Engineering and Technology Journal 43 (11) (2025) 879-890

Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Plastic roads: evaluating the role of waste PET in hot mix asphalt – a review

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HIGHLIGHTS

- PET-modified asphalt enhances rutting resistance, stability, and fatigue life at a dosage of 4–6%
- Wet and dry mixing techniques have a significant influence on mechanical performance and moisture resistance
- A Life Cycle Assessment (LCA) reveals a potential reduction of up to 47.4% in Global Warming Potential using PET
- Fine particle PET enhances dispersion and interfacial bonding while reducing permanent deformation
- Economic feasibility improves when PET replaces bitumen, resulting in lower material and maintenance costs

Keywords:
PET waste
Hot mix asphalt
Rutting resistance
Sustainability
Plastic recycling
Road construction

ABSTRACT

Plastic pollution has become a global environmental crisis, with millions of tons of polyethylene terephthalate (PET) waste accumulating in landfills and ecosystems. One promising solution is the integration of waste PET into hot-mix asphalt (HMA), offering the dual benefits of sustainable waste management and enhanced pavement performance. This review critically examines the mechanical, environmental, and economic impacts of PET-modified asphalt. Studies indicate that PET improves rutting resistance, durability, and flexibility, with optimal performance observed at moderate PET dosages (4– 6%). However, excessive PET content (> 6%) can lead to stiffening and premature cracking, while very high PET concentrations (> 20%) may reduce load-bearing capacity. Beyond mechanical benefits, the incorporation of PET significantly reduces carbon emissions and energy consumption, with Life Cycle Assessment (LCA) studies reporting a 47.4% reduction in Global Warming Potential (GWP). Economic analyses indicate that PET-modified asphalt can reduce bitumen consumption, resulting in potential cost savings; however, processing and collection costs remain significant barriers to the large-scale adoption of this technology. Despite promising laboratory results, long-term field trials remain limited, and concerns about phase separation, regulatory approval, and large-scale feasibility hinder widespread implementation. Future research should focus on long-term field evaluations, optimization of PET processing methods, and the development of standardized industry guidelines. Additionally, hybrid polymer modifications and multi-polymer blends should be explored to enhance performance and sustainability. With continued innovation and policy support, PET-modified asphalt presents a viable pathway toward greener and more durable road infrastructure.

1. Introduction

The plastic waste problem remains ever-present in our current day and age. Polyethylene terephthalate (PET) a plastic often used in bottles and packaging is one of the worst offenders in this regard. Due to its resistant and non-biodegradable properties, it tends to be stored in landfills or natural environments, especially in developing countries with incomplete recycling infrastructure [1-3]. Put bluntly, in many low- and middle-income countries, the collection truck simply never shows up. Municipal waste budgets average well below 0.5% of GDP, leaving whole neighborhoods unserved and recovery equipment decades out of date [4-9]. In the resulting vacuum, an army of informal waste pickers salvages what value it can, but the PET they reclaim is heterogeneous and hard to turn into high-grade recyclate [5]. Policy levers that work elsewhere—such as extended producer responsibility and landfill levies—are either embryonic or enforced in name only, giving brand owners little incentive to close the loop [7]. Meanwhile, plastic generation continues to rise faster than any formal recovery capacity can be established [6,8]. These intertwined constraints explain why researchers look beyond orthodox recycling and toward downstream valorisation routes—such as blending shredded PET directly into asphalt—that can function even when the “upstream” system is weak. Traditional methods of disposal, such as incineration, present further environmental and public health concerns as they

http://doi.org/10.30684/etj.2025.159983.1956
Received 10 May 2025; Received in revised form 14 June 2025; Accepted 04 July 2025; Available online 01 August 2025
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generate hazardous gases and waste when burned, and release toxins into the atmosphere and groundwater [10,11]. Then there are the challenges to the road construction industry.

Asphalt concrete (AC) or Hot Mix Asphalt (HMA), the main composite material used in flexible pavement systems, is vulnerable to deformation, cracking, and moisture damage [12-14]. These issues lead to shortened pavement life and increased maintenance budgets. Researchers have thus resorted to recycled materials, including PET, to enhance the performance of asphalt pavements and address the issues of plastic waste pollution [15]. Adding PET to the asphalt layer has the dual advantage of reducing waste in the environment and enhancing pavement performance. From experimental studies, it has been inferred that PET is capable of enhancing the stiffness and tensile strength of asphalt, thereby improving its resistance to rutting and fatigue, and reducing the demand for asphalt [16-19]. Nevertheless, such benefits are extremely dependent on PET dose, particle size, and way of incorporation. An excess of PET may lead to brittleness and poor compaction, which could affect the quality of the pavement [20]. There are also significant environmental benefits to consider. Life Cycle Assessment (LCA) analysis data have shown that incorporating PET into bitumen can reduce energy consumption and CO_2 emissions. Economically, there may be savings due to lower binder consumption; however, the availability of PET will influence this, as well as the use of a supply chain for PET collection and the degree of process control required. Despite promising results, the applicability of PET for use as asphalt is still considered experimental. Most of the evidence supporting the technology is based on laboratory-scale studies, rather than long-term field experiences. A lack of standardized protocols, inconsistent processing, and inadequate regulatory guidance hinders wider adoption.

This review summarizes the current body of research on PET-modified asphalt, with particular focus on mechanical performance, environmental impact, and economic feasibility. It also highlights key limitations and suggests pathways for future research and field implementation.

2. Methods of incorporating PET into hot mix asphalt

The method used to incorporate polyethylene terephthalate (PET) into asphalt mixtures plays a critical role in determining both the performance and uniformity of the final mix. Two primary approaches—wet mixing and dry mixing—are most commonly discussed in the literature, each with its own trade-offs and implementation challenges [21]. In the wet process, the PET is added to the hot bitumen and then added to the aggregates. As a result, the polymer can be mixed more effectively with the binder, which tends to provide greater elasticity, heat resistance, and resistance to moisture damage [22]. However, these gains come with some nuances: PET usually needs to be ground into fine particles and occasionally pretreated. A common requirement is the use of high-shear mixing at elevated temperatures to obtain homogeneity [23]. The operation is technically challenging, and inhomogeneous dispersion may lead to phase separation or non-uniform mechanical properties under load. In contrast, the dry mixing method involves introducing the PET into the hot aggregates before applying the binder. This technique is simpler to perform and can be easily integrated into the existing asphalt production apparatus without modification, thereby making it easier to adopt for field trials [24]. There are still limitations to it.

As PET does not chemically interact with the binder during mixing, the risk of non-uniform distribution and poor interfacial adhesion is high, especially if particle size and distribution are not strictly controlled. The mechanical behavior of dry-mixed mixtures is highly sensitive to these factors. To address the limitations of both methods, some researchers have proposed hybrid techniques that incorporate elements of each. For example, PET can be partially melted or blended with a fraction of the binder before being introduced into the full mix. These hybrid strategies aim to combine the performance benefits of wet mixing with the logistical simplicity of dry methods [25,26]. Ultimately, selecting an incorporation method involves balancing processing capacity, target performance goals, and cost. While wet mixing may deliver superior mechanical properties, its complexity limits its scalability, especially in resource-constrained settings. Dry mixing, though more accessible, demands careful material control to ensure consistent results in real-world applications.

2.1 Comparative assessment of wet and dry mixing routes

Pavement engineers often treat the “wet” and “dry” routes as interchangeable, yet the two approaches influence binder chemistry, plant logistics, and long-term performance in very different ways [27-29]. Five recent studies that evaluated both techniques head-to-head are distilled in Table 1, and their collective message is crystal clear: wet blending delivers cleaner binder dispersion and better moisture tolerance; dry (or “modified-dry”) staging punches higher on strength and is cheaper to run—but only if PET particle size is kept tight. Choudhary et al. [30], prepared identical dense-graded mixes with 2.5–7.5% PET using both routes and found that the modified-dry protocol increased Marshall Stability by 28%, while wet blending produced a smaller 19% gain; however, it pushed the TSR up by a full ten points, indicating stronger aggregate–binder adhesion. White and Hall’s TRB trial showed that the two routes yield statistically similar stiffness and rutting resistance; however, wet batches exhibited wider result scatter and required an additional hour of high-shear conditioning [31].

A large spanish study focused on moisture damage, finding that dry mixes performed better in terms of fatigue and flow, while wet mixes reduced post-conditioning strength loss by half at the same 6% PET dose [32]. Binder-level rheology tells the same tale—Chen et al. [33], doubled the complex modulus $|G^*|$ with an 8 % PET/PE wet blend, though only after raising mixing temperature to 185 °C and holding for 60 min. Finally, Xu et al.’s wide-angle review points out that wet routes routinely consume ≈15 % more plant energy per tonne but virtually eliminate binder drain-down during storage [34].

Formal specifications for recycled-plastic asphalt are still sparse; however, a few jurisdictions have codified procedures that practitioners can rely on. India was first: IRC SP:98-2013 sets out gradation windows, PET size limits (≤ 4 mm), and a maximum

8% plastic-by-bitumen dose for both wet and modified-dry routes [35]. The Indian Ministry of Road Transport & Highways later made the addition of plastic mandatory for national highways through Circular RW/NH-33044/2015, effectively mainstreaming the practice [36]. Australia's Austroads Technical Guide TG-TP21 provides laboratory and plant-scale protocols for PET and PE modifiers, including wet-blend storage stability thresholds and limits for reclaimed asphalt [37]. In North America, the FHWA TechBrief FHWA-HIF-21-042 outlines best practices for project pilots, recommending high-shear blending at 170 ± 5 °C and staged dry dosing for plants lacking a polymer mill [38]. PIARC's global survey on "Innovative Plastics in Roads" collates these national rules, emphasising common denominators: sub-4 mm particle size, PET dosages <10 % binder mass, and mandatory moisture-susceptibility checks before field rollout [39]. While these documents differ in detail, they provide a starting point that could be harmonized into a wider ISO-style standard—an essential step for transitioning PET asphalt from pilot projects into routine procurement.

Table 1: Key laboratory findings from studies that tested both routes under identical conditions

Performance metric	Wet mixing	Dry / Modified-dry mixing	Ref.
Marshall Stability	+19 % at 6 % PET	+28 % at 6 % PET	[30]
Tensile-Strength Ratio (TSR)	Increased to 10 points (to 92 %)	Increased to 3–4 points	[30]
Complex modulus |G*| (DSR)	2.0 × control at 8 % PET/PE; requires 185 °C & 1 h shear	1.4 × control at 8 % PET; standard drum temps	[33]
Field compaction & retrofit	Viscous binder; needs high-shear mill + heated storage	No plant change, but particle size must be < 4 mm	[31]
Moisture damage (post-conditioning strength)	Strength loss cut by ~50 % vs. control	Minor TSR gain; no drain-down control	[32]
Plant energy demand	≈ 15 % higher than conventional HMA	≈ 3 % higher than conventional HMA	[34]

3. Mechanical performance of pet-modified asphalt

The mechanical performance of asphalt is crucial in affecting its service life and structural integrity. Asphalt mixtures with PET are likely to meet the requirements of resistance to deformation, cracking, and fatigue when optimal to moderate PET contents are used as the modifier. Researchers have studied critical parameters (e.g., Marshall Stability, Indirect Tensile Strength (ITS), Resilient Modulus (MR), and creep resistance) to investigate the effect of PET on performance. The big picture is positive, but, as is always the case, there are trade-offs when the dosages are too high.

3.1 Effect of PET on marshall stability and flow behaviour

Marshall Stability and Flow are essential indicators of an asphalt mixture's mechanical performance. Stability measures the maximum load a specimen can withstand before failure, while Flow reflects the deformation at that point. PET modification has been shown to significantly influence both parameters, enhancing performance at optimal dosages but leading to degradation when overused. Agha et al. [22], reported a 27.3% increase in Stability at 4% PET by binder weight, attributing the improvement to enhanced cohesion. However, Stability declined beyond 6%, likely due to increased brittleness and rigidity. Similarly, Choudhary et al. [40], observed a 20% increase in Stability at 8% PET, followed by a decrease at higher dosages. Mahdi et al. [23], confirmed that the optimal PET range for stone matrix asphalt lies between 4% and 6%, with excessive content reducing performance due to internal stresses and binder dilution. The method of PET incorporation is also critical. Kumar et al. [41], found that the modified dry (M-Dry) process, which gradually introduces PET, achieved higher Stability, particularly at 5% due to better dispersion and improved coating of aggregates. Osorto et al. [42], supported these findings, observing better interlocking and load distribution up to 6% PET. However, performance declined beyond this range due to polymer agglomeration and reduced compaction. As shown in Figure 1, mixes with 5% PET using the M-Dry process outperform both the control and standard dry-mixed variants. This pattern holds for both coarse and fine PET, emphasizing the importance of particle size and mixing method. Flow behavior is more sensitive to PET content. Additions between 2–4% typically reduce Flow, reflecting increased stiffness and resistance to deformation [21,43]. However, at PET levels above 6%, the Flow increases sharply. Al-Hadidy et al. [16], reported significant Flow increases beyond this point, compromising structural reliability. Ali et al. [44], found that Flow remained within ASTM D6927 limits up to 14% PET but exceeded the 4 mm threshold at higher contents. Earlier studies by Baghaee et al. [45], and Ziari et al. [46], similarly reported that high PET contents soften the matrix, reduce internal friction, and increase susceptibility to rutting. Ziari et al. [46], also noted greater variability in Flow and compaction quality above 8%. As illustrated in Figure 2, the Flow inflection point generally falls between 6% and 10% PET. Beyond this range, deformation exceeds acceptable limits, particularly in dense-graded mixtures. These findings confirm that PET can offer mechanical benefits only when dosage and mixing conditions are carefully controlled.

3.2 Influence of PET on indirect tensile strength (ITS) and fatigue resistance

The Indirect Tensile Strength (ITS) test is commonly used to evaluate an asphalt mixture's ability to resist cracking, particularly under stresses induced by temperature fluctuations or traffic loads. Alongside this, fatigue resistance provides insight into how the material behaves under repeated loading, an essential indicator of its long-term durability. When added in moderate amounts, PET has shown the potential to improve both ITS and fatigue life. Osorto et al. [42], also highlighted that the size and distribution of PET particles are responsible for such improvements. Their results show that fine and uniformly distributed PET, especially when added in a dry-mixing process, improves the energy absorption amounts in the asphalt under tension. On the contrary, poor dispersion or clumping of PET generates stress concentration regions that may weaken and accelerate the development of early cracks in the pavement. This implies that PET's role in determining tensile and fatigue properties is not solely controlled by dosage alone, but is also significantly influenced by processing and mixing conditions. Baghaee et al. [45], further reinforced this conclusion through fatigue life testing.

Their results indicated that mixtures containing 4–6% PET performed best, with improved stress distribution and internal cohesion. These enhancements were linked to the softening behavior of PET at elevated mixing temperatures, which allows it to absorb more strain without cracking. However, when PET content exceeded this optimal range, the mixture became overly stiff, leading to earlier fatigue failure due to reduced flexibility. Similarly, Sojobi et al. [25], reported a 12.5% increase in ITS at a 6% PET dosage (by binder weight), demonstrating a consistent improvement in resistance to tensile cracking. These findings collectively underscore the importance of precise control over PET content, particle characteristics, and mixing conditions to realize performance gains without introducing new weaknesses. Their findings, as reflected in Figure 3, align with broader trends that show peak ITS and fatigue life values within the 4–6% PET range, followed by a decline at higher dosages. Similarly, Rahman et al. [47], observed that the addition of only 0.7% PET fibers extended fatigue life by over 41%. This demonstrates that even minimal PET incorporation—when properly processed—can delay fatigue damage and increase mixture resilience under repeated loading [48]. However, this performance gain has limitations. Hake et al. [49], reported that when PET content exceeded 8%, ITS values began to decline due to increased stiffness and reduced ductility. Mahdi et al. [23], made similar observations, noting that while PET increased tensile strength at low concentrations, higher levels led to brittleness and earlier failure under tensile stress.

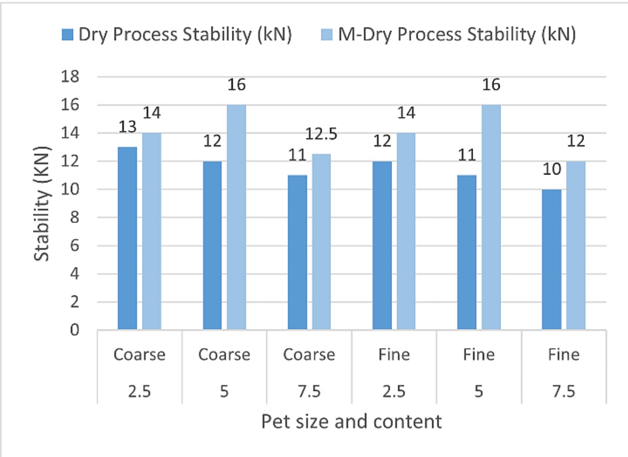

Figure 1: Effect of PET size and mixing method on marshall stability of asphalt mixtures. Adapted from [20]

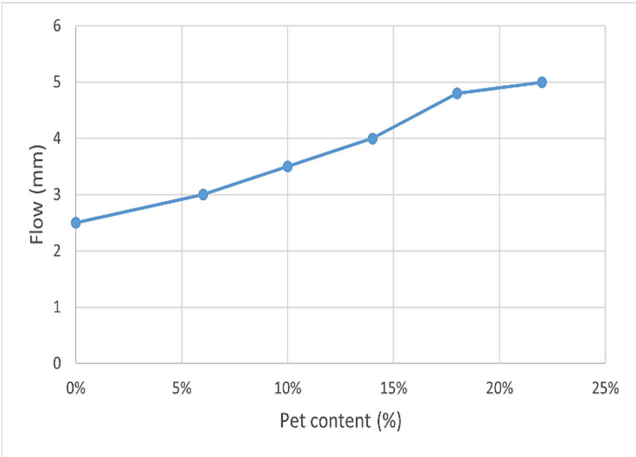

Figure 2: Marshall Flow values for PET-modified asphalt at different PET contents. Adapted from [45]

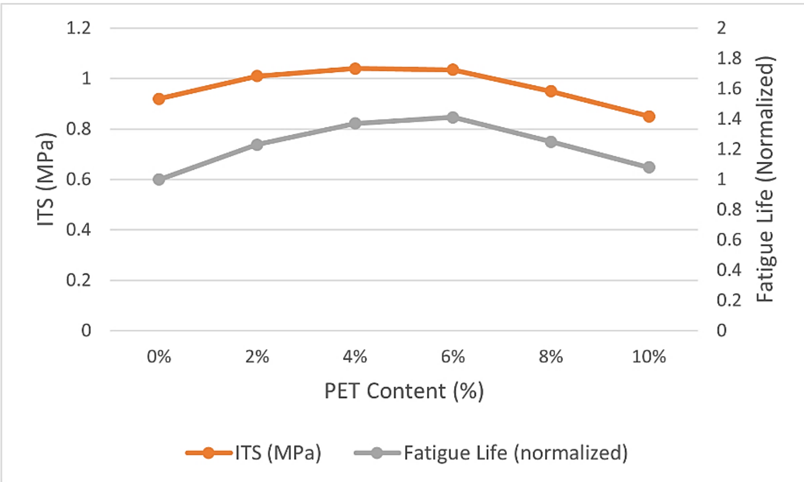

Figure 3: Effect of PET content on Indirect Tensile Strength (ITS) and normalized fatigue life. Data derived from [20,22,43,47]

3.3 Effect of PET on resilient modulus and creep resistance

The Resilient Modulus (MR) characterizes the capacity of an asphalt mixture to recover its shape under repeated loading, and the creep resistance is used to characterize the ability to resist permanent deformation due to long-term sustained loading. Together, these two parameters strongly suggest how asphalt performs under heavy and repeated traffic loading, particularly in hot climates, where rutting has been a persistent problem. The efficiency of PET in improving both properties has been consistently showing promise of such trends. Osorto et al. [42], found that PET-modified asphalt mixtures with 4–6% PET increased the resilient modulus values and decreased deformation, especially under repeat loading conditions. These enhancements were attributed to the higher binder-particle interaction and the reduced viscoelastic response. Choudhary et al. [40], supported these results in their Dynamic Creep tests conducted at 40 °C, reporting a 50% reduction in permanent deformation at 6% PET content compared to unmodified mixtures. Further evidence from Kalantar et al. [21], confirmed that PET-enhanced mixes exhibited higher MR values and lower cumulative strain under cyclic loads. Agha et al. [22], also observed improved performance during wheel tracking tests, noting lower creep rates when PET was added at a binder weight of 4–6%. These findings suggest that PET reinforcement can enhance stiffness and reduce rutting susceptibility when used within a moderate dosage range [50,51]. However, performance gains taper off at higher PET contents. Rahman et al. [52], reported that beyond 20% PET, stiffness values began to decline. The deterioration was attributed to a disrupted aggregate skeleton and increased plasticity in the mix, resulting in reduced load transfer. Osorto et al. [42], echoed this observation, indicating that excessive PET content resulted in poorly compacted zones and inconsistent structural responses. These results reinforce a recurring conclusion in PET-modified asphalt research: performance benefits are realized when PET is used in moderate amounts, typically between 4% and 6%. In the context of resilient modulus and creep resistance, PET behaves as an effective reinforcing agent. But if overused, the very properties that make PET attractive—its flexibility and plasticity—can become liabilities under traffic loading.

4. Rutting and moisture susceptibility of PET-modified asphalt

In real-world road performance, two of the most common and costly failure modes are rutting and moisture damage. Rutting compromises the surface profile due to permanent deformation under repeated traffic loads. At the same time, moisture susceptibility leads to stripping, where water disrupts the bond between binder and aggregate, accelerating pavement deterioration. Several studies have assessed the performance of PET-modified asphalt under these stressors. While the results are generally positive, they are also highly dependent on the PET dosage, particle size, and mixing technique.

4.1 Rutting resistance of PET-modified asphalt

Rutting is the most prevalent and recognizable form of pavement distress, characterized by permanent deformation caused by the repeated loads of passing traffic, particularly in hot weather. It is typically determined through laboratory experimentation, including the Dynamic Creep test and the Hamburg Wheel Tracking (HWT) test. Several works have confirmed that use of PET in asphalt mixes has good potential for improving the rutting resistance, however, its effect is highly influenced by the PET content and size Rahman et al. [47], studied PET levels between 0.25 and 1% and reported that the inclusion of 1% PET decreased the rut depth by 42% compared with the control mix. Their analysis indicated that smaller PET particles (10 × 2.5 mm) offered better rutting resistance due to improved dispersion and stronger bonding within the asphalt matrix. Osorto et al. [42], also reported that finer PET particles enhanced resistance to permanent deformation, further confirming the role of particle size in performance.

In Dynamic Creep testing at 40 °C, Choudhary et al. [40], observed a 50% reduction in permanent deformation at 6% PET content. Similarly, Rahman et al. [47], reported improved rutting resistance in stone matrix asphalt containing 4–6% PET, confirmed through both laboratory-scale HWT and Marshall rutting tests. However, the relationship between PET content and rutting resistance is not strictly linear. Beyond the optimal PET range—typically around 6–8%—performance may decline. Overuse of PET can lead to overly stiff mixtures, which, although resistant to rutting, may become prone to thermal cracking or fatigue failure under low temperatures or repeated loading conditions [23,25,52]. Moreover, PET particle size and shape are critical. Larger, irregular particles often result in poor dispersion and localized stress concentrations, undermining structural integrity. As illustrated in Figure 4, asphalt mixes incorporating smaller PET particles (10 × 2.5 mm) consistently demonstrate superior rutting resistance compared to those with coarser PET particles, highlighting the importance of surface contact and uniform distribution within the mix. In conclusion, PET can substantially enhance rutting resistance when used within optimal parameters. Best results are achieved with PET contents between 4–6%, in fine particle form, and when appropriate mixing strategies are applied [53, 54]. As with other modifiers, success depends on achieving a balance between the stiffness of the mixture and the flexibility required to absorb traffic-induced stresses without initiating cracks.

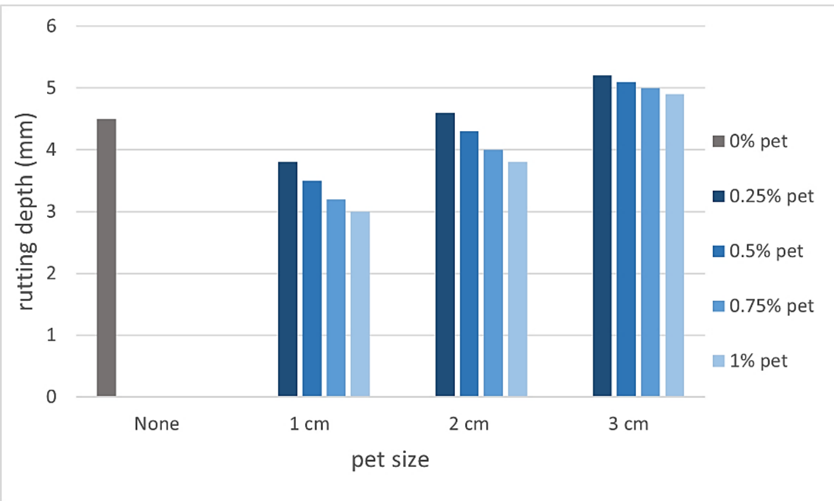

Figure 4: Effect of PET size and content on rutting depth in HMA, Adapted from [47]

4.2 Moisture susceptibility of PET-modified asphalt

Moisture damage remains one of the most persistent challenges in asphalt pavement performance. Water infiltration weakens the adhesive bond between bitumen and aggregate, leading to stripping, ravelling, and early structural failure. The Tensile Strength Ratio (TSR)—the ratio between the strength of conditioned (wet) and unconditioned (dry) samples—is commonly used to evaluate moisture susceptibility, with higher values indicating better resistance. Rahman et al. [47], demonstrated that the TSR of asphalt mixtures increased from 78% to 92% with the addition of 4% PET used as a fine aggregate replacement. This improvement was attributed to PET's hydrophobic nature, which limits water intrusion and helps maintain binder-aggregate adhesion. Similarly, Mahdi et al. [23], reported TSR values exceeding 95% at 6% PET content, reinforcing the role of PET in mitigating moisture-induced damage. Further support comes from Kalantar et al. [21], who found that PET-modified mixtures produced using the wet mixing method exhibited significantly higher TSR values than those mixed using dry techniques. This was linked to improved polymer dispersion and more uniform binder interaction with the PET surface.

At the microstructural level, Vasudevan et al. [55], used surface free energy and MD simulation to assess the interfacial bonding behavior induced in the presence of moisture conditions, they found that, adhesion energies were significantly greater for PET-modified binder–aggregate systems. More importantly, the addition of PET changed the predominant failure mode from adhesive failure to cohesive failure, implying that enhanced interfacial adhesion and structural continuity were achieved. Osorto et al. [42], confirmed these findings and added that PET enhances adhesion and phase stability, particularly in high-humidity or moist conditions. At the same time, due to the modification by PET, the phase separation during blending is restrained in PET-modified asphalt, thereby improving the durability of the mixture. However, these benefits depend on proper dosage and dispersion. Choudhary et al. [40], cautioned that excessive PET—above 8%—can lead to poor integration within the asphalt matrix. At high concentrations, PET may fail to blend uniformly, resulting in phase separation, uneven aggregate coating, and reduced moisture resistance.

4.3 Field performance evidence

Although laboratory findings have driven most of the early enthusiasm for PET-modified asphalt, a handful of full-scale road trials now demonstrate that the promised gains are sustained under real traffic and weather conditions. In India, Biswas et al. [56], compared a five-year-old arterial in Pune surfaced with a 6% PET dry-mix to an adjacent control lane. The rut depth remained below 3 mm, and the pavement-condition index was four percentage points higher than that of the conventional section, despite identical axle loading. Across the UK, the Cumbria "Live Lab" programme has monitored nine MacRebur™ sites laid in 2019–2020; after two winters, the cores still show elastic-modulus gains of 8–12 % with no abnormal cracking or skid loss, and wheel-tracking on recovered slabs confirms the predicted rut resistance [57]. Australia's Austroads test track near Brisbane offers a heavily instrumented counterpoint: a 250 m lane containing 6 % wet-blended PET has endured roughly six million equivalent single-axle loads in eighteen months; resilient modulus is nine per cent above the control SMA, texture depth is unchanged, and no binder drain-down has been detected in 50 °C cores [58].

In North America, Virginia DOT's Phase-I field study on I-64 and I-95 compared two plant-produced dry-mix overlays with the agency's standard D and E surfaces; after two freeze–thaw winters, the recycled-plastic sections match the SBS-modified reference for falling-weight deflection, roughness, and surface distress, while lab tests on plant cores show equal or better rutting and fatigue indices [59]. Even porous asphalt has begun to see service use. Hao et al. [60], tracked tropical trial patches in Singapore for thirty months. They found that a 5% PET addition preserved permeability and Cantabro durability while improving moisture and rut resistance relative to blank controls. Taken together, these geographically diverse trials—ranging from monsoon-soaked arterials to accelerated loading facilities—show that when PET content is kept in the 4–6 % "sweet spot" and particle size is well controlled, the laboratory advantages of higher stiffness, lower rut depth, and better moisture tolerance translate into durable, serviceable pavements on the ground. For quick comparison, Table 2 distils headline findings from recent laboratory and field investigations published between 2015 and 2025, showing how PET content, incorporation route, and mix type influence strength, rutting, moisture resistance, and any reported trade-offs.

Table 2: Mechanical and durability outcomes reported for PET-modified asphalt mixtures in recent studies (2015 – 2025)

Mix type / PET route	PET content (% by binder)	Key performance	Noted trade-off	Ref.
Dense-graded / wet	4	increase 27% Marshall Stability; increase 9% TSR	Harder field compaction	[22]
BC/modified-dry	6	reduced 45% rut depth (HWT)	Slight drain-down	[40]
SMA/wet	5	increased 18% ITS; increased 50% fatigue life	Mixing temp +15 °C	[23]
DBM/dry	8	increased 11% Resilient Modulus	Flow > ASTM limit	[47]
Field (India)/dry	6	Rut depth < 3 mm after 5 yrs	—	[13]
Field (UK)/wet & modified-dry	4-6	Modulus +10%; no crack increase (24 mo)	—	[31]

5. Environmental and economic considerations of PET-modified asphalt

The integration of recycled PET into asphalt mixtures offers dual advantages: it addresses growing concerns over plastic waste and contributes to sustainable pavement solutions. In Iraq, formal PET recycling is still in its infancy; however, scattered academic and pilot-scale efforts demonstrate that local processing is technically feasible. Aziz et al. [61], surveyed Erbil's waste stream. They found that plastics already account for 27% of municipal solid waste, but only a fraction is formally recovered because the city lacks dedicated sorting lines. Follow-up work by the same group quantified the economic potential of a city-scale shredding and baling scheme, estimating a net revenue of 175 USD t^{-1} for clean PET flakes if collection were mechanised [62]. Baghdad's situation is similar: Mohsin and Mustafa [63], reported that no large-scale recycling plant operates within the capital, forcing most PET waste into open dumps despite a projected 30% waste growth.

Karbala's municipal audit during the Arba'een pilgrimage showed only a ~5% recovery, all handled by informal pickers, with no formal PET processing chain in place [64]. Even so, several Iraqi research groups have demonstrated small, functional recycling loops: Ashoor et al. [65], blended locally shredded PET (5–15 %) into asphalt binder with measurable rheological gains, while Al-Qaissy and Ali [66], used PET bottle strips as reinforcement in hollow concrete blocks, proving a campus-scale shredding-and-reuse model. These studies confirm that although nationwide infrastructure is lacking, credible local PET-processing nodes already exist and could supply feedstock for PET-modified asphalt projects. Beyond mechanical improvements, PET-modified asphalt supports environmental goals by reducing landfill accumulation and carbon emissions, while promoting principles of a circular economy [55-67]. Economically, the use of PET can lower production and maintenance costs by partially replacing virgin materials, making it an attractive option for both environmentally and budget-conscious infrastructure development.

5.1 Environmental benefits of PET-modified asphalt

PET waste presents a significant environmental challenge, with billions of containers still being disposed of in landfills or incinerators. As traditional recycling falls short, integrating PET into asphalt pavements has emerged as a scalable and sustainable approach to reuse. This approach reduces plastic waste and offsets the use of virgin bitumen, one of the most carbon-intensive road materials [67-69]. Shanmugapriya et al. [70], conducted a Life Cycle Assessment (LCA) that demonstrated PET replacement resulted in a 47.4% reduction in Global Warming Potential and a 38% decrease in overall environmental impacts. Similarly, Yu et al. [71], reported a 22% decrease in water consumption during asphalt production with the inclusion of PET, while SEM analysis confirmed the uniform dispersion of PET. PET-modified mixes also demonstrated reduced leachate toxicity, thereby lowering environmental risks, including soil and groundwater contamination. Arshad et al. [24], noted further benefits, including reduced binder drain down and increased durability, which extend pavement lifespan and reduce maintenance needs. Additional LCA studies by Al-Sabagh et al. [72], found that PET-modified asphalt has a lower environmental impact than conventional mixtures. As shown in Figure 5 and Table 3, PET-modified pavements achieve lower scores across major sustainability metrics.

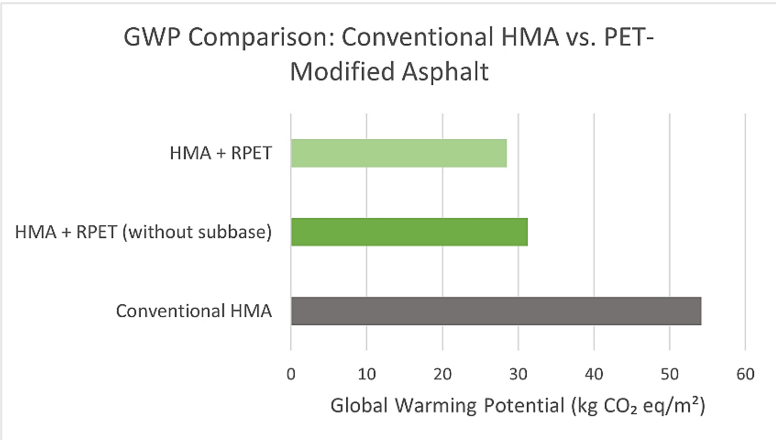

Figure 5: GWP Comparison for Conventional HMA vs. PET-Modified Asphalt Adapted from [42]

Table 3: Global warming potential (GWP) for different asphalt pavement structures. adapted from [42]

Description	Surface course (cm)	Binder Layer (cm)	Base layer (cm)	GWP (kg CO_2 eq/m²)	Life cycle phase considered
Conventional HMA pavement	15	-	22	54.165	-
HMA + RPET (without subbase)	7.5	-	20	31.283	Pavement construction
HMA + RPET	6.4	-	20	28.489	Pavement construction

Recent fieldwork also indicates that the environmental balance remains favourable once secondary effects are taken into account. Huang et al. [73], detected only 1.7 mg m^{-2} of PET particulates released from two-year-old road cores—well below EU soil-quality thresholds—and showed that a routine fog-seal can halve even that trace shedding. Boom et al. [74], reported a 12% rise in CO_2-equivalent emissions when wet mixing at 180 °C; however, the increase disappeared after the burner ducts were retrofitted with afterburners and activated carbon filters. Laboratory leachate tests by Smith and Tighe [75], found ethylene glycol monomer concentrations an order of magnitude below the WHO drinking-water limits, dropping to background levels after seven wet–dry cycles. Finally, life-cycle modelling from the EU SusPAN consortium shows that PET-asphalt can be milled back into reclaimed asphalt pavement (RAP) at up to 20% without rheological drift, provided rejuvenators are used—closing the loop and further reducing the material's footprint [76].

5.2 Economic feasibility of PET-modified asphalt

While the environmental benefits of PET-modified asphalt are well documented, its economic viability depends on dosage, process type, and local infrastructure. Kalantar et al. [21], found that wet mixing with 4–6% PET reduced material costs by 1.4–2.1%, whereas dry mixing increased costs by up to 5.5% due to higher energy demands. Arshad et al. [24], reported up to 10% cost savings over a 1,000 m road section when PET replaced 6% of the bitumen, taking into account reductions in binder and aggregate costs. Long-term benefits are also notable. Hake et al. [49], observed a 30% increase in pavement lifespan with PET, resulting in lower maintenance and rehabilitation costs. However, initial setup costs—such as for PET shredding or high-shear mixing equipment—can offset savings, especially in regions lacking organized waste systems [23,30,45]. As shown in Figure 6, PET-modified asphalt can be economically feasible, particularly in contexts where long-term savings and synergies in waste management outweigh the upfront costs.

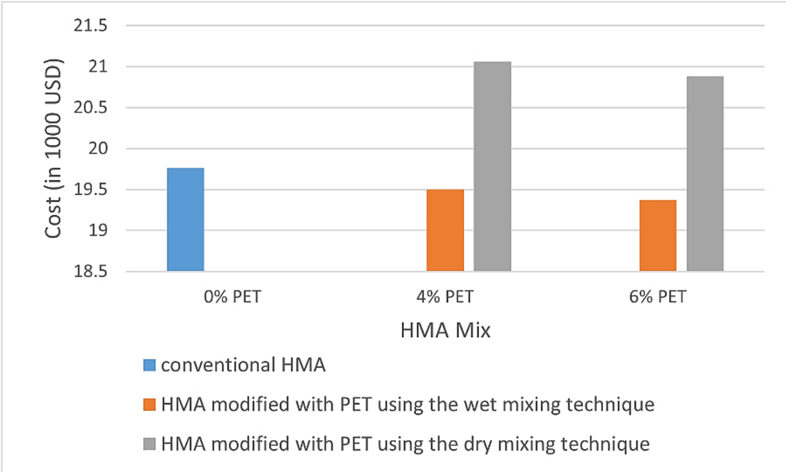

Figure 6: Cost comparison of PET-modified asphalt vs. conventional HMA. Adapted from [47]

6. Limitations, research gaps, and future directions

While PET-modified asphalt shows strong promise in improving pavement performance and sustainability, several limitations and uncertainties still hinder its widespread adoption. A key technical issue is phase separation during wet mixing, where uneven dispersion of PET can lead to structural inconsistencies in the binder [25]. Excessive PET content also leads to brittleness and premature cracking, extending beyond the optimal 4–6% range; however, stiffness may paradoxically decline again at very high contents (> 20%) [49,47]. Most studies focus on short-term lab tests (e.g., Marshall Stability, ITS), leaving long-term field durability underexplored [24]. Scalability and economic feasibility vary significantly across different regions. Wet mixing requires specialized equipment, while dry mixing risks inconsistent polymer distribution. The economic benefits depend heavily on local PET waste collection and preprocessing systems [21]. Without a reliable supply chain, cost advantages diminish. Research gaps remain in hybrid binder systems, particle size optimization, and field validation. Studies suggest that combining PET with SBS or EVA may improve performance and reduce phase separation risks [30]; however, experimental data are limited. Variations in PET processing—such as shred size and heating time—also introduce inconsistencies in results [25, 70]. Moreover, although LCAs have shown PET asphalt to be environmentally beneficial, these results are context-specific and depend on local recycling infrastructure [70]. Moving forward, the development of standardized protocols, chemical surface treatments (e.g., MPET for better compatibility) [25], and long-term performance trials across diverse climates and traffic conditions are essential. Expanding research on polymer blends and defining practical, scalable guidelines will be key to unlocking PET's full potential in sustainable road construction.

7. Conclusion and recommendations

The incorporation of polyethylene terephthalate (PET) into Hot Mix Asphalt (HMA) provides a promising strategy to address two global concerns: reducing plastic waste and improving pavement performance. Research consistently demonstrates that PET, when used in moderate amounts (typically 4–6%), can enhance mechanical properties such as rutting resistance, tensile strength, and mix stability. Life Cycle Assessments (LCAs) further support PET's environmental value, showing reductions in carbon emissions, energy use, and bitumen dependency. For example, Osorto and Casagrande [26], reported a 47.4% reduction in Global Warming Potential when PET was used to replace bitumen partially. However, PET's effectiveness is highly dosage-dependent. Exceeding the optimal content may lead to excessive stiffness, thermal cracking, or, at higher levels (> 20%), a reduction in structural strength. Furthermore, practical barriers such as phase separation during wet mixing, inconsistent dispersion in dry mixing, and the lack of standardized processing guidelines limit widespread adoption.

These issues are compounded by regional variations in PET waste availability and processing capacity, which influence the economic feasibility of large-scale implementation. To transition PET-modified asphalt from lab-scale innovation to an industry standard, several coordinated steps are necessary. Long-term field trials should be prioritized to validate durability under diverse traffic loads and climates. Optimizing PET content, particle size, and blending protocols is crucial for achieving a balance between stiffness and flexibility. Blending PET with other polymers (e.g., SBS or EVA) may further enhance performance; however, establishing standardized specifications is crucial for ensuring consistent quality control across regions. Additionally, broader economic and environmental feasibility studies should be conducted, especially in areas lacking waste management infrastructure. Finally, governments and transport agencies are encouraged to invest in pilot projects and real-world demonstrations, generating data and confidence to support mainstream adoption.

In summary, PET-modified asphalt is not a universal solution. Still, it offers a scientifically grounded, environmentally beneficial, and potentially cost-effective alternative to conventional asphalt, provided that its limitations are addressed through careful design, rigorous testing, and supportive policy development.

Author contributions

Conceptualization, **A. Ali, M. Khalid, A. Adulateef,** and **R. Mahmoud**; methodology, **M. Khalid**; project administration, **M. Khalid**; resources, **A. Adulateef**; software, **A. Adulateef**; supervision, **M. Khalid**; validation, **A. Ali, M. Khalid,** and **R. Mahmoud**; visualization, **A. Ali, A. Adulateef,** and **R. Mahmoud**; writing—original draft preparation, **A. Ali**; writing—review and editing, **A. Ali, M. Khalid, A. Adulateef,** and **R. Mahmoud**. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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