Enhancing Bituminous Mix Performance Using Waste Plastics: Experimental Insights and Sustainability Considerations

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***Abstract*: The dual challenge of managing the rising volume of plastic waste and improving the long-term performance of road pavements has become an important focus of research in sustainable infrastructure. Plastics, due to their non-biodegradable nature and extensive use across industries, contribute significantly to global environmental pollution, while flexible pavements are constantly exposed to increasing traffic loads, moisture damage, and climatic variations. These parallel issues create an opportunity to recycle waste plastics effectively by incorporating them into asphalt mixes, thereby addressing both waste management and pavement durability concerns.**

This study evaluates the suitability of six categories of post-consumer thermoplastics—polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS)—for improving the performance of bituminous concrete. Each plastic type was introduced into a dense-graded bituminous mix at dosages of 5%, 7.5%, and 10% by weight of binder. A series of standard bituminous tests were conducted to assess their impact, including ductility, penetration, softening point, Marshall stability, and Marshall flow. Together, these properties provide a comprehensive view of the strength, stiffness, temperature susceptibility, and deformation resistance of the modified mixes.

The findings reveal that the inclusion of plastics generally enhances the high-temperature resistance and load-bearing capacity of the mixes, reflected by improvements in both softening point and Marshall stability. However, the effect on flexibility-related properties such as ductility and flow was observed to vary significantly with the type and proportion of plastic. HDPE at 10% and PP at around 7.5% produced the most balanced results, offering increased stability without severe compromise in ductility. PS at 10% dosage yielded the highest stability among all mixes, though it was accompanied by a moderate reduction in ductility. On the other hand, LDPE and PVC, while increasing stiffness, caused substantial decreases in ductility at the tested dosages, suggesting limited suitability under field conditions where flexibility is critical. PET demonstrated intermediate behaviour, with moderate improvements across most properties.

Overall, the study provides clear insights into the property interactions of commonly available waste plastics when blended with bitumen. By mapping the performance trade-offs across different plastic types and dosages, the research contributes practical guidance for selecting materials that achieve both engineering benefits and environmental sustainability. The outcomes reinforce the potential of plastic-modified bituminous pavements as a dual solution to waste recycling and infrastructure performance enhancement.

***Keywords*: Bituminous pavements, Polymer-modified asphalt, Performance evaluation, Waste plastics**

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I. Introduction

Global plastic production has exceeded 350 million tonnes per year and continues to rise, with a significant share ending up in landfills or leaking into terrestrial and aquatic ecosystems. Road construction, one of the largest consumers of construction materials, offers an attractive pathway to valorise plastic waste by incorporating it into bituminous mixes as a performance-enhancing modifier. Decades of research on polymer-modified bitumen (PMB) have shown that polymers can tailor binder rheology, raising softening point and rut resistance while controlling temperature susceptibility [1]. Translating that insight to waste polymers, many studies report stability gains and enhanced deformation resistance when plastic is judiciously dosed in asphalt mixes [2]. However, property improvements are not uniform across plastic types or contents. Excessive stiffening can reduce binder ductility and mix flow, elevating the risk of brittle cracking under thermal or traffic-induced strains. A practice-ready synthesis therefore requires mapping not only the direction of change but also the trade-offs among key indicators—ductility, penetration, softening point, Marshall stability, and flow—across multiple plastics and contents.

The present work addresses this gap using a dataset that evaluates six common waste plastics (PET, HDPE, PVC, LDPE, PP, PS) each at 5%, 7.5%, and 10% by binder weight in a dense-graded bituminous concrete (BC). Rather than rely on multi-criteria decision-making frameworks, we emphasise transparent, reproducible descriptive statistics, trend plots, and correlation analysis. This choice aligns with the needs of practitioners who seek clear cause-and-effect interpretations and replicable thresholds for field trials. Our objectives are to (i) quantify the effect of plastic type and content on binder-level indicators (ductility, penetration, softening point), (ii) examine how those changes manifest in mix-level Marshall stability and flow, and (iii) discuss the trade-offs that determine practical optima for heavy-duty pavements in warm climates.

II. Literature Review

The search for improved performance of bituminous mixes has a long trajectory, beginning with early recognition that binders could be strengthened through reinforcement. Historical accounts show that even ancient builders mixed fibrous materials into earthen binders to enhance strength and durability [3]. The modern scientific study of asphalt reinforcement gained momentum in the mid-20th century, when Zube (1956) embedded wire mesh into asphalt overlays as a strategy to delay reflective cracking [4]. His findings suggested that mechanical reinforcement could extend service life without requiring excessively thick overlays, an insight that influenced subsequent generations of pavement design [5; 6].

A. Fibres as Reinforcement and Polymer-Modified Bitumen

By the 1960s, attention shifted to mineral and synthetic fibres. Researchers observed that fibres could significantly improve tensile strength and mitigate fatigue and thermal cracking in asphalt mixes [7;3]. Glass fibre, for example, has been shown to enhance both deformation resistance and crack propagation control [8;9]. Subsequent studies reported additional benefits such as reduced moisture damage, improved resistance to reflection cracking, and slower ageing of the binder [6; 8]. Mechanistically, fibres act by altering the viscoelastic behaviour of bitumen and mixes, resulting in higher stiffness and enhanced rutting resistance, yet without entirely sacrificing flexibility [10]. Dynamic modulus tests have confirmed that fibre incorporation reduces permanent deformation and moisture susceptibility, while increasing load-bearing capacity. These insights consolidated fibre reinforcement as a widely accepted strategy for extending pavement life across varying climatic conditions.

Parallel to fibre research, polymers emerged as another means of addressing bitumen's temperature susceptibility. Among virgin polymers, styrene-butadiene-styrene (SBS) became the most prominent, giving rise to polymer-modified bitumen (PMB). SBS modification was shown to provide substantial gains in rutting resistance at high temperatures and crack resistance at low temperatures [11]. Robertus et al. (1995) and Raol et al. (2014) reported superior performance of SBS-modified mixes under heavy traffic, which justified its use in high-duty pavements worldwide [7;12]. Yet, challenges remain. The cost of virgin polymers can be prohibitive, and storage stability issues have been documented. Urquhart et al. (2016), for instance, observed degradation of SBS-modified binders when subjected to prolonged hot storage, while Zorn et al. (2011) demonstrated how polymer addition fundamentally shifts binder rheology and microstructure [13;14]. These findings established polymer modification as a powerful but not problem-free strategy, raising questions about economic and operational sustainability [15; 16].

B. Waste Rubber as a Precursor to Plastics

The search for more sustainable modifiers opened the door to recycled materials. Crumb rubber from waste tires emerged as one of the earliest large-scale recycled additives, used either through the wet process (asphalt rubber) or the dry process (rubberised aggregates). Studies demonstrated that crumb rubber could increase Marshall stability, improve elasticity, and extend pavement durability [12]. Beyond performance, tire rubber offered environmental benefits by diverting waste streams from landfills and reducing the reliance on virgin aggregates [15]. The relative success of rubber modification provided proof-of-concept that waste polymers could be viable asphalt modifiers, leading naturally to the exploration of post-consumer plastics.

C. Waste Plastics as Asphalt Modifiers

Research into waste plastics has since expanded rapidly, targeting polymers such as polyethylene terephthalate (PET), high-density polyethylene (HDPE), polypropylene (PP), low-density polyethylene (LDPE), and polystyrene (PS). Two major incorporation routes have been explored: the wet process, in which plastics are melted and blended into bitumen, and the dry process, in which shredded plastic is added directly to hot aggregates. Both approaches have yielded encouraging but sometimes mixed results.

Laboratory investigations have consistently shown that plastic addition increases the stiffness and softening point of binders, while reducing penetration values—implying enhanced rutting resistance at high temperatures [17; 18]. For example, Mahrez and Karim (2010) demonstrated that PET bottle waste reduced penetration and increased softening point, while Rahman and Wahab (2013) confirmed PET's ability to improve stiffness and permanent deformation resistance [20;21]. However, PET's relatively high melting point often complicates blending, resulting in uneven distribution and reduced ductility if mixing is poorly controlled.

Alternative plastics have shown varying promise. Vasudevan et al. (2010) pioneered the dry-process use of mixed municipal plastics as coatings on aggregates, reporting a dramatic increase in Marshall stability and improved field durability with pothole resistance even under heavy service [10]. Subsequent evaluations (Dwivedi et al., 2017; Sharma et al., 2016) highlighted that plastic-modified pavements may also prove cost-effective across their life cycle, owing to reduced maintenance needs [11;22].

HDPE and LDPE have been among the most widely studied. Hınıslıoğlu and Ağar (2004) showed that adding waste HDPE at an optimum level (~4% by weight of bitumen) increased Marshall stability by nearly 50% and improved the Marshall quotient, underscoring enhanced resistance to permanent deformation [23]. LDPE, often derived from packaging films or bags, has likewise demonstrated strength and stiffness gains, though excessive content risks brittleness and poor low-temperature performance [24; 25].

Polypropylene (PP) stands out in comparative studies for delivering balanced performance improvements. Essawy et al. (2013) reported that PP-modified asphalt outperformed other waste plastics across multiple parameters, likely owing to PP's higher melting point and compatibility. Conversely, polystyrene (PS) has produced mixed outcomes [16]. While Lastra-González et al. (2016) found that PS stiffened asphalt binders, the overall performance gains were less consistent compared to PE, PP, or rubber fibres [25]. Compatibility challenges appear to limit PS's effectiveness unless high dosages are used, which can compromise flexibility [26].

Taken together, these studies demonstrate both the potential and variability of waste plastics as asphalt modifiers. Improvements in high-temperature rutting resistance and Marshall stability are well established across polymer types, but challenges persist regarding low-temperature ductility, long-term durability, and process ability [27]. Results often hinge on polymer chemistry, dosage, and blending conditions, underscoring the importance of optimised process control.

Waste plastics offer a dual advantage: performance enhancement and environmental sustainability through recycling. Yet, inconsistencies across studies—particularly with PET and PS—highlight the need for standardised testing protocols and deeper investigation into compatibility, ageing behaviour, and field validation [28]. The literature suggests that HDPE, PP, and carefully managed LDPE have the greatest potential for widespread adoption, while PET and PS demand further technological refinement.

III. Methodology

This study examines the effect of post-consumer thermoplastics on the performance of bituminous mixes, with particular emphasis on strength and durability parameters that govern pavement behaviour. To generate reliable and reproducible outcomes, a structured methodology was followed so that comparisons could be meaningfully drawn with conventional mixes. Each stage of the investigation—ranging from selection and preparation of materials to sample moulding, testing, and data analysis—was carefully designed to comply with relevant Indian Standards and international specifications, thereby ensuring methodological rigor. Importantly, the process was also arranged to isolate the role of plastic modification, allowing the influence of each plastic type and dosage to be assessed objectively.

The binder employed in this research was a viscosity-graded paving bitumen of grade VG-30, which is approximately equivalent to 60/70 penetration grade bitumen. This particular grade was selected because it represents the most commonly used binder in India, offering proven suitability across diverse climatic conditions and traffic categories. To provide the mineral skeleton of the mix, dense-graded Bituminous Concrete (BC) aggregates were incorporated. Their gradation was chosen in accordance with the Ministry of Road Transport and Highways (MoRTH) specifications, thereby reflecting standard field practice and ensuring that the laboratory findings remain transferable to real-world applications. Overall, the experimental framework establishes a systematic approach to studying plastic-modified bituminous mixes. The progression of the work—from collection and processing of waste plastics through mix preparation and testing—is outlined schematically in Fig 1, which highlights the logical flow of activities undertaken during the study.

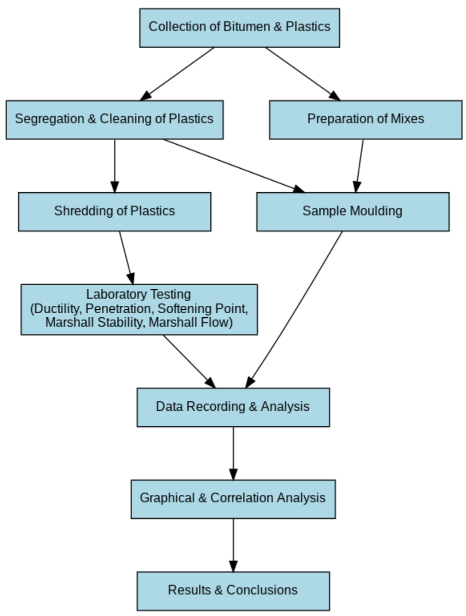

Fig.1Experimental Methodology Framework

A. *Collection and Preparation of Plastic Waste*

Six types of post-consumer thermoplastics were identified for the modification process. These included:

1. Polyethylene terephthalate (PET)
2. High-density polyethylene (HDPE)
3. Polyvinyl chloride (PVC)
4. Low-density polyethylene (LDPE)
5. Polypropylene (PP)
6. Polystyrene (PS)

These plastics were sourced from everyday municipal waste streams such as discarded bottles, packaging films, carry bags, and disposable containers. Since impurities such as dirt, food residue, and moisture can hinder the performance of modified binders, all plastic samples were subjected to thorough segregation and cleaning. After drying, they were mechanically shredded into small flakes ranging from 2 to 4 mm in size. This size range was deliberately chosen, as smaller particles facilitate better dispersion in the hot binder and reduce the risk of agglomeration during mixing.

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B. Modification of Bitumen

The incorporation of shredded plastics into the bitumen was carried out using the wet mixing process. This method was selected over the dry process because it allows more uniform dispersion of polymer within the binder, which enhances compatibility and produces more consistent results in laboratory testing.

The VG-grade binder was first heated in a thermostatically controlled container to a temperature of approximately 160 °C, which is sufficiently high to reduce the viscosity of the binder while avoiding thermal degradation. At this temperature, shredded plastic flakes were gradually introduced into the hot binder at three different dosage levels—5%, 7.5%, and 10%—based on the weight of the binder. Each mixture was subjected to mechanical shear mixing for about 30 to 45 minutes. The extended mixing time ensured that the plastic dispersed thoroughly and blended uniformly with the bitumen, thereby minimising heterogeneity.

C. Preparation of Test Specimens

For mix testing, Marshall specimens were prepared using the standard Marshall compaction procedure. Each specimen was compacted with 75 blows per face using a mechanical hammer, which simulates the heavy traffic load conditions expected in practice. Importantly, all specimens—both modified and unmodified—were prepared at the control optimum binder content (OBC). The OBC was determined beforehand for the unmodified binder, and its value was maintained consistently across all mixes to isolate the effect of plastic modification. By controlling this variable, the influence of the polymer additive could be studied without the confounding effect of variations in binder content.

D. Laboratory Testing of Materials

To characterise the properties of the modified binders, a series of conventional binder tests were conducted in accordance with Indian Standard (IS) specifications:

- **Penetration Test (IS: 1203):** Measured the hardness or consistency of the bitumen and its susceptibility to temperature variations.
- **Ductility Test (IS: 1208):** Evaluated the ability of the binder to elongate before rupture, providing insights into flexibility and cohesion.
- **Softening Point Test (IS: 1205):** Determined the temperature at which the binder attains a particular degree of softening, thus indicating its resistance to deformation under high service temperatures.

In addition to binder characterisation, the mechanical properties of the plastic-modified mixes were assessed using the Marshall stability and flow test in accordance with ASTM D1559. This test was conducted at a controlled temperature of 60 °C, which approximates the service temperature of flexible pavements in hot climatic regions. Marshall stability measured the maximum load-bearing capacity of the specimen before failure, while Marshall flow indicated the deformation that occurred at the point of maximum load. Together, these two parameters provided a comprehensive understanding of both the strength and flexibility of the mixes.

For each test condition, three replicate specimens were prepared and tested. Replication not only reduces the influence of random errors but also enhances the statistical validity of the results. The average of the three readings was reported for each condition, ensuring that the conclusions were based on consistent data rather than isolated observations.

The data obtained from binder and mix tests were systematically recorded and analysed. Comparisons were made between the unmodified control mix and the polymer-modified mixes at different substitution levels. Special emphasis was placed on identifying the dosage level and type of plastic that produced the most desirable combination of strength, durability, and workability. Correlation analysis was subsequently performed to identify relationships among the test parameters—for instance, between penetration and softening point or between Marshall stability and flow. Such relationships provided deeper insights into the mechanisms by which plastic modification influences binder performance.

In summary, the methodology involved a carefully structured sequence of steps: selection of standard paving materials, systematic processing of six categories of plastic waste, controlled wet process modification of VG-grade bitumen, and preparation of Marshall specimens at a uniform OBC. Comprehensive binder and mix tests were performed in line with IS and ASTM standards, with replication ensuring data reliability. This rigorous approach enabled the study to isolate and evaluate the impact of post-consumer plastics on the engineering properties of bituminous mixes, thus contributing to sustainable pavement research.

IV. Results and Discussions

The effect of varying proportions of waste plastic on the mechanical strength characteristics of the bituminous mixes was evaluated through Marshall stability analysis. Figure 2 presents the variation of Marshall stability with respect to plastic content across all six plastic types. A general upward trend in stability was observed as the percentage of plastic increased, suggesting that polymer addition enhances the load-bearing capacity of the bituminous mixes. Among the six plastics, polystyrene (PS) and low-density polyethylene (LDPE) at 10% modification produced the highest stability values, highlighting their potential as effective stiffening agents. High-density polyethylene (HDPE) exhibited a near-linear increase in stability throughout the dosage range, indicating a consistent reinforcing effect. In contrast, polypropylene (PP) demonstrated an optimum performance at around 7.5% substitution, beyond which the stability values plateaued or slightly declined. This non-linear trend may be attributed to limited dispersion or the onset of excessive rigidity at higher plastic levels. These observations are in broad agreement with earlier studies on polyolefin modifiers, which have reported similar patterns of performance improvement followed by a threshold beyond which benefits taper. Overall, the results indicate that the influence of plastic type and dosage is critical in optimising Marshall stability, emphasising the need for identifying an appropriate modification level for each polymer.

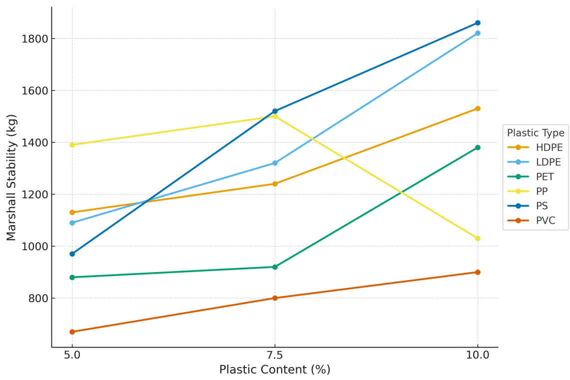

Fig. 2 Marshall stability vs plastic content for each plastic type

Figures 3 and 4, which illustrate the ductility and penetration characteristics, further emphasise the classic stiffness–flexibility trade-off.

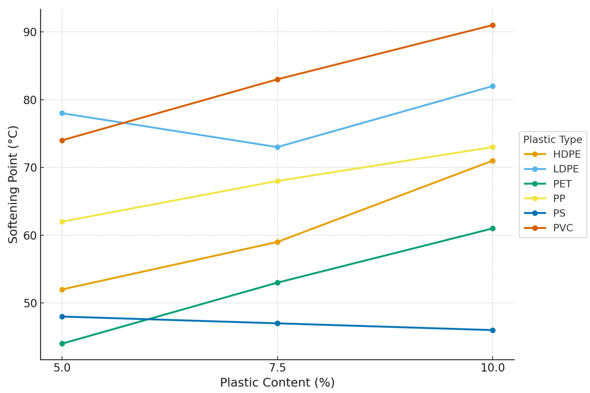

Fig. 3 Softening point vs plastic content for each plastic type

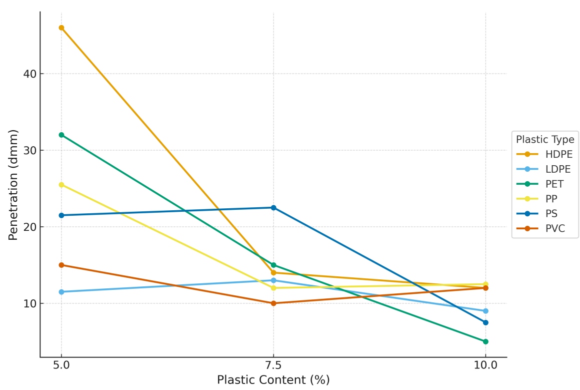

Fig. 4 Penetration vs plastic content for each plastic type

While stability and softening point values (Figure 5) generally improved with increasing plastic content, ductility and penetration showed a marked decline, particularly for LDPE and PVC at higher dosages. This indicates that although the modified binders became stronger and more resistant to deformation at elevated temperatures, they simultaneously lost some of their flexibility. Such stiffening could influence the long-term fatigue resistance of pavements under repeated traffic loading.

Marshall flow results (Figure 6) complemented these findings. Flow values for HDPE and PET remained within acceptable limits across the dosage range, suggesting a balanced performance. Conversely, PP and PS demonstrated reduced flow with increasing content, indicating a tendency toward brittleness. PVC and LDPE showed relatively higher flows at intermediate levels; however, LDPE became significantly stiffer at 10% content, aligning with its high stability values.

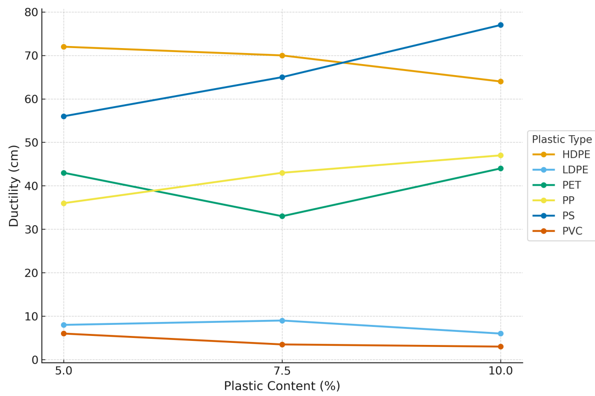

Fig. 5 Binder ductility vs plastic content for each plastic

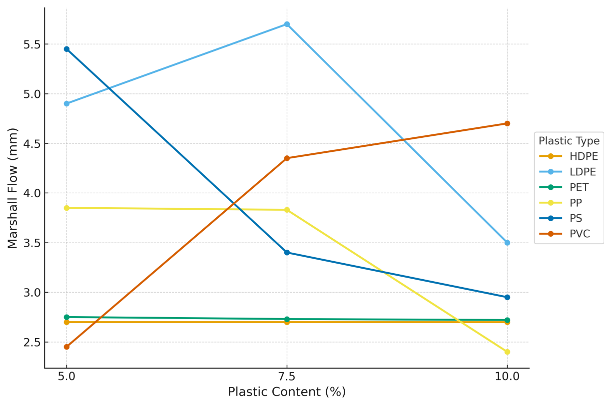

Fig. 6 Marshall flow vs plastic content for each plastic type.

The experimental results collectively demonstrate the significant influence of plastic modification on the engineering properties of bituminous mixes. Marshall stability values consistently improved with increasing plastic content, with LDPE and PS showing the highest gains at 10% dosage, indicating enhanced load-bearing capacity. HDPE also provided a steady increase, whereas PP exhibited an optimum at 7.5%, suggesting that excessive addition may lead to reduced performance.

Softening point results revealed a general upward trend for most plastics, particularly PVC and HDPE, reflecting improved resistance to high-temperature deformation. In contrast, PS showed little improvement, highlighting variation in thermal response among plastic types. Penetration values, however, decreased sharply with increasing content, confirming the stiffening effect of polymers on the binder. Ductility results supported this finding, as mixes modified with PVC and LDPE displayed considerable reductions in flexibility, while PS retained relatively higher ductility at increased dosages.

Marshall flow values generally remained within acceptable limits, though variations indicated different balance points between stiffness and flexibility across plastics. Overall, the results underline the classic trade-off: improved stability and softening resistance are often accompanied by reduced ductility and penetration. These outcomes suggest that optimum plastic content depends not only on stability gains but also on maintaining adequate flexibility for long-term pavement performance.

V. Conclusion and Recommendations

The present study provides a comprehensive evaluation of the performance of bituminous binders and mixes modified with six categories of post-consumer thermoplastics—HDPE, LDPE, PET, PP, PS, and PVC—at substitution levels of 5%, 7.5%, and 10% by weight of binder. Laboratory investigations covered a set of key parameters fundamental to pavement design, namely penetration, softening point, ductility, Marshall stability, and Marshall flow. Taken together, the findings offer valuable insights into both the potential and the limitations of waste plastics in road construction.

Across all plastic types, certain general patterns emerged. First, the softening point of the binder increased with plastic addition, reflecting greater resistance to deformation at elevated temperatures. Similarly, Marshall stability values showed significant improvements, underscoring the capacity of plastic-modified mixes to bear heavier loads. Conversely, penetration values declined, highlighting the stiffening effect of polymer modification. The response of ductility and Marshall flow, however, was more complex and strongly dependent on the type of plastic incorporated.

In terms of specific performance trends, high-density polyethylene (HDPE) at around 10% addition consistently produced balanced and reliable improvements across binder and mix properties. Polypropylene (PP), particularly at the 7.5% dosage, also demonstrated an optimal balance between enhanced strength and acceptable flexibility, making both HDPE and PP strong candidates for practical implementation. Polyethylene terephthalate (PET), especially at 10%, emerged as another broadly favorable modifier, though its use may require careful blending and process control to mitigate dispersion issues. Polystyrene (PS) displayed the capacity to generate very high stability values at 10% without severe ductility loss, a result that highlights its promise but also warrants additional field validation. On the other hand, low-density polyethylene (LDPE) and polyvinyl chloride (PVC) tended to yield stiff mixes with substantial ductility reduction at higher dosages, raising concerns about their long-term fatigue resistance and overall durability.

Based on these findings, a set of practical recommendations can be made. For agencies and practitioners seeking rapid, scalable circular-materials interventions, HDPE and PP waste streams should be prioritised for wet-process binder modification, as they provide a reliable combination of stability enhancement and workable flexibility. PET may also be deployed effectively provided blending protocols are optimised. PS, though promising in terms of stability, requires further controlled trials before large-scale adoption. LDPE and PVC should be employed cautiously, and if used, they should be combined with elasticity-restoring strategies such as blending with elastomers, crumb rubber, or other additives to counteract ductility loss.

Looking ahead, the present work can be extended in several important directions. Laboratory testing should move beyond conventional strength indicators to include moisture susceptibility, fatigue and aging resistance, and storage stability of the modified binders. Field-scale pilot projects are also essential to validate laboratory findings under real traffic and climatic conditions. Finally, comprehensive life-cycle assessment (LCA) studies should be undertaken to quantify the broader environmental and economic implications of using plastic waste in pavements.

In conclusion, the results affirm that while plastic modification of bitumen is not a universal solution, it holds substantial promise when the right type of plastic is chosen at the right dosage. A selective, evidence-based approach to plastic incorporation—emphasising HDPE, PP, and PET—can simultaneously address waste management challenges and contribute to more durable and sustainable pavements.

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Data Availability Statement

All the data used in this work is available with the corresponding author and can be obtained on request.

Declaration of Competing Interests

There is no conflict of interest against this manuscript.

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