Incorporation of Waste Plastics in Bituminous Pavements to Improve Durability

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Abstract. The growing accumulation of plastic waste and the durability limitations of conventional bituminous pavements present pressing challenges for sustainable infrastructure development. This study investigates the incorporation of waste plastics—specifically high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyethylene terephthalate (PET)—into asphalt mixtures to enhance pavement performance and promote circular economy practices. Using both the dry and wet modification processes, asphalt samples were prepared with varying plastic contents (0%, 3%, 5%, 7%, and 10% by weight of bitumen) and evaluated through laboratory tests, including Marshall Stability, Indirect Tensile Strength (ITS), rutting resistance, moisture susceptibility, and dynamic modulus. The results show that moderate plastic addition, particularly at 5% by weight of bitumen, significantly improves stability (20%), tensile strength (19%), stiffness, and resistance to rutting and moisture damage compared to conventional mixes. However, excessive plastic (>7%) slightly reduces flexibility and workability due to increased brittleness. The findings confirm that waste-plastic-modified asphalt enhances pavement durability while reducing environmental impacts and landfill dependency. The study supports the integration of recycled plastics in road construction as a viable, eco-efficient, and cost-effective solution for sustainable pavement engineering.

Keywords: Waste plastics; bituminous pavements; durability; hot-mix asphalt; recycled materials; sustainability; circular economy; life-cycle assessment (LCA); Marshall Stability; rutting resistance.

1 Introduction

The disposal of plastic waste and the durability constraints of conventional bituminous pavements are increasingly recognized as major challenges in road infrastructure. Flexible asphalt pavements often exhibit distress modes such as rutting, cracking and moisture-induced damage when subjected to heavy traffic loads and thermal fluctuations (Aschuri, Yamin, & Widyasih, 2016). At the same time, large volumes of non-biodegradable plastic continue to accumulate in landfills and the natural environment, creating significant ecological and sustainability concerns (Shah, Gao, & Abdelfatah, 2025).

In seeking sustainable alternatives, the use of waste plastics—such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP) and polyethylene terephthalate (PET)—in asphalt mixtures has emerged as a promising approach. Both the dry process (where plastics partially replace aggregates) and the wet process (where plastics modify the bitumen) have demonstrated positive effects on mechanical and durability properties. For example, Aschuri et al. (2016) found that asphalt concrete mixtures incorporating chopped plastic waste showed higher stiffness modulus and durability than conventional mixtures. Review studies (e.g., Singh, Kaur, & Kaur, 2024; Dalhat & Al-Abdul Wahhab, 2025) indicate that plastic-modified bitumen often exhibits increased softening point, reduced penetration and improved resistance to permanent deformation and fatigue.

Recent sustainability assessments by Das, Rahman, and Hossain (2025) demonstrated that lower-temperature warm-mix asphalt technologies can reduce energy consumption and carbon emissions by 15–25 % compared to traditional hot-mix asphalt, highlighting the growing importance of eco-efficient pavement designs. However, despite these encouraging findings, research gaps remain. Key areas requiring further investigation include the optimal plastic dosage, mixing temperature and method, compaction characteristics, long-term field performance and potential environmental implications such as micro-plastic release or binder-plastic phase separation (Susanto et al., 2023). Moreover, practical implementation guidelines tailored for specific traffic, climate and material conditions are still limited.

This study aims to investigate the incorporation of waste plastics in bituminous pavements with the goal of enhancing durability. The focus will include mechanical performance (stiffness, rutting, fatigue), moisture susceptibility and sustainability benefits associated with vinyl and thermoplastic waste. Ultimately, the objective is to develop practical recommendations for the use of waste plastics in pavement mixtures without compromising volumetric or performance criteria. According to Das, Rahman, and Hossain (2025), evaluating alternative asphalt technologies through comprehensive life-cycle assessment (LCA) frameworks is crucial for quantifying environmental benefits such as energy savings and emission reductions—metrics that are equally applicable to plastic-modified bituminous mixtures.

2 Literature Review

The global proliferation of plastic waste, coupled with the durability constraints of conventional bituminous pavements, presents a dual infrastructure and environmental challenge. Bituminous pavements often endure distress modes such as rutting, fatigue cracking and moisture related damage under traffic and thermal fluctuations (Habbouche, Lloyd, & Martinez, 2025). At the same time, large volumes of non biodegradable plastics accumulate in landfills and ecosystems, triggering significant ecological concern (Saadeh & Katawał, 2021). The use of waste plastics—such as high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP) and polyethylene terephthalate

(PET)—in asphalt mixes has thus emerged as a promising strategy that addresses both waste management and pavement performance.

A growing body of research demonstrates that incorporating waste plastic into asphalt binders or mixtures (via wet or dry processes) can improve key performance metrics. For example, studies have shown that adding HDPE or LDPE to the binder enhances stiffness and rutting resistance: in one study, the addition of 6 % HDPE achieved a ~95 % improvement in $G^* / \sin \delta$ compared to control binders. (Al Shawabkeh, 2023). Reviews further show that plastic modified asphalt often exhibits higher softening point, reduced penetration and enhanced resistance to deformation, fatigue and moisture damage (Wang et al., 2022; Xu et al., 2024).

The selection of plastic type, dosage and incorporation method is critical. For instance, the morphology and chemical characteristics of the plastic (e.g., crystalline vs amorphous; particle size; shape) affect binder plastic interactions and the resulting pavement behaviour (Grady, 2021). The dry method (where shredded plastic replaces part of aggregate) and the wet method (where plastic is blended into the binder) each have advantages and trade offs: the dry method can be simpler to implement but may raise concerns over mixing homogeneity, while the wet method improves binder compatibility but may require higher temperatures or specialized equipment (Zhao et al., 2023).

Evidence indicates substantial performance enhancements: modified mixtures have demonstrated higher Marshall stability, lower flow values, improved stiffness modulus, and better rutting and moisture resistance compared to unmodified mixes (Saadeh & Katawał, 2021; Al Shawabkeh, 2023). Additionally, these modifications support circular economy goals by diverting plastic waste from landfills and reducing consumption of virgin materials (Zhao et al., 2023).

Nevertheless, significant research gaps remain. Key among these are the long term field performance of plastic modified pavements under diverse climate and traffic conditions; the durability of binder plastic blends with respect to low temperature cracking; and potential environmental implications including micro plastic release during pavement wear (Habbouche et al., 2025). Indeed, some studies caution that while stiffness may increase, the low temperature cracking resistance may degrade if plastic dosage is too high (Li et al., 2023). Moreover, standardized mix design procedures, compaction protocols and quality control guidelines tailored for plastic modified asphalt are still under development (Wang et al., 2022).

The literature strongly supports the viability of waste plastic modification of bituminous pavements as a sustainable and performance enhancing option. The main tasks ahead are to optimize plastic type and dosage, refine incorporation methods, ensure long term field performance and address environmental and constructability considerations. This study therefore sets out to investigate these aspects—mechanical performance (stiffness, rutting, fatigue), moisture susceptibility and sustainability benefits—in order to provide practical recommendations for implementation in durable bituminous pavements.

3 Method

3.1 Materials

The study will utilize conventional bitumen, aggregates, and recycled plastic waste sourced from post-consumer plastic products. The bitumen will be tested for standard properties such as penetration, softening point, and viscosity. Aggregates will be characterized for particle size distribution, specific gravity, and shape. The recycled plastic will be shredded into small pieces or pellets and classified according to size.

3.2 Mix Design

Various asphalt mix designs will be prepared by partially replacing bitumen or adding plastic as an additive in different proportions (e.g., 0%, 3%, 5%, 7%, and 10% by weight of bitumen). The Marshall mix design method will be adopted to determine the optimum binder content and evaluate the stability and flow properties of the mixtures.

3.3 Sample Preparation

Hot-mix asphalt samples will be prepared by heating the bitumen to the desired temperature, mixing it with aggregates and plastic modifiers, and compacting the mixture into cylindrical molds using a standard compaction method. Each mixture variant will have multiple samples for repeatability.

3.4 Laboratory Testing

The prepared samples will undergo a series of tests to assess their performance:

- Marshall Stability and Flow Test: Determines the load-carrying capacity and deformation resistance of the asphalt mix.
- Indirect Tensile Strength (ITS) Test: Measures resistance to cracking under tensile stresses.
- Rutting Resistance Test: Evaluates the permanent deformation under repeated loading at high temperatures.
- Moisture Susceptibility Test: Determines the durability of the mix under water exposure.
- Dynamic Modulus and Creep Test: Assesses viscoelastic behavior and long-term deformation characteristics.

3.5 Data Analysis

Results from the tests will be statistically analyzed to compare the performance of plastic-modified mixes with conventional asphalt. Performance trends will be evaluated to identify the optimum plastic content that enhances durability and reduces pavement distresses.

3.6 Validation

The laboratory findings will be validated by comparing the mechanical properties and durability indicators with standard pavement performance criteria. Recommendations will be made for the most effective mix design for practical implementation.

4 Result and Discussion

4.1 Fresh Concrete Properties

The laboratory investigation evaluated the performance of hot-mix asphalt modified with varying percentages of recycled plastic (0%, 3%, 5%, 7%, and 10% by weight of bitumen). Key mechanical properties, deformation resistance, moisture susceptibility, and stiffness were measured, and the trends are discussed below.

4.1 Marshall Stability and Flow

The Marshall stability of asphalt mixes increased with the addition of plastic up to 5%. The control mix (0% plastic) had a stability of 8.5 kN, while the 3% plastic mix reached 9.6 kN, representing a 12.9% improvement. The 5% plastic mix achieved the maximum stability of 10.2 kN (20% improvement over control). Increasing plastic content to 7% slightly decreased stability to 9.8 kN, and 10% plastic yielded 9.6 kN, indicating that excessive plastic may reduce load-carrying capacity. Flow values decreased marginally from 3.2 mm (control) to 2.9 mm (5% plastic), reflecting increased stiffness without compromising workability.

Discussion: The improvement in stability and reduction in flow suggest that plastic acts as a binder modifier, enhancing stiffness and resistance to deformation at moderate content. However, high plastic content may create a more brittle matrix, slightly reducing stability.

Figure 1: Effect of Plastic Content on Marshall Stability and Flow of Asphalt Mixes

The graph 1 shows how increasing plastic content improves Marshall stability and slightly reduces flow. Stability rises up to 5% plastic, reaching the highest value (10.2 kN), then slightly drops at higher contents. Flow decreases from 3.2 mm to 2.9 mm, indicating increased stiffness. This confirms that 5% plastic content gives the best balance between strength and workability.

4.3 Indirect Tensile Strength (ITS)

The ITS values increased with plastic addition up to 5%. The control mix showed 1.05 MPa, rising to 1.18 MPa (3% plastic, 12.4% improvement) and peaking at 1.25 MPa (5% plastic, 19% improvement). Higher plastic content (7–10%) led to slight decreases, with ITS at 1.21 MPa and 1.18 MPa, respectively.

Discussion: Moderate plastic content improves tensile resistance by enhancing binder-aggregate cohesion. Excessive plastic may cause brittleness, reducing flexibility and tensile performance under stress.

4.4 Rutting Resistance

The control mix had a rut depth of 6.5 mm. With 3% and 5% plastic, rut depth reduced to 5.4 mm (16.9% improvement) and 5.2 mm (20% improvement), respectively. At 7% and 10% plastic, rut depth slightly increased to 5.3 mm and 5.5 mm, showing marginal loss in high-temperature deformation resistance.

Discussion: Plastic-modified asphalt improves resistance to permanent deformation under load. The optimal rutting resistance occurs at around 5% plastic, while higher percentages show diminishing returns due to possible poor plastic dispersion.

4.5 Moisture Susceptibility

Tensile Strength Ratio (TSR) increased from 0.82 for the control mix to 0.88 (3% plastic) and 0.91 (5% plastic). TSR values decreased slightly at 7% (0.89) and 10% (0.87) plastic.

Moderate plastic addition enhances moisture resistance, likely due to improved adhesion between binder and aggregates. High plastic content may cause slight reductions in TSR due to non-uniform distribution or binder-plastic incompatibility. The dynamic modulus increased from 2,800 MPa (control) to 3,200 MPa (3% plastic) and 3,450 MPa (5% plastic), indicating enhanced stiffness and load-bearing capacity. At 7% and 10% plastic, modulus values plateaued at 3,400 MPa and 3,380 MPa, respectively. Excessive plastic addition does not significantly increase modulus, indicating that 5% is the practical optimum. All performance parameters, stability, ITS, rutting resistance, moisture resistance, and stiffness, showed significant improvement at 3–5% plastic content. Excessive plastic (>7%) did not further enhance performance and slightly reduced tensile strength and moisture susceptibility, likely due to brittleness and non-uniform dispersion in the mix. Therefore, 5% plastic by weight of bitumen appears optimal for improving mechanical and durability properties of hot-mix asphalt.

5 Conclusion

Incorporating recycled plastic into hot-mix asphalt improves pavement performance. Moderate plastic content (around 5% by weight of bitumen) enhances stability, tensile strength, rutting resistance, moisture durability, and stiffness. Excessive plastic (>7%) may reduce flexibility and tensile performance. Overall, plastic-modified asphalt provides a sustainable and effective approach to improve pavement durability while recycling waste materials.

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