all mixtures, indicating excellent resistance to raveling and surface wear[15]. More recently, Putra et al. studied PA mixtures containing waste mask fibers and showed that 1% mask content at the optimum asphalt content enhanced stability, Cantabro resistance, stiffness and fatigue performance[16]. The hybrid performance also compares favorably with polymer-modified PA mixtures, where synthetic polymers (EVA) and cellulose or glass fibers are used together [17]. Suggesting that recycled materials such as PET or PPE could offer a lower-cost and more sustainable alternative to conventional fibre systems.

2. Research Gap and Objectives

Despite extensive global investigations into polymer-modified asphalt, significant research gaps remain. There is limited data on incorporating PPE-derived plastic waste, including shredded mask fibres and PET fragments, into PA mixtures. Previous studies have mainly focused on dense-graded asphalt or polymer addition through the wet process for asphalt mixtures. In contrast, the dry mixing method for blending plastic waste into PA systems remains limited. Therefore, this study aims to address these gaps by designing and evaluating sustainable PA mixtures that incorporate various forms of recycled plastic waste, including consumer-grade PET and PPE-derived single-use face mask (SUFM) fibres, using the dry mixing technique. The objectives are to (i) improve the mechanical and functional performance of PA, (ii) promote environmental sustainability by diverting plastic waste from landfills, and (iii) develop cost-effective pavement solutions that enhance stormwater infiltration, groundwater recharge, and urban flood mitigation.

3. Materials and methods

3.1. Methodology

This section outlines the experimental methodology adopted to produce and characterize the PA mixtures incorporating repurposed polymeric materials modified via dry processes. Two primary materials based on plastic were utilised: PET from post-consumer drinking cups and SUFM, mainly polypropylene. These materials were chosen because they are found in both municipal and medical waste streams and can help improve mixed pavement performance, turning a problem into an advantage. At the same time, a hybrid PA mixture was created for this research by combining both PET and SUFM fibers to test the synergistic effects of their concurrent presence under one system. From previous studies, the optimal dosing range for each additive was determined through independent laboratory tests. Table 1summarizes the PA mixtures investigated in this study, including mixture codes, additive types, contents, and testing repetitions. Detailed aggregate gradation and optimum binder content (OBC) determination are presented in the Materials and Results sections, respectively. The experimental program contained four main parts:

1- Materials characterization, including the physical and mechanical tests of aggregates and bitumen.

2- Mix design and sample preparation: including selection of aggregate gradation, optimizing the binder content, and incorporating the additives through the dry processes.

3- Laboratory testing, which covered volume, mechanical, and hydraulic properties assessment work

4- Performance interpretation: A comparison between single-modified and hybrid mixtures in terms of PET and SUFM roles was made to measure the combined effects on durability, permeability, and sustainability of PA pavements.

Table 1. Summary of PA mixtures used in this study

Mixture code	Additive material	Additive content/ by weight of aggregate	Binder content	No. of replicates
PET	Recycled PET particles	1 %	OBC	3 per test
SUFM	Shredded single-use face masks	1 %	OBC	3 per test
Hybrid	Recycled PET particles + Shredded single-use face masks	0.5 % PET + 0.5 % SUFM	OBC	3 per test

3.3 Materials

3.3.1 Asphalt Binder

A 40/50 penetration-grade bitumen supplied by Al-Dorra refinery was used. Its key properties, penetration, softening point, ductility, and viscosity, are presented in Table 2 and were measured according to the American Society for Testing and Materials (ASTM) and the Iraqi State Corporation for Roads and Bridges (SCRB)[18].

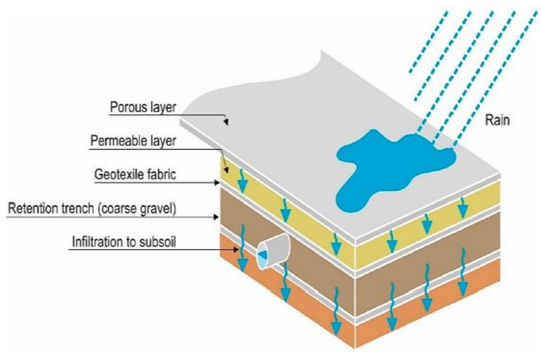


Figure 1. Cross-Section of Porous Asphalt Mixtures [19].

Table 2. Properties of the asphalt binder.

Laboratory Tests	Unit	ASTM	Test Results	SCRB
Penetration at 25°C-100g-5sec, 0.1mm	1/10 mm	D5-13	43	40-50
Ductility at 25°C, 5 cm/min	cm	D113-07	140	< 100
Flash point	°C	D92-16	295	< 232
Fire point	°C	D92-16	305	-
Softening point R&B (4±1) °C/min.	°C	D36-14	52	51-62

3.3.2 Aggregate

This research involved formulating a porous asphalt mixture using ASTM grading. Tables 3 and 4 show the properties of the aggregates from the Al-Nibaie quarry, which is widely used in Iraq for asphalt mixing plants and aggregate grading. Figure 2 shows the particle distribution curve for the aggregates used in this study. It also shows the upper and lower limits of the aggregate that can pass through the sieve, according to ASTM standards.

Table 3. Physical properties of aggregate

Properties	Standard ASTM	aggregate	
		Fine	coarse
Bulk specific gravity	C127-128-15[20]	2.685	2.611
Apparent specific gravity	C127-128-15[20]	2.733	2.662
Water absorption %	C127-128-15[20]	0.73	0.52
Los Angeles abrasion	C131-14[21]	-	17.72
flat and elongated particles, 10% max	D4791-19[22]	-	5
Fractured pieces %	D5821-13[23]	-	98
Clay content by Sand equivalent% 45min	D2419-14[24]	51	-

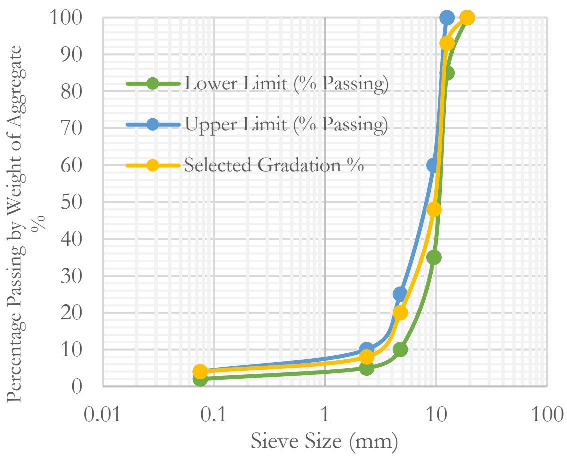


Figure 2. The aggregate gradations utilized in this study.

Table 4. Grading distribution of aggregates followed in preparing PA mixture samples

Sieve size (mm)	ASTM D7064−13 Passing %	Selected Passing %
19.0	100	100
12.5	85-100	93
9.5	35-60	48
4.75	10-25	20
2.36	5-10	8
0.075	2-4	4

3.3.3. Mineral Filler

This study utilized hydrated lime (HL) as both a filler and an anti-stripping ingredient, sourced from a local market. Table 5 shows the physical properties of HL. The chemical composition consists of calcium and sodium ions. The strong basic ions react with the acidic parts of bitumen to make salts that cover the surface of the aggregate. The aggregate's increased roughness helps it stick better to the asphalt binder, reducing the risk of stripping. On the other hand, the oxygen atoms in HL's chemical structure mix with the aliphatic chains of asphalt molecules to make a weak carboxylic acid that can interact with the strong Ca^{++} and Na^{+} ions [25], [26], [27], [28].

Table 5. Properties of HL.

Properties and Chemical Composition, %	HL
Specific gravity	2.50
Lime (Cao)	69
Silica (SiO_2)	1
Magnesia (MgO)	2
Sulfuric Anhydride (SO_3)	1
Loss on Ignition	27

3.3.4. Single-use face mask (SUFM)

This study incorporated shredded face masks as an additive in the PA mixture. The masks' physical properties are summarized in Table 6. Focusing on new masks, the research aimed to replicate the disinfection process and examine the physical changes in the treated masks. To achieve this, the masks were disinfected by heating them in an oven at 70°C for 60 minutes [29], followed by exposure to 100°C for 10 minutes to minimize the risk of bacterial contamination [30]. Subsequently, the metal nose strips and ear loops were removed from the masks. The disinfected masks were then shredded using a paper shredder, producing mask fibers measuring 50 mm in length and 5 mm in width. In previous study, face masks were typically shredded into strips of approximately 40 mm × 5 mm. In the present work, the available paper-shredding device produced slightly longer strips (about 50 mm × 5 mm). Because the mask material softens at the mixing temperature and blends with the binder rather than acting as a stiff fiber, the exact initial length of the strips has limited impact on their behavior in the mixture. Therefore, the slight difference in fiber length is considered negligible[6].

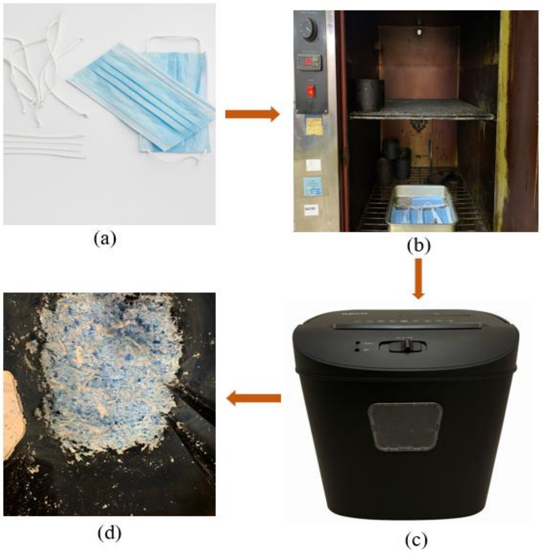


Figure 3. Procedure to prepare shredded single-use face masks: (a) Disassemble components of disposable face masks, (b) Disinfection of the single-use face masks, (c) Shredding Machine, (d) Shredded single-use face masks

Table 6. Physical properties of SUFM - adapted from [6].

Properties	Results	ASTM Standard
Specific gravity	0.91	D792-20[31]
Melting point	160°C	D7138-16 [32]
Aspect ratio	24	-
Water absorption (24 hours)	8.9%	D570-98[33]
Elongation at break	118.5-119.3%	D638-14[34]
Tensile strength	4.22-4.27 MPa	D638-14[34]
Tensile strength at break	3.95-3.99 MPa	D638-14[34]

3.3.5 Recycled polyethylene terephthalate (PET)

Local disposable water cups made of plastic waste were collected, washed, stripped of their labels and caps, and ground to 2.36 mm. Table 7 delineates the characteristics of PET used in this study and Figure 4 depicts the methodology for producing crushed PET particles from PET cups.

Table 7. Properties of PET- adapted from [35].

Properties	Values	ASTM standards
density	1.35 g/cm³	D792
Tensile strength	11,500 psi	D638
Melting temp.	250°C	D7138
Water absorption	0.1%	D570

Figure 4. Procedure to prepare crushed PET: (a) Collecting disposable plastic cups; (b) Plastic cups after cutting; (c) Crushing plastic; (d) Crushed plastic

4. Mixture Preparation

In accordance with standard laboratory protocols, the aggregates were oven-dried, weighed, and mixed to achieve the specified gradation. The binder was heated to the designated mixing temperature, and the chosen polymeric additives were integrated using the dry method before combining the hot aggregates and binder. The viscosity of the asphalt binder is assessed using a Brookfield rotating viscometer at two temperatures, 135°C and 165°C, to guarantee adequate fluidity for pumping and mixing. Asphalt Institute (2016) determined the mixing and compaction temperatures for the asphalt binder at the intersection of the viscosity-temperature line with the viscosity ranges of 0.170 ± 0.020 Pa.s and 0.280 ± 0.030 Pa.s, as shown in Figure 5. The findings suggest that the mixing and compaction temperatures range from (155-161)°C and (142-148)°C, respectively. Standard Marshall moulds used (102 mm diameter × 63.5 mm height). Specimens were compacted with a Marshall compactor hammer, applying 50 blows to each face.

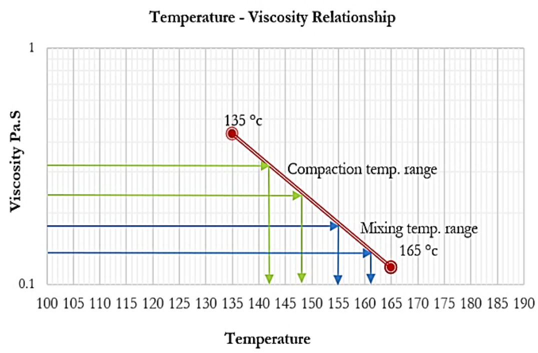


Figure 5. Viscosity-Temperature Graph for Asphalt Cement

5. Testing Program

The tests were conducted following ASTM, American Association of State Highway and Transportation Officials (AASHTO), and Federal Highway Administration (FHWA) specifications, which include a series of volumetric, mechanical, and hydraulic tests, Each test was performed on three replicates per mixture to ensure statistical reliability :

1- Air-void content is calculated by determining the bulk specific gravity and theoretical maximum specific gravity following ASTM C29 [36], AASHTO T 209 [37], and ASTM D3203 [38].

2-Falling-Head Permeability test to determine hydraulic performance for the compacted samples following ASTM D7064 [39], [40]. The tests were conducted at room temperature (25 ± 2 °C) with vertically applied flow, and each specimen was tested three times per replicate mixture.

3-Draindown test was evaluated following ASTM D6390-11 [41]. Loose mixtures were placed in wire baskets and conditioned at mixing temperature for 60 min, representing production temperature.

4- Cantabro abrasion test: In this test, Marshall compacted specimens were placed into the Los Angeles abrasion Machine without steel spheres, following ASTM C131 [21]. The machine was rotated at 30–35 rpm for 300 revolutions. Unaged specimens were tested at 25 oC, while aged specimens were conditioned at 60 °C for 7 days before testing. The test was then performed at 25 °C. The Cantabro loss was expressed as a percentage of the test specimen's original weight.

5- Marshall stability and flow test for compacted samples to evaluate the mechanical properties were obtained according to ASTM D6927 [42]. Specimens were conditioned in a water bath at 60 °C for 30–40 min before testing. Stability was measured under a loading rate of 50.8 mm/min.

6- indirect tensile strength (ITS) test and tensile strength ratio (TSR) to determine moisture susceptibility following AASHTO T283 [43]. Dry samples were conditioned at 25 °C for 2 hours before testing. Wet-conditioned samples were subjected to freezing at -18 °C for a minimum of 16 hours. After freezing, the samples were immersed in a water bath at 60 °C for 24 hours, followed by a final immersion at 25 °C for an additional 2 hours before testing, and TSR was calculated as the ratio of wet to dry strength.

6. Results and Discussion

Based on laboratory tests, the OBC for the PA mixture was determined by evaluating five asphalt contents within the range of 4.0% to 6.0%, with increments of 0.5%, in accordance with the general guidance of ASTM D7064. For each binder content, the key performance parameters were evaluated, including air voids, Cantabro loss, draindown, and permeability, as shown in Table 8. The OBC was selected to achieve a balanced performance across all criteria. Very low binder contents (e.g., 4.0–4.5%) resulted in high air-void contents and unacceptable Cantabro losses, indicating insufficient binder film thickness and weak aggregate interlock. Conversely, higher binder contents (5.5–6.0%) produced lower air voids but led to excessive draindown and reduced permeability, which are undesirable for PA. A compromise value was determined by selecting the best-performing binder content for each parameter and averaging the recommended values. This procedure resulted in an OBC of 5.3%, which provided the best overall balance between durability and functional performance. It is also important to note that no cellulose or stabilizing fibers were used in the control mixtures, which explains the relatively higher Cantabro and draindown values at lower asphalt contents. The selected binder content (5.3%) minimized these deficiencies while maintaining adequate permeability and structural stability. The draindown value at the selected OBC was slightly higher than the typical limit. This behavior is expected because the control mixture did not contain any additives, which are commonly used in PA to reduce binder drainage. The subsequent analyses focused on evaluating the performance of the modified mixtures. Figures 6 and 7 present the test results for the PA specimens. The incorporation of PET plastic waste resulted in a modified combination with an air-void percentage of 18.05%, within the FHW and ASTM ranges for open-graded mixtures (15–20%). [44]. The SUFM samples exhibited a marginally elevated value of 19.26%, attributed to the fibrous structure of mask fibers. The hybrid samples observed the lowest air-void content at 15.29%. This reduction indicates a higher packing density and a more uniform coating, suggesting better binder distribution and stronger bonding between the mixture components. The cantabro loss values of unaged mixtures also decreased from 16.43% for SUFM to 14.87% with the inclusion of PET waste, and the hybrid combination achieved the lowest losses of 14.53% among all modified samples. In underage conditions, hybrid mixtures showed slightly higher durability (23.93%) than PET (24.08%) and SUFM (24.37%). The superior performance of the hybrid mix is attributed to the synergistic balance between the flexibility of fibers on the mask and the rigidity of PET particles in assisting resistance against raveling and particle loss. This pattern is broadly consistent with previous work on PET-modified PA and OGFC mixtures, where PET contributes to mixture stiffening and improved aggregate–binder interaction. For example, Mabui et al. reported that adding PET in combination with modified Asbuton increased Marshall stability of PA while keeping void structure and permeability within specification limits[13]. Similarly, a study by Nazmey et al. showed that EVA polymer with cellulose fiber improves the abrasion resistance of the PA mixtures, as it decreased the cantabro abrasion loss by 25.1% compared to the control mixtures[17]. Marshall stability values increased for the hybrid blend. The PET modified samples showed a load carrying capacity of 7.0 kN, and SUFM realized up to 6.1 kN, while the hybrid configuration reached 8.2 kN. The flow decreased from 2.9 mm for PET and 3.1 mm for SUFM to 2.5 mm for the hybrid form, indicating that the structure's stiffness increased while its flexibility remained relatively constant. This modification occurs mainly through two mechanisms. First, at typical hot-mix asphalt temperatures, thermoplastic PET particles soften and partially melt, forming a thin polymer film that coats aggregate surfaces and enhances the aggregate–binder interfacial bond [45]. Second, finer PET particles partially disperse into the binder, acting as an active filler that increases binder stiffness and viscosity, particularly at elevated temperatures. The hydraulic conductivity decreased from 0.2291 cm/s (PET) and 0.3299 cm/s (SUFM) to 0.2095 cm/s (hybrid), with all blends exceeding the ASTM minimum value of 100 m/day (0.11574 cm/sec). Previous studies on PET-modified PA reported that enhanced mastic stiffness and improved aggregate coating can partially obstruct smaller interconnected pores, leading to a reduction in permeability of about 28.37% while remaining within acceptable drainage limits [14]. In the present hybrid system, the combined presence of PET particles and SUFM fibers can interact with binder films by physically retaining the binder within the skeleton and forming fiber–mastic bridges, which increases mixture cohesion and alters pore geometry by increasing flow-path tortuosity[46], explaining the observed permeability decrease. The dry ITS using the hybrid combination reached 760.7 kPa, which is higher than that achieved for PET (750.9 kPa) and SUFM (758.5 kPa), indicating an increase in tensile resistance due to better aggregate interlocking and improved binder/aggregate adhesion. Similarly, the wet ITS for the hybrid was 638.1 kPa rather than the dry ITS of PET and SUFM, which were 629 kPa and 621.6 kPa, respectively, thus validating better moisture resistance. This improvement shows that the hybrid mixture exhibits a balanced set of mechanical properties derived from both components. All combinations had TSR values above 80%, i.e., PET (83.8%), SUFM (82%), and Hybrid (83.9%). Zhu et al. observed that the TSR value increased as the mask fiber content increased to 1.0%, indicating improved resistance to moisture damage in the mixes. The enhanced moisture damage resistance was due to mask fibres forming a protective layer around aggregates and the asphalt binder, thereby reducing the water absorption capacity of the mineral aggregates. In addition, mask fibres increased the adhesion and crack resistance of the asphalt mixture, thereby preventing moisture from damaging it [47]. The slightly lower TSR observed in the SUFM-modified mixture can be explained by the characteristics of mask fibers. The nonwoven micro-fibrous structure of mask waste can introduce fine interconnected voids, and if the binder coating is insufficient, these voids may facilitate water penetration and initiate mild stripping, leading to a marginal decrease in TSR[48]. Both modifiers' adhesion and cohesion mechanisms improved the hybrid mixture's TSR. Dry added PET softens during mixing and forms a thin polymer coating around aggregate particles. This increases binder viscosity, film thickness, making it more water-resistant[49]. Fibers reinforce supplementally by absorbing light fractions from the binder and stabilize and thicken the mastication. The fibers also form a three-dimensional reinforcing network in the mixture, strengthening the binder layer and keeping aggregate particles mechanically interlocked [2], [50]. The hybrid mixture exhibited the highest TSR, confirming improved resistance to moisture-induced damage and effective strength retention after conditioning. Draindown results also showed reduced binder loss in all fiber-containing mixtures, as fibers absorbed and retained part of the binder during mixing and compaction. This behavior is consistent with previous studies reporting that cellulose, polymeric, and synthetic fibers significantly reduce binder draindown by increasing mastic viscosity and surface retention[51] [52]. From a practical perspective, the observed improvements in stability and abrasion resistance indicate that the hybrid PET–SUFM PA mixture may provide enhanced resistance to raveling and surface degradation under low to moderate traffic conditions. Although permeability decreased slightly, it remained within the acceptable range for PA, suggesting that drainage performance would still be maintained in the field. These characteristics make the proposed mixture suitable for applications such as low-volume roads, parking areas, and urban stormwater management layers. However, this study was limited to laboratory-scale testing and did not investigate long-term aging, temperature sensitivity, or field performance.

7. Sustainability Consideration

Broader reviews indicate that recycling plastic waste into asphalt mixtures can reduce costs and greenhouse gas (GHG) emissions by repurposing non-biodegradable materials and avoiding landfill leachate generation and incineration-related emissions[53].

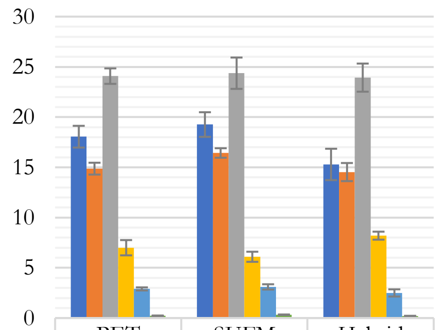
Table 8. OBC Results

Asphalt Binder Content %	Air Void %	Draindown %	Abrasion loss Aged %	Abrasion loss Un-Aged %	Permeability %
4	23.8	0.09	56.2	48.5	365
4.5	21.8	0.13	43.8	37.2	323
5	19.3	0.2	29.2	22.1	308
5.3	18.9	0.36	27.9	20.2	304
5.5	18.5	0.52	26.6	18.3	302.
6	18.1	0.88	23.2	13.9	233

In pavement applications, PET incorporation improves durability, extending service life and deferring emissions associated with rehabilitation and reconstruction activities [54]. A study by Abernathy et al. found that plastic-modified asphalt pavements utilizing PET and HDPE through the dry method enhanced pavement longevity by 14–65%, depending on structural design and traffic conditions [55]. Additionally, Capuano et al. emphasized that the integration of recovered plastics into asphalt advanced circular economy objectives by redirecting substantial amounts of post-consumer plastics from landfills [56]. Life cycle assessment studies consistently demonstrate that plastic-modified asphalt pavements can reduce GHG emissions, raw material consumption, and maintenance frequency, particularly when locally sourced waste plastics are used, and transportation and preprocessing impacts are minimized[57]. In this context, previous research reported that combining 40% reclaimed asphalt pavement (RAP) with 2% PET can reduce life cycle costs by up to 31.8% while decreasing GHG emissions by approximately 37.6%[58]. Although microplastic release is a concern for long fibers, most particles remain encapsulated within the mastic. The improved raveling resistance observed in this study further suggests a lower likelihood of surface shedding during service. Nevertheless, future research should quantitatively assess wear-particle emissions in porous asphalt systems to better understand long-term environmental implications. Moreover, the incorporation of polymers inside the asphalt matrix can reduce microplastic emissions when designs are optimized [57]. Bualuang et al. assessed airborne microplastic contaminant particles in dry-mixed plastic-modified asphalt composed of PE, PP, polystyrene (PS), and PET, reporting no detectable microplastic contamination exceeding Fourier Transform Infrared Spectroscopy (FTIR) similarity thresholds throughout the mixing, laying, or in-service simulation phases[59]. Overall, the use of PET–SUFM hybrid additives offers clear sustainability benefits with manageable environmental risks, supporting the relevance of this work within the broader context of sustainable pavement design.

8. Conclusion and Future Recommendations

This study assessed the efficacy of hybrid porous asphalt mixtures incorporating recycled PET and single-use face mask (SUFM) fibers, as opposed to mixtures modified with each component separately. To evaluate the synergistic effect of the polymer combination, enhancements were measured against the least effective mixture (SUFM) for each characteristic. The Marshall stability of the hybrid mixture combination improved by approximately 34%, which is higher than that of SUFM. This indicates that PET stiffness and the adhesive property of SUFM fibers collectively influenced the structure. The flow value decreased by approximately 19%; that is, internal stability improved, and deformation became less likely. The air-void content decreased by about 20%, and the permeability decreased by approximately 36%, so it drains well while retaining its strength. The hybrid mixture enhanced the durability of the samples by reducing abrasion loss by approximately 11% for unaged samples and 2% for aged samples. The ITS results showed improvements of 0.3% in the dry condition and 2.7% in the wet condition, with an increase in TSR of 2.3%. This means that the material is more resistant to moisture and more stable, cohesive, and durable while still allowing enough air to pass through.



	PET	SUFM	Hybrid
Air Voids %	18.05	19.26	15.29
Cantabro un-aged %	14.87	16.43	14.53
Cantabro aged %	24.08	24.37	23.93
Stability kN	7.0	6.1	8.2
Flow mm	2.9	3.1	2.5
Permeability cm/ sec	0.2291	0.3299	0.2095

Figure 6. Laboratory test results for PA specimens

Future research should expand this study to field-scale evaluations of the long-term performance of hybrid PA mixtures under real climate and traffic conditions. Furthermore, doing a life-cycle cost evaluation is crucial to measure the economic and environmental advantages of utilizing recovered PET and SUFM waste in pavement construction. Subsequent inquiries should concentrate on fume emissions and potential exposure hazards throughout production and installation operations to enhance comprehension of their effects on the environment and workers in the asphalt sector.

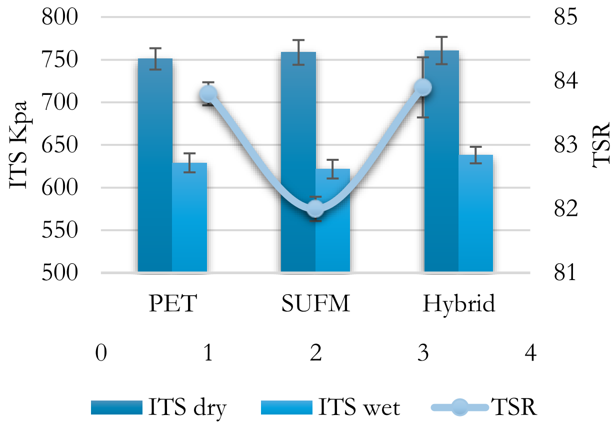


Figure 7. Moisture Susceptibility Test result

9. Data availability

Data will be made available on request.

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