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A Critical Literature Review: Evaluate the Strength and Stability of the Waste Polyethylene Terephthalate (PET) Modified Flexible Pavement

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Abstract: The global plastic production exceeding the capability of waste management and it being projected that approximately 79 percent of all plastics produced prior to 2015 were either disposed of in a landfill or in the natural environment. Recent past the use of polyethylene terephthalate (PET) as a component of flexible pavement is very popular. Furthermore, due to their high-volume consumption of both aggregates and bituminous binder, flexible pavements have been identified as a potential large-scale application of shredded or ground PET. The purpose of this review paper is to provide a critical evaluation of current laboratory-based research focused on the use of waste PET as an additive to modify the properties of bituminous binders and asphalt mixtures. This review will cover the various types of PET (characteristics); methods of incorporating PET into asphalt binder (wet process, dry process, fibre, flake/powder); and how PET impacts the mechanical, rheological, durability and environmental performance of asphalt mixtures. Overall, these studies indicate that PET has the ability to increase the stiffness of an asphalt mixture and also increase rutting resistance. In addition, several studies indicated that under certain conditions PET could improve fatigue life and moisture resistance of asphalt mixtures. However, there appears to be significant variability in the results among the reviewed studies. The factors most responsible for the observed variability appear to be the dose rate at which PET was added (the reported optimal ranges varied greatly, i.e. from around 0.4 percent by aggregate weight to over 12 percent by binder weight), particle size distribution of the PET, method of mixing, base material composition, etc. Several studies indicated that adding PET resulted in reduced stability, increased air void content or decreased rutting resistance. Therefore, based on the information contained within the studies reviewed herein, several areas where additional research is required were identified. These include standardized testing protocols for characterizing PET particles; limited research regarding aging; lack of field performance data; lack of life cycle cost analysis data; and several unanswered microplastic issues.

Keywords: *Waste PET; Flexible Pavement; Bituminous Mixtures; Plastic Modification; Asphalt Concrete; Pavement Performance; Sustainable Infrastructure.*

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I. INTRODUCTION

Flexible pavements bear most of the country's road traffic due to the fact that their development can occur through phases, they can be easily repaired and made of local raw materials. However, the flexibility of the pavement is limited by a few recurring types of failures. Rutting occurs under long-lasting, large loads at elevated temperatures; Fatigue cracking develops from repeated strains caused by traffic load and is generally considered a principal type of failure in asphalt pavements (Modarres & Hamedi, 2014a); Thermal cracking appears at lower temperatures when the binder is too rigid; and Moisture damage weakens adhesive bonds between the binder and aggregate and causes increased stripping and raveling (Agha et al., 2023). Polymer modified binders like SBS binders can counteract several of these forms of distress, however polymer modified binders are typically much costlier than conventional binders. Consequently, the use of less costly and derived from waste products (like plastics) is being investigated (Ahmadinia et al., 2012).

Waste from plastic production represents an increasingly large environmental burden. Approximately 8,300 million tonnes of virgin plastic were produced by 2015 and roughly 60 percent (about 6,300 million tonnes) of

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the total amount of plastic produced was discarded and only approximately nine percent of all plastic generated was recycled (Geyer et al., 2017), Among all packaging polymers, Polyethylene Terephthalate (PET) accounts for nearly half of the packaging materials and is commonly used for beverages packaged in bottles. The reason that PET is an ideal packaging material is that it is resistant to degradation. This property makes it persist in both landfills and the natural environment and results in its fragmentation into microplastics and nanoplastics (Fahmy et al., 2024). Moreover, mechanical recycling of post consumer PET is additionally complicated by contamination and the reduction of molecular weight during each successive process cycle (Awaja & Pavel, 2005).

Road construction offers an opportunity to utilize large quantities of waste PET since the volume of materials needed to construct roads is very large and since bituminous mixtures can tolerate heterogeneous, poor quality additives much better than many manufacturing processes. PET has been incorporated into bituminous mixtures as a binder modifier, as a particulate or fiber additive and as a substitute for up to 50% of the aggregate (Hassani et al., 2005; Ahmadinia et al., 2012; Choudhary et al., 2018). Improved stiffness, enhanced rutting resistance, extended fatigue lives in certain mixes, reduced binder requirements and disposal of plastic wastes in landfills have all been attributed to the addition of PET to hot-mix asphalt. However, reports of detrimental effects associated with adding PET to hot-mix asphalt have appeared in the literature. For example, PET has been shown to decrease stability, increase air void content and reduce rutting resistance under dynamic creep conditions depending on concentration (Ogundipe, 2019; Fahmy et al., 2024; Arshadi et al., 2024). Reviews that have summarized ways that PET may be added to bitumen based paving materials have identified areas where there are inconsistencies in previous research regarding the effect of adding PET on properties of bituminous paving materials.

Therefore, the objective of this review is to: (i) compile experimental data regarding the modification of bituminous pavements using PET; (ii) provide rationale explaining why there are discrepancies among different investigations involving the use of PET as a modifier in flexible pavements; (iii) define the areas requiring additional investigation prior to the use of PET in flexible pavement applications.

II. PROPERTIES AND CHARACTERISTICS OF WASTE PET

➢ *Chemical Structure and Basic Properties*

The PET molecule can be thought of as an example of a semi-crystalline thermoplastics, it is made up from a polymerisation reaction of TPA or TPE with Ethylene Glycol. The molecular weight of the repeating units for PET is approximately 192g/mol. However due to the differing levels of crystallinity and previous thermal treatments the physical and thermal properties of PET are different depending upon whether the PET being considered is either Bottle Grade, Fibre Grade, Recycled Material etc.

Table 1 Physical, Mechanical and Thermal Properties of PET (Indicative Values)

Property	Indicative value	Relevance to pavement use
Repeat-unit molar mass	≈192 g/mol	Polar ester linkages; contrast with non-polar bitumen
Density	≈1.41 g/cm³ (varies with crystallinity)	Much lower than aggregate; mass-based dosage overstates volume fraction (author's interpretation)
Glass transition temperature	≈69–115 °C (technique- and crystallinity-dependent)	Overlaps upper range of pavement service and mixing temperatures
Melting temperature	≈265 °C	Well above typical mixing temperatures; PET remains solid in dry process
Breaking strength	≈50 MPa	Tensile reinforcement potential, notably for fibres
Young's modulus	≈1,700 MPa	Far stiffer than bitumen; stiffening of mastic
Yield strain	≈4%	Limited extensibility
Chemical resistance	Resistant to many organic solvents, oxidation and biodegradation (Fahmy et al., 2024)	Persistence in the environment; limited dissolution in bitumen

Sources: Values as Compiled from Awaja and Pavel (2005); Chemical-Resistance Statement from Fahmy et al. (2024). Values are Indicative; Bottle-Grade Waste PET will Vary and should be Characterised for Each Study.

➢ *Behaviour at Construction and Service Temperatures*

It is noticed that when PET (glass-transition about 70°C, Tg) is used in HMA mixtures at service temperatures, it will be in a state just below being fully rubbery (and thus soft). Therefore, the it is expect that the PET will behave like a relatively stiff inclusion in the HMA during warm weather conditions (Fahmy et al. (2024). The behavior of PET under service conditions has not been studied in the literature reviewed. a) in-service refers to traffic loading. b) Rubberiness is an elastic deformation mechanism which occurs once all rigid structures in a polymer have relaxed (Choudhary et al. (2018). For PET, this begins at about 80°C. At lower temperatures, it remains quite rigid. At high temperatures, however, there is little evidence that PET degrades mechanically, even though thermal degradation can occur. A key advantage of using recycled plastic materials in asphalt concrete mixes is the ability to use these thermoplastics as 'inclusions' -- i.e., as non-brittle inclusions dispersed throughout the mix. These inclusions help improve resistance to low-temperature cracking and fatigue. Thus, while other recycling approaches focus on incorporating recycled plastics into binders, this study

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focuses on utilizing recycled plastics as discrete inclusions dispersed through the mix (Khedaywi et al., 2023).

➢ *Compatibility with Bitumen and Aggregate*

PET is a polar polyester while Bitumen is largely nonpolar colloid so we expect poor Thermodynamic Compatibility. So PET will most likely act as a Filler or Reinforcement rather than a Dissolved Polymer. The experimental data are in agreement that PET causes Stiffness: The Penetration of PET modified Binders was Lower (El-Naga & Ragab, 2019); Their Softening Points were Higher (El-Naga & Ragab, 2019); They had Greater Complex Modulus with More Elastic Response (Khedaywi et al., 2023); and Harder Bitumen (Agha et al., 2023). Dry Process PET Requires Significant Mixing and Shear Forces to Obtain Uniform Dispersion (Agha et al., 2023). Adhesion to Aggregate is Variable: Better Adhesion Between Constituents Was Indicated by Fahmy et al. (2024) for their Stability Gains While Choudhary et al. (2018) Identified Poor Adhesion When PET Is Weakened by Heat from an Aggregate.

➢ *Form, Size and Processing*

Pavement waste PET can be entered into pavement construction through three primary pathways. Flakes of shredded PET (i.e. less than or equal to 2.36mm) are generated as an end product after PET bottles have been washed, dried and crushed. However, due to the flake form nature of PET derived flakes from PET bottles, they should generally be discouraged from being considered as a replacement for coarse aggregates (Choudhary et al., 2018). Fine powders or fine grinds of PET material (e.g. 0.45mm; Mashaan et al., 2021; <150µm in comparison to Choudhary et al.) are more suitable for wet blend applications. Fibers which have been cut to lengths ranging from 6-18mm are most commonly utilized to provide crack control (Ahmed et al., 2024; Saleh et al., 2024). The size of the individual particles within a sample is recognized as a variable factor. For instance, while Choudhary et al. (2018) evaluated 2.36-1.18mm and 0.30-0.15mm particle sizes, Taherkhani & Arshadi (2019) specifically investigated particle-size distribution due to previous PET studies that reported inconsistent results with respect to particle size. Additionally larger flake sizes will result in increased surface area, as well as reduced compaction potential (Fahmy et al., 2024). On the other hand smaller particle sizes would likely produce a more uniform dispersion throughout the mixture however may also increase the amount of energy required to process the fine particles.

III. APPLICATION TECHNIQUES OF WASTE PET IN FLEXIBLE PAVEMENTS

➢ *Wet Process*

MECHANISM OF WET PROCESSING. When PET is melted into a binder it is then mixed at a high temperature with aggregate and thus PET has the opportunity to modify the rheological properties of the binder. Mashaan et al. (2021), studied C320 binders containing PET, ground down to a size of 0.45mm; they found that when 6-8 % PET was added to binder there were improvements in stiffness and elastic properties. They indicated that the addition of 8 % PET resulted in the highest values for all of these parameters; further, this combination exhibited the best performance characteristics of stability, Marshall ratio and rutting resistance. In contrast, Khedaywi et al. (2023) measured binder properties after adding PET (0-20% by volume – see Fahmy et al. [2024]) to 60/70 binder. They observed an increase in softening point and complex modulus, increased rutting resistance of binder, decreased ductility and slightly reduced thermal cracking resistance (that still remained well below acceptable levels).

ADVANTAGES AND LIMITATIONS OF WET PROCESSING. Wet processing allows for good dispersion of the additive and makes it possible to use existing plants and equipment once the modified binder is manufactured. However, the high temperatures required to melt a polymer with a melting point close to 265°C create a requirement for considerable shear energy to mix together the binder and polymer. Additionally, there exists potential for hardening of the binder and uncertainties associated with long-term storage stability of the final product. None of the reviewed literature assessed storage stability of the modified binders. Diab & Al Qadi (2024) evaluated environmental impacts on production of recycled plastic asphalt concrete using wet process recycling methods involving high shear energy to determine that those processes have a large environmental footprint.

➢ *Dry Process*

Mechanism. PET is added to heated aggregate (aggregate prior to heating or after heating at the final mixing cycle), in order for PET to act as separate semi-crystalline phase and partial filler. Fahmy et al. (2024) specifically added PET in the last stage of the mixing process, in order to maintain the semi-crystalline structure of PET. Dry mixing was also utilized by Modarres & Hamedi (2014a, 2014b) and Ahmadinia et al. (2012).

Benefits and disadvantages. The advantage of the dry method over the hot mix asphalt method is that it does not require the mixing of binders, has no need for a binder which will be stable during storage, and can use coarse PET. Disadvantages include poor dispersion, high dependency upon particle size and length of time required to mix, low compaction, and potential loss of adhesion due to softening of PET on aggregate (Ahmadinia et al. 2012; Choudhary et al. 2018; Fahmy et al. 2024).

➢ *PET Fibre Incorporation*

PET fibers are primarily utilized to provide crack control reinforcement. Saleh et al. (2024) investigated PET fiber content of 0.05–0.30 % in asphaltene enriched high performance mixture mixes and evaluated the properties of these materials including compactability, dynamic modulus, low temperature indirect tensile strength and Hamburg wheel track using both dry and wet mixing methods. Ahmed et al. (2024) also studied three different fiber lengths and determined that the cracking tolerance index was maximized at 105 for 12mm fiber length compared to 61 (control), 87 (6mm) and 99 (18mm). The authors stated that the increase

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in failure energy is directly related to the length of the fiber. Based on the author's understanding, PET fibers help to span micro cracks while redistributing applied stresses. However, if the length or density of the fiber network becomes excessive, it can create balling during compaction which will have an adverse effect on the compactability of the material. Therefore, the compactability tests conducted by Saleh et al. (2024) addressed the very real practical limit of how much fiber should be added into the matrix prior to compaction.

➢ *PET Flakes and Powder*

Flakes and powder are the forms used in most studies (Ahmadinia et al., 2012; Moghaddam et al., 2012; Choudhary et al., 2018; Mashaan et al., 2021). Flakes behave as a partial replacement for fine aggregate or filler in dry mixes, whereas powders are required for wet blending. The principal practical issues are shape (flakiness), packing and compaction, and the influence of particle size on moisture resistance (Choudhary et al., 2018).

Table 2 Comparison of Wet and Dry Processes for PET Modification

Aspect	Wet process	Dry process
Incorporation	PET blended into hot bitumen first (Mashaan et al., 2021)	PET added to heated aggregate or at end of mixing (Fahmy et al., 2024)
PET form	Fine powder or melted PET	Flakes, coarser particles, fibres
Role of PET	Binder modifier (stiffening, elasticity)	Discrete stiff inclusion / partial filler
Main reported strength	Better moisture resistance in direct comparison (Agha et al., 2023)	Better fatigue resistance, stability and flow in direct comparison (Agha et al., 2023)
Main limitations	High melting point, shear/energy demand, storage stability and compatibility unresolved	Dispersion, compaction, possible adhesion loss (Choudhary et al., 2018)
Moisture-damage evidence	Optimum 6% PET (Agha et al., 2023)	Modified dry best in comparison of dry variants (Choudhary et al., 2018)

The only verified direct comparison under a common experimental programme is Agha et al. (2023), who found that the dry route gave better stability, flow and fatigue cracking resistance, whereas the wet route gave better moisture resistance. The two routes therefore appear to trade mechanical stiffness against moisture durability. The author interprets this as arising from the different location of PET: in the dry route PET remains a rigid particulate inclusion that can carry load but may disturb the aggregate–binder interface, whereas in the wet route PET is spread through the binder, where it hardens the mastic and may reduce stripping. Because dosage bases, binder grades and PET sizes differ between studies, cross-study ranking of the two routes is not currently justified.

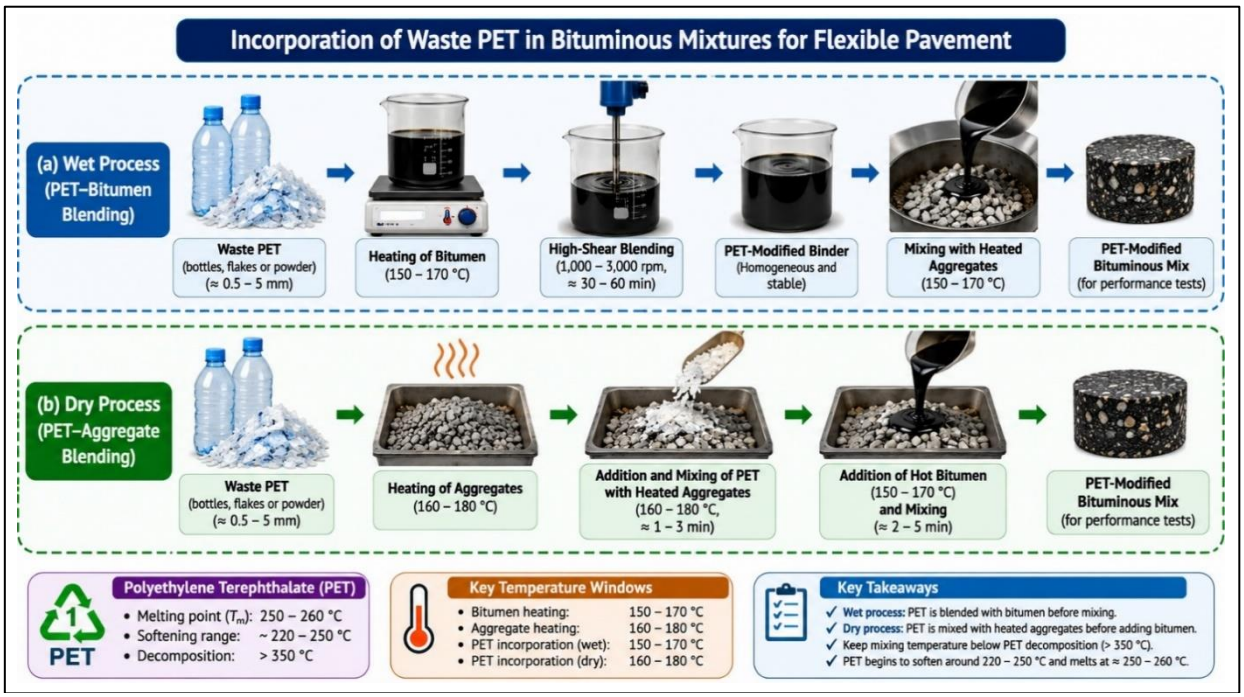

Fig 1 Incorporation of Waste PET in Bituminous Mixtures for Flexible Pavement

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IV. EFFECT OF PET MODIFICATION ON ENGINEERING PROPERTIES OF FLEXIBLE PAVEMENT

The findings below are those reported by the cited authors; Table 4 summaries them. Dosage bases differ across studies (by binder mass, aggregate mass or as binder replacement), so percentages are not directly comparable.

- *Marshall Stability and Flow*

Some studies have been contradictory. Fahmy et al. (2024) stated that the addition of 8% PET (by weight of binder) resulted in a rise in stability. Stability can be increased by up to approximately 26%. Fahmy et al. (2024) showed that there is an acceptable range of binder content below which all mixes flowed freely; this was at approximately 3–3.5% binder content. Mashaan et al. (2021) indicated that both increased stability and Marshall quotient were achieved through the inclusion of 8% PET. However, Ameri and Nasr (2017) found an increase in stability due to the use of devulcanized PET. Conversely, Ogundipe (2019) noted that replacement of 4–16% of the optimum amount of bitumen with PET resulted in lower stability for the modified mixtures compared to the reference mixture. The highest point for stability occurred when 12% PET was used, but even then, it was a 20% decrease from the reference value. Arshadi et al. (2024) reported that the addition of PET (0–9% by weight of binder) resulted in a decline in stability.

- *Bulk Density, Air Voids, VMA and VFB*

Fahmy et al. (2024) stated that PET (a material far less dense than an aggregate) was found to lower bulk density by around 7–9%, increased air voids to a degree of about 2–3 percentage points, decreased voids filled with asphalt, and did not have any significant impact upon VMA except due to the effects of reduced binder usage. The authors believed the increase in air voids can be explained by the increased surface area associated with crushed PET along with its decreased compatibility. Although Choudhary et al. (2018), and Arshadi et al. (2024), measured volumetric parameters, as summarized above there were no specific values provided for directionally comparative analysis; therefore, this information will not be used. In practice, it is the author's opinion that based on this study, PET has the potential to provide underestimation of its mass when using mass-based applications of product, and thus PET mixture designs require re-optimization (not just adjustment based on dosing).

- *Indirect Tensile Strength (ITS)*

It has been assessed by El-Naga and Ragab (2019), Ameri and Nasr (2017), Moghaddam et al. (2014a, b), and others. Pet tends to improve or increase the mechanical strength of mixtures as concluded by El-Naga and Ragab (2019); twelve percent PET being the optimal percentage; Ameri and Nasr (2017) also report improved mechanical strengths when using devulcanised PET. However, Moghaddam et al. (2014b) have stated that the addition of PET changes the properties of a mixture based on the level of load applied (Section 6.5). Since there are no available abstracts that provide a quantifiable assessment of how different percentages of PET compare to each other for ITS, it makes it difficult to make an objective comparison of ITS from PET recycled materials.

- *Tensile Strength Ratio and Moisture Susceptibility*

Moisture Performance was the most consistent favorable property among all properties evaluated in the studies. Fahmy et al. (2024), compared to the control (82.5%), the TSR increased to 88.6% and Stability Loss decreased by 9.5%. This compares to a decrease in moisture sensitivity by Ameri & Nasr (2017); Agha et al. (2023) found that the wet route provided better results than other routes with an optimal PET of 6%; and Choudhary et al. (2018) showed the modified dry process exhibited the highest moisture resistance. Fahmy et al. (2024) have indicated three possible mechanisms as to why there may be improved moisture performance; these are enhanced adhesion between components, prevention of PET softening due to heat exposure from hot aggregate; and the possibility that stiffer mastics and/or use of hydrophobic polymers could inhibit the loss of cohesion caused by water. However, the studies were unable to investigate whether or not this would occur.

- *Rutting Resistance and Permanent Deformation*

Most research has shown that there is an increase in resistance to permanent deformation. Moghaddam et al. (2014a) showed that adding PET flakes to an asphalt (at 0.2 – 1 % of total aggregate weight) was able to reduce permanent strain at both low and high stress levels (300 & 400 kPa) and various temperatures (10, 25, 40 ° C). Moghaddam et al. (2014b) furthered these findings by stating that the behavior of PET based mixtures was significantly different when subjected to either static or dynamic loads. When subjected to static load, the addition of PET resulted in no improvement over control mixtures. However, when subjected to dynamic load, the use of PET resulted in a significant improvement in resistance to rutting. Rut depths have been observed to be reduced using PET mixtures. A study by Khedaywi et al. (2023) also demonstrated improved resistance to rutting of asphalt binders.

There are some examples where researchers have obtained counter evidence for the above mentioned benefits. Fahmy et al. (2024) conducted a Hamburg Wheel Track Test and measured the difference in rut depth prior to the application of PET (7.18mm) and after (7.46mm), representing an approximate 3.75% increase. This increase was directly attributed to the lower stiffness of the PET containing mixture. Arshadi et al. (2024) demonstrated that increasing amounts of PET added to their base asphalt mixture (0 – 9%) actually caused an increase in rutting due to dynamic creep testing; however, increasing amounts of recycled asphalt pavement (RAP) also improved the rutting performance of the base asphalt mixture. These differing results indicate that the use of PET will not result in universal improvements in rutting performance.

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➢ *Fatigue Performance and Cracking Resistance*

Fatigue test data are much better than they were. Moghaddam et al. (2012) concluded that the PET reinforced stone mastic asphalt mixture exhibited significantly longer fatigue lives compared to the unreinforced mixture in indirect tension fatigue tests conducted at 20 °C. Modarres and Hamedi (2014b) stated that the addition of PET enhanced fatigue behavior at both 5°C and 20°C; furthermore, the authors indicated that the fatigue behavior exhibited by the PET-modified material was similar to that observed for materials modified with SBS at 20°C. In a study also authored by Modarres and Hamedi (2014a), the authors demonstrated that fatigue life is dependent upon the initial strain experienced by the mixture, with an inversion of the relationship between fatigue life and resilient modulus occurring at approximately 210 microstrain. In studies examining dry routing as an alternative method for improving fatigue performance, Agha et al. (2023) found dry routed mixtures exhibit superior fatigue performance relative to wet routed mixtures. Ahmed et al. (2024) concluded that adding PET fibers into high performance mixtures increases the failure energy and the cracking tolerance index associated with low temperature cracking. Conversely, Khedaywi et al. (2023) determined that the addition of PET fibers slightly reduced the thermal cracking resistance of binders. While the favorable fatigue data have largely been generated from a single research group using primarily stone mastic asphalt or dense mixtures, it will be necessary for additional researchers to independently verify these findings through testing across various binder types.

➢ *Resilient Modulus and Stiffness*

The nonmonotonous response to the addition of PET is illustrated by stiffness data. Moghaddam et al. (2012) and Modarres and Hamedi (2014b) demonstrated that when PET content is below a certain threshold, the stiffness increases with increasing PET; however, above this same threshold, it decreases. By employing Response Surface Methodology (Moghaddam et al., 2015) to identify the combination of parameters yielding maximum stiffness in mixtures containing PET, a maximum stiffness was achieved at approximately 0.41% PET by aggregate mass. Although Fahmy et al. (2024) observed higher stability in their selected mixture due to increased PET content than in the control sample, the Marshall stiffness measured in this study was slightly less than that of the control, resulting in what they interpreted as higher flexibility. Conversely, Mashaan et al. (2021) indicated that there is an increase in Marshall quotient at 8 % PET.

➢ *Thermal Stability and Temperature Susceptibility*

The overall effects are dependent on both temperature and processing conditions. Binder-scale effects indicated by Enieb et al. (2021), showed when adding different percentages of rPET (1.5% and 2.5%), to an additive such as crumb rubber resulted in lower temperatures sensitivity and increased rheology characteristics of the binder. In contrast, Khedaywi et al. (2023) were able to demonstrate better rigidity and elasticity at high temperatures, but with some small amount of reduction of low-temperature crack resistance.

➢ *Durability and Ageing Behaviour*

Direct evidence for long-term aging has been somewhat limited. While Mashaan et al. (2021) framed their research on the impact of aging to pavement stiffness and rutting, they also identified a need for additional long-term modulus and fatigue tests. In addition, Enieb et al. (2021) assessed the short-term properties of asphalt binders. The best indication of potential long-term durability comes from the moisture-related studies referenced. The author hypothesizes that the stiffening induced by PET may exacerbate the oxidative aging hardening of the asphalt binder at lower temperatures, which will increase its susceptibility to fatigue crack growth; however, these findings are not supported or presented within the reviewed literature.

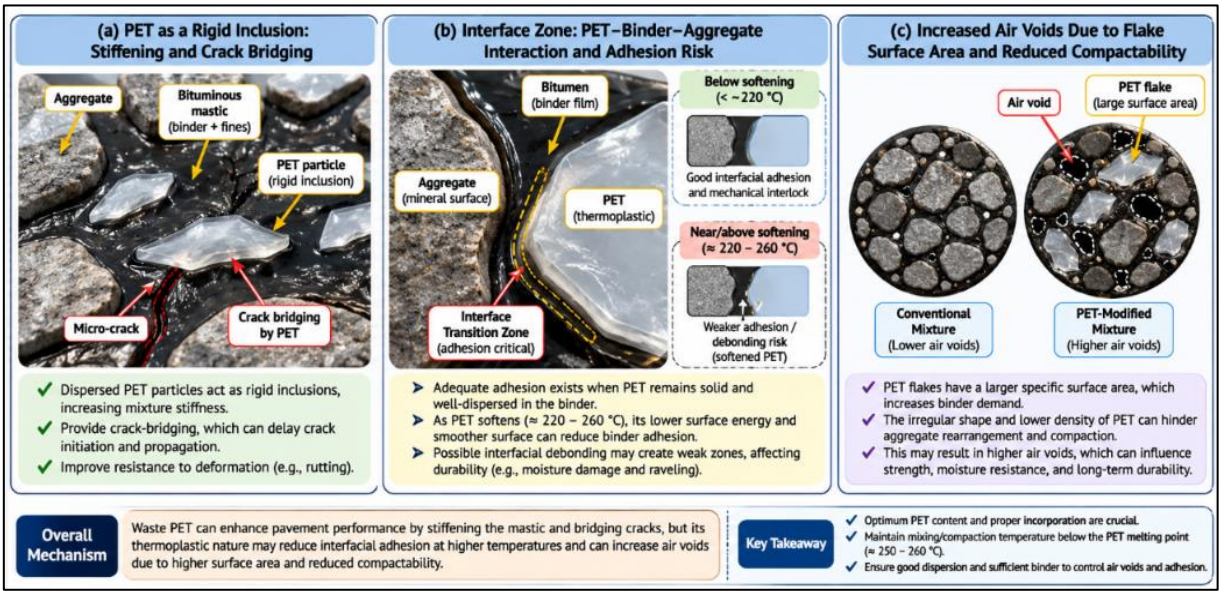

Fig 2 Schematic Representation of the Mechanisms Governing the Interaction of Waste PET Particles with Bituminous Mastic and Aggregates in Flexible Pavement Mixtures.

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V. REVIEW OF PREVIOUS EXPERIMENTAL STUDIES

Verification and scope of the findings. Each of the bibliographic details listed below were cross-checked with the publishers' records, an index or libraries. The results come from the abstracts, publisher's websites and, for Fahmy et al. (2024), the entire open-source document; however, as access to the complete version of the articles of the others were unavailable, the "n.r." (not available in the accessed record) should have been replaced by the information available in the original article prior to submission. A total of 21 experimental studies verified for inclusion; references were not added beyond those which were verified for a target amount. There are fewer studies from 2020–2026 than were briefly expected due to the fact that most foundational PET research has been done since 2011–2019 and, more importantly, there were only studies that could be verified that were kept. No sufficient literature that could be verified for inclusion was found in 2025-2026.

Table 3 Comparative Review of Previous Experimental Studies

Author(s) and year	Type of PET	Technique	PET content	Mixture type	Tests conducted	Major findings	Optimum PET
Ahmadinia et al. (2011), Kaur & kumar 2025	Waste bottle PET	Dry	n.r.	SMA	Engineering properties; ANOVA	Positive effect on SMA properties	4–6% of binder mass (thesis record; Ahmadinia, 2012)
Ahmadinia et al. (2012)	Waste bottle PET	Dry	0–10% of binder mass	SMA	Wheel tracking, moisture, resilient modulus, drain-down	Lower binder drain-down; other outcomes n.r.	n.r.
Moghaddam et al. (2012)	Waste PET, ≤2.36 mm	n.r.	Several levels	SMA	Indirect tensile stiffness and fatigue (20 °C; 250–450 kPa)	Stiffness up at low PET, down at high; fatigue life significantly higher	n.r.
Moghaddam et al. (2014a)	PET flakes	n.r.	0–1% of aggregate mass	Asphalt mixture	Dynamic creep (300/400 kPa; 10/25/40 °C)	Permanent strain markedly reduced	n.r.
Moghaddam et al. (2014b)	Waste PET	n.r.	n.r.	Asphalt mixture	Marshall, ITS, ITSM, static and dynamic creep	Unsuitable under static loading; superior under dynamic loading	n.r.
Moghaddam et al. (2015)	Waste PET	n.r.	n.r.	Asphalt mixture	Stiffness modulus (RSM)	Stress and PET content similarly influential	0.41% of aggregate mass
Modarres & Hamedi (2014a)	Ground PET	Dry	2–10% of binder mass	Asphalt concrete	Resilient modulus, fatigue (5/20 °C)	Fatigue life strain-dependent (≈210 με crossover); models developed	n.r.
Modarres & Hamedi (2014b)	Ground PET	Dry	2–10% of binder mass	Asphalt concrete	Stiffness, fatigue (5/20 °C), SBS comparison	Stiffness up then down; fatigue improved; comparable to SBS at 20 °C	n.r.

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Author(s) and year	Type of PET	Technique	PET content	Mixture type	Tests conducted	Major findings	Optimum PET
Ameri & Nasr (2017)	Devulcanised PET	n.r.	n.r.	Asphalt mixes	Marshall, ITS, wheel track	Higher stability; lower moisture susceptibility and rutting	n.r.
Choudhary et al. (2018)	Shredded bottle PET (two size fractions)	Dry; modified dry	2.5, 5, 7.5% of binder mass	Asphalt mix	Volumetrics, Marshall, moisture	Modified dry process best for moisture resistance	n.r.
El-Naga & Ragab (2019)	Recycled PET	Dry and wet (per later citing study)	n.r.	Asphalt mixtures	Binder tests, Marshall, ITS, rutting, KENPAVE	Lower penetration, higher softening point, higher strength; modelled life 2.81×	12%
Ogundipe (2019)	Waste PET	Bitumen replacement	4–16% of optimum bitumen	Asphalt concrete	Marshall	Stability lower than control	12% (still ≈20% below control)
Taherkhani & Arshadi (2019)	Ground waste PET, graded sizes	n.r.	0–10% of binder mass	Asphalt concrete	Marshall, ITS, moisture, dynamic creep	Content and size effects examined; quantitative results n.r.	n.r.
Enieb et al. (2021)	Recycled PET (with crumb rubber)	Binder modification	1.5, 2.5%	Binder	Penetration, softening, viscosity, temperature susceptibility	Reduced temperature sensitivity	n.r.
Mashaan et al. (2021)	Ground PET (0.45 mm)	Wet	6–8% highlighted	Asphalt mixes (C320 bitumen)	Binder tests; Marshall, Marshall quotient, rutting	Greatest stability and rutting gains at 8%	8%
Agha et al. (2023)	Crushed bottle PET	Wet and dry	2–10%	HMA (60/70)	Moisture, indirect tensile fatigue, Marshall	Dry: better fatigue, stability, flow; wet: better moisture	6% (moisture)
Khedaywi et al. (2023)	Waste PET	Wet	0–20% by volume	Binder (60/70)	Conventional and Superpave PG tests	Higher stiffness, rutting resistance; lower ductility; slight thermal-cracking loss	n.r.
Fahmy et al. (2024)	Crushed bottle PET	Dry	6, 7, 8% of binder mass; binder 3–4%	Binder-course HMA	Marshall, stability loss, TSR, Hamburg, SEM	Stability up to +26%; TSR 82.5→88.6%; rut depth +3.75%; air voids +2–3	8% PET at 3% binder

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Author(s) and year	Type of PET	Technique	PET content	Mixture type	Tests conducted	Major findings	Optimum PET
						points	
Arshadi et al. (2024)	Waste PET with RAP	n.r.	0, 3, 6, 9% of binder mass	Asphalt concrete with 0–30% RAP	Volumetrics, Marshall, ITS, creep, fatigue	Stability and creep rutting resistance decreased with PET; RAP offset effects	n.r.
Saleh et al. (2024)	PET fibres	Combined dry and wet	0.05–0.30%	Asphaltene-modified HPAC	Compatibility, dynamic modulus, low-temperature ITS, Hamburg	Binder with 12% asphaltenes suitable; mixture results n.r.	n.r.
Ahmed et al. (2024)	PET fibres (6, 12, 18 mm)	n.r.	n.r.	Asphaltene-modified HPAC	Cracking tolerance	Index 61 (control), 87, 105, 99 for 6, 12, 18 mm	12 mm length

SMA, Stone Mastic Asphalt; HPAC, High-Performance Asphalt Concrete; RSM, Response Surface Methodology; n.r., Not Reported in the Accessible Record.

Three major forms of inconsistency among these three studies occur. The first source is the difference in how each study expresses dosages. Each uses a base that could be considered as either "binder", "aggregate", or "mixture" mass. Therefore, there would be no basis for comparing the optimum amounts of 0.41%, 4-6%, 8% and 12% mentioned by Moghaddam et al. (2015), Ahmadinia (2012), Mashaan et al. (2021); Fahmy et al. (2024) and El-Naga & Ragab (2019); Ogundipe (2019), respectively. A second source of inconsistency is the use of binder replacement versus binder adjustment. Binder replacement has been found to have a negative effect on the stability of mixes while addition of PET to binders (with adjustments made to the amount of binder used) increases the stability of mixes. This suggests that both film thickness and stiffness of mastics control the stability of mixes. A third source of inconsistencies are the differences in testing modes. There may be a large number of PET-based mixtures that are very unstable when tested statically, however those same mixtures may exhibit improved performance in terms of stability when subjected to dynamic testing (e.g. Moghaddam et al., 2014b).

Table 4 Summary of the Influence of PET on Flexible Pavement Properties

Property	Reported direction	Representative studies	Likely controlling factors
Marshall stability	Mixed: up (up to ≈26%) or down	Fahmy et al. (2024); Mashaan et al. (2021) vs Ogundipe (2019); Arshadi et al. (2024)	Dosage basis, binder content, PET size
Bulk density / air voids	Density down; air voids up	Fahmy et al. (2024)	PET specific gravity, flake surface area, compactability
ITS	Generally up (limited quantitative data)	El-Naga & Ragab (2019); Ameri & Nasr (2017)	Dosage, size
TSR / moisture	Mostly improved	Fahmy et al. (2024); Agha et al. (2023); Choudhary et al. (2018)	Mixing route, adhesion, PET softening
Rutting	Mostly improved; exceptions	Moghaddam et al. (2014a); Mashaan et al. (2021) vs Fahmy et al. (2024); Arshadi et al. (2024)	Loading mode, dosage, binder content
Fatigue / cracking	Mostly improved; fibres improve cracking tolerance	Moghaddam et al. (2012); Modarres & Hamedi (2014b); Ahmed et al. (2024)	Strain level, temperature, mixing route
Stiffness	Non-monotonic	Moghaddam et al. (2012, 2015); Modarres & Hamedi (2014b)	Dosage, metric, temperature
Temperature susceptibility	Binder susceptibility reduced; low-temperature cracking mixed	Enieb et al. (2021); Khedaywi et al. (2023)	Binder type, dosage
Durability / ageing	Insufficient evidence	Mashaan et al. (2021)	—

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VI. ENVIRONMENTAL AND SUSTAINABILITY ASSESSMENT

Waste diversion. Pavement roadways can take up a lot of materials, but PET dosages are relatively small compared to the overall weight of the roadway. The author has made some example calculations based on these principles. For example, if 6% of PET is added to the asphalt binder and 5% asphalt binder makes up the entire mix, this means approximately .03% PET of the entire roadway. As such, the amount of waste diverted per ton of roadway is very small, and thus whether there is an actual benefit to adding PET is determined by how many tons of roadway are being laid down at one time. Also, PET adds about 7-9% less to the overall bulk density when mixed with the other components in the asphalt (Fahmy et al., 2024), which could decrease the overall mass per square yard of roadway.

Reduced use of bitumen and circular economy. Fahmy et al. (2024) have stated that a combination of 8% PET and 3% binder meet the design requirements of a roadway, while stating they saved about 32.3% in bituminous binder. Additionally, El-Naga and Ragab (2019) used modeling techniques to demonstrate a 281 times longer pavement life span and approximately 20% savings in layer thickness due to the use of PET in the roadway. However, these are both laboratory and modeling results and do not reflect what has occurred in the field. From a perspective of the circular economy, roadways provide a durable repository for all types of PET including those contaminated with debris or otherwise not suitable for bottle-to-bottle recycling. However, it appears that diverting clean PET away from higher value uses may be counterproductive.

Energy usage and Life-Cycle Assessment. To process the collected PET into usable forms, several steps need to occur: collection, sorting, washing, shredding and transporting (Diab & Al-Qadi, 2024; Fahmy et al., 2024). A Life-Cycle Assessment (LCA) conducted by Diab and Al-Qadi (2024) compared the environmental impacts associated with various types of modified hot-mix asphalt including waste-plastic-modified mixes versus SBS-modified mixes. Results indicated that LCA performance metrics were superior for waste-plastic-modified mixes when compared to SBS-modified mixes except for ozone depletion. While the authors recognized that the processing step involving high-shear wet-mixing had significant energy consumption and environmental impacts related to greenhouse gas emissions, they also identified that transportation distances significantly impacted the environmental benefits of using waste-plastic-modified mixes. It should be noted that their analysis did not focus on PET specifically and as such, additional research focused solely on PET is required.

Release of Microplastics and Leachate. An investigation conducted by Duan et al. (2024) assessed the potential release of microplastics from pavement constructed with Linear Low-Density Polyethylene (LLDPE)-modified pavement. They concluded that the release of microplastics from pavement is three orders of magnitude smaller than tire wear particles. A separate study performed by Enfrin et al. (2022) investigated the release of microplastics resulting from different methods of utilizing recycled plastic in pavement construction. Specifically, their results demonstrated that the release of microplastics was earlier and greater when using recycled plastic as a binder additive as opposed to using it as an aggregate replacement. They also found that colder temperatures and acidic environments increased the rate of release. It should be noted that neither study specifically addressed PET as part of its investigation.

Costs and Implementation. Compared to commercially available products designed to modify asphalt binders, waste polymers are typically much cheaper (Ahmadinia et al., 2011), and since reducing the amount of binder used in roadway construction will improve costs described by Fahmy et al. (2024). Nevertheless, before adopting large amounts of PET in roadway construction, standardized specifications for PET will need to be developed along with quality control standards for any potentially contaminated feedstocks (Awaja & Pavel, 2005), modifications to plants involved in producing asphalt binders to accommodate either dry additions or wet additions under high shear conditions, and performance-based standards for determining acceptability.

VII. RESEARCH GAPS AND FUTURE RESEARCH DIRECTIONS

The verified literature supports PET as a promising but poorly standardised modifier. The gaps below follow directly from the inconsistencies in above sections.

Table 5 Identified Research Gaps and Recommended Future Investigations

Research gap	Evidence in reviewed literature	Recommended future investigation
Non-standard PET size and shape	Sizes range from 0.45 mm to 2.36 mm flakes and 6–18 mm fibres	Report gradation, shape and specific gravity; factorial size × dosage × route experiments
Inconsistent dosage bases	Optima from 0.41% (aggregate mass) to 12% (binder mass/replacement)	Report PET by volume and mass of mixture; re-optimise binder content for each dosage
Limited long-term and field performance	Almost all studies are short-term laboratory work; modelled life gains (El-Naga & Ragab, 2019)	Accelerated pavement testing and instrumented field sections
Fatigue and moisture inadequately investigated	Fatigue evidence is concentrated in few groups; few moisture tests at multiple conditioning levels	Independent replication using multiple binders and conditioning cycles
Compatibility and	Wet-process storage stability not	Storage stability, microscopy and chemical analysis of wet

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storage stability	quantified	binders
Ageing and durability	Ageing evidence limited (Mashaan et al., 2021)	Short- and long-term ageing of binders and mixtures with fatigue and low-temperature testing
Environmental risk and life-cycle assessment	No PET-specific microplastic, leaching or LCA data	PET-specific microplastic quantification, leaching tests and cradle-to-grave LCA
Laboratory–field correlation	Contradictory static versus dynamic results (Moghaddam et al., 2014b)	Performance-related testing with mechanistic–empirical modelling and field validation

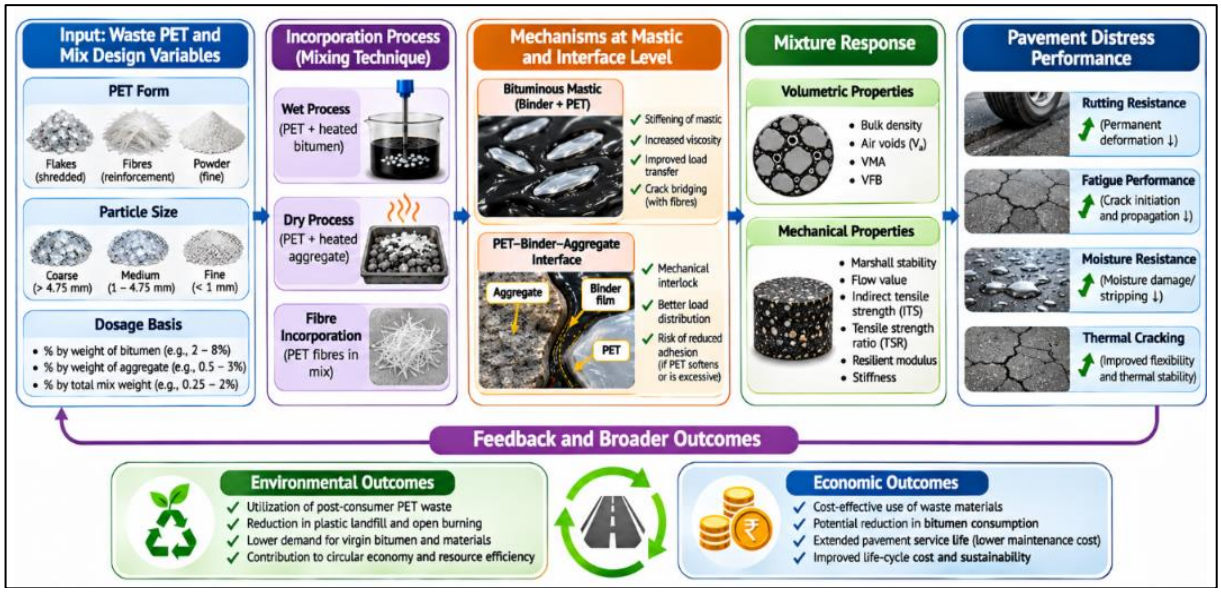

Fig 3 Conceptual Framework Illustrating the Influence of Waste PET Characteristics and Incorporation Techniques on the Performance of Flexible Pavement.

VIII. CONCLUSION

Waste PET (Polyethylene Terephthalate) is technologically compatible as an additive to modify flexible pavement materials; however, there are no scientific data supporting claims that waste PET will improve performance. Studies have found verified results showing increased modulus, greater rutting resistance when subjected to dynamic loading conditions, longer fatigue life in various mix design combinations and overall better resistance to water damage with less bulk density and potentially less binder content. Conversely, studies indicate that incorporation of waste PET into pavements may result in reduced stability to the modified binders used in replacement binders, increase air voids, show larger rut depths than unmodified pavements in Hamburg testing procedures and provide decreased dynamic creep resistance as a function of PET concentration in Reclaimed Asphalt Pavement (RAP) containing mixes.

Therefore, optimum dosages of waste PET are dependent upon size of PET (form), mass of additive added (dosage basis), amount of binder contained within the mix, method of mixing and type of test conducted and cannot be generalized among all types of pavement. Optimal amounts of waste PET added ranged from .41% by aggregate mass to 12% by binder mass. The dry method appears favorable to both stability and fatigue in contrast to the wet method which provides better moisture resistance based on limited comparative study data. Additionally, incorporating fibers into the PET mixture has shown potential for improving cracking resistance.

There remain a number of unresolved questions including compatibility and long-term storage stability, aging characteristics, standardized characterization methods for PET, micro-plastic contamination risks associated with PET use, and development of life cycle analysis and cost assessments unique to PET-modified asphalt. Therefore, laboratory to field validation through well-controlled experiments is necessary prior to recommending PET-modification inclusion into specification documents. In order to address these areas of uncertainty a controlled experiment program should compare the effects of different incorporation methods, and different sizes of PET additives on a common dosage basis using routine moisture susceptibility, rutting, fatigue and aging tests.

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