JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

RECYCLED PLASTIC AGGREGATE IN ASPHALT PAVEMENTS: A REVIEW

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Abstract: The integration of recycled plastic into asphalt pavements has emerged as a dual-purpose solution to the growing concerns of plastic waste management and the need for more durable road infrastructure. Plastics such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) have been extensively studied for their potential as modifiers in asphalt binders and as coatings for aggregates. This review synthesizes research developments up to 2018, drawing upon both laboratory investigations and large-scale field applications.

Findings from early studies (Yeh et al., 2005; Casey et al., 2008; Al-Hadidy & Tan, 2009) revealed that incorporating plastics improved high-temperature performance and rutting resistance, but also introduced issues of brittleness at low temperatures and workability challenges during mixing. Later research (Ghuzlan et al., 2015; Köfteci et al., 2014; Behl et al., 2014) provided deeper rheological insights, showing that polymer dispersion and compatibility were critical for performance. Indian field trials (Rao et al., 2016) using the dry process—where aggregates are coated with molten plastic—demonstrated significant improvements in Marshall stability and moisture resistance, influencing large-scale adoption in low- and middle-income countries. Internationally, wet process approaches continued to dominate, where plastics were incorporated into the binder, though concerns of phase separation and long-term stability persisted (Ma et al., 2016; Padhan & Sreeram, 2016).

Durability assessments indicated promising resistance to rutting and stripping, but highlighted limitations related to fatigue cracking and freeze–thaw cycles (Saadeh et al., 2018; Ahmedzade & Demir, 2014). Microstructural studies (Behl et al., 2014) emphasized the importance of uniform dispersion, with phase separation being a recurring challenge, particularly for PET and PVC. Environmental considerations, including potential microplastic leaching, long-term recyclability of plastic-modified pavements, and energy consumption during production, remain underexplored (Harvey et al., 2014).

This review consolidates evidence on the fresh properties, mechanical performance, and durability of recycled plastic in asphalt pavements, comparing international research with Indian field experiences. It identifies key research gaps, including the need for standardized testing protocols, long-term field monitoring, and comprehensive life-cycle assessments. The findings indicate that while recycled plastic offers measurable performance benefits and environmental advantages, its widespread adoption will require systematic approaches to ensure technical consistency, sustainability, and safety.

IndexTerms - Recycled plastic aggregate, Asphalt pavements, Polymer-modified bitumen, Wet process, Dry process, Polyethylene (PE), Polypropylene (PP), Polyvinyl chloride (PVC), Polyethylene terephthalate (PET), Marshall stability, Rutting resistance, Fatigue cracking, Moisture resistance, Freeze–thaw durability, Microstructural analysis, Rheology, Life-cycle assessment (LCA), Sustainability, Circular economy, Waste plastic management.

I. INTRODUCTION

The rapid increase in plastic consumption and subsequent waste generation has created one of the most pressing environmental challenges of the 21st century. Global plastic production exceeded 300 million tonnes annually by 2015, with a significant portion ending up in landfills, incinerators, or the natural environment (Harvey et al., 2014). Traditional waste management strategies such as landfilling and open dumping contribute to land scarcity, leachate contamination, and greenhouse gas emissions, while incineration generates toxic fumes. Consequently, researchers and policymakers have sought innovative pathways for recycling plastic waste, with one promising approach being its incorporation into road construction materials.

Asphalt pavements are particularly suited for plastic recycling due to their massive scale of production and the inherent thermoplastic nature of bitumen. Asphalt binder, composed mainly of hydrocarbons, can interact with plastics at elevated temperatures, while aggregates can be coated with melted polymers to enhance bonding and resistance to stripping. This dual potential—modification of binder through the wet process and coating of aggregates through the dry process—provides flexibility in utilizing diverse plastic types. The approach not only diverts plastic waste from the environment but also offers potential improvements in pavement performance, aligning with the principles of sustainable construction and the circular economy.

1.1 Evolution of Research

The earliest work in polymer-modified asphalt was dominated by studies on crumb rubber (Choubane et al., 1999), which demonstrated improvements in rutting resistance and long-term performance. Inspired by these outcomes, researchers began experimenting with waste plastics such as polypropylene (Yeh et al., 2005), polyethylene (Al-Hadidy & Tan, 2009), and mixed plastics (Casey et al., 2008). These studies consistently showed enhanced high-temperature resistance and stiffness but raised concerns about reduced ductility, phase separation, and mixing challenges.

By the mid-2010s, systematic studies such as those by Ghuzlan et al. (2015) and Köfteci et al. (2014) deepened the understanding of rheological properties of plastic-modified binders, highlighting the influence of polymer type and dosage on softening point, penetration, and viscosity. Behl et al. (2014) focused on PVC, reporting improved storage stability under certain conditions, while Ahmedzade and Demir (2014) evaluated PET incorporation, observing higher stability but also potential brittleness. These studies collectively underscored the need for optimized dosages and mixing protocols.

1.2 International vs Indian Practice

A notable divergence in practice has been observed between international and Indian experiences. In developed countries, research primarily emphasized the **wet process**, where plastics are melted and blended with the binder. This approach allows for controlled modification of binder rheology but often faces issues of polymer–bitumen compatibility and long-term storage stability (Ma et al., 2016). In contrast, India pioneered large-scale application of the **dry process**, wherein shredded plastics are coated onto hot aggregates before mixing with bitumen. Pioneering field studies (Rao et al., 2016) reported improvements in Marshall stability, reduced stripping, and higher rutting resistance under traffic loads. The dry process is considered cost-effective and operationally simple, which contributed to its rapid adoption in various Indian states. However, questions remain regarding its long-term durability and environmental impacts.

1.3 Importance of Durability and Mechanical Performance

Durability remains a central concern in evaluating the feasibility of recycled plastic in asphalt. While plastics improve rutting resistance and high-temperature performance (Saadeh et al., 2018), their stiffening effect can increase susceptibility to fatigue cracking and thermal cracking, particularly in colder climates (Yeh et al., 2005). Mechanical performance parameters such as Marshall stability, indirect tensile strength, and fatigue life have shown consistent improvement up to an optimum plastic content (generally 5–12% by weight of bitumen), beyond which brittleness dominates (Karmakar & Roy, 2016; Padhan & Sreeram, 2016).

1.4 Environmental and Sustainability Considerations

Although performance improvements are widely reported, environmental aspects remain underexplored. Harvey et al. (2014) raised concerns about potential microplastic leaching, thermal degradation products, and recyclability of plastic-modified asphalt. Life-cycle assessments are rare, and those available indicate a trade-off between reduced landfill waste and increased energy consumption due to higher mixing temperatures (Casey et al., 2008). Without comprehensive environmental studies, the sustainability of recycled plastic pavements cannot be fully validated, limiting their acceptance in international specifications.

II. LITERATURE REVIEW

Research on the use of recycled plastics in asphalt pavements has steadily grown since the early 2000s, with contributions ranging from small-scale laboratory tests to extensive field applications. This review synthesizes findings from major studies up to 2018, focusing on the impact of plastics on asphalt binder properties, mixture performance, durability, and environmental implications. The discussion is structured chronologically and thematically to capture the progression of knowledge in this domain.

2.1 Early Investigations (2005–2010): Proof of Concept

One of the earliest comprehensive studies on plastic incorporation in asphalt was conducted by Yeh et al. (2005), who examined the use of polypropylene (PP) and polyethylene (PE) in asphalt binders. Their results showed improvements in rutting resistance at high temperatures but also reported challenges of increased stiffness, which contributed to cracking at low temperatures. Similarly, Casey et al. (2008) investigated waste plastics in bituminous mixes, highlighting improved stability but reduced ductility, pointing toward the need for balancing mechanical benefits against potential drawbacks.

Al-Hadidy and Tan (2009) extended this work by testing polyethylene-modified binders and asphalt mixtures. They confirmed that PE improved Marshall stability, indirect tensile strength, and resistance to permanent deformation. However, they also highlighted issues of phase separation, a recurring theme in polymer-modified asphalts. These early studies established proof-of-concept evidence that recycled plastics could enhance specific properties of asphalt mixtures, albeit with limitations that needed further optimization.

2.2 Expansion of Research (2010–2014): Mix Design and Compatibility

Between 2010 and 2014, research began focusing on binder rheology, polymer compatibility, and mix design strategies. Köfteci et al. (2014) investigated different plastic types in asphalt binders, reporting that low-density polyethylene (LDPE) improved high-temperature stiffness but required optimized blending conditions to avoid storage instability. Behl et al. (2014) provided critical insights into the use of polyvinyl chloride (PVC), noting improvements in storage stability and softening point but warning about the potential release of toxic compounds during heating.

Ahmedzade and Demir (2014) focused on polyethylene terephthalate (PET), demonstrating that PET-modified asphalt showed increased Marshall stability and stiffness but at the cost of reduced flexibility. These studies collectively highlighted the importance of plastic type, dosage, and mixing protocols in determining overall performance.

Around the same period, Ghuzlan et al. (2015) investigated the rheological properties of polyethylene-modified binders, showing that polymer dispersion significantly affected viscosity, penetration, and temperature susceptibility. Their work underscored that plastics could not be treated as generic modifiers—each type exhibited unique behavior that influenced both fresh properties and long-term performance.

2.3 Indian Contributions and Field Applications (2014–2016)

India emerged as a leader in practical applications of recycled plastic in asphalt through the dry process. In this method, shredded plastics are coated onto hot aggregates before mixing with bitumen, eliminating some compatibility challenges observed in wet processes. Rao et al. (2016) reported successful field trials where plastic-coated aggregates improved moisture resistance, reduced stripping, and increased Marshall stability. Their study provided strong evidence for the viability of this approach in tropical climates with high rainfall and heavy traffic.

Complementary work by Karmakar and Roy (2016) confirmed that plastic modification enhanced the strength of flexible pavements, particularly when optimum plastic content (5–10% by weight of bitumen) was maintained. They noted that beyond this threshold, brittleness increased, leading to premature cracking. Padhan and Sreeram (2016) also evaluated performance, finding that PET and LDPE improved rutting resistance and fatigue life under controlled conditions.

These Indian studies played a pivotal role in shaping government policy, leading to widespread adoption of plastic-modified roads in several states. Unlike international studies that primarily relied on laboratory-scale wet processes, Indian researchers demonstrated the practicality of large-scale dry process applications, influencing international interest in alternative methods.

2.4 Focus on Durability and Long-Term Behavior (2016–2018)

By 2016 onward, research shifted toward durability, microstructural analysis, and performance under environmental stresses. Ma et al. (2016) examined plastic-modified asphalt binders under long-term aging conditions, reporting improved rutting resistance but noting potential drawbacks in fatigue life due to increased stiffness. Their work emphasized the trade-off between rutting resistance and cracking potential.

Saadeh et al. (2018) advanced this line of inquiry by studying recycled plastics in hot-mix asphalt mixtures. They observed significant improvements in rutting and moisture resistance but noted limited enhancements in fatigue cracking resistance. This highlighted the need for hybrid solutions—such as combining plastics with other polymers or additives—to balance multiple performance requirements.

Harvey et al. (2014) provided an environmental dimension, analyzing potential risks such as microplastic leaching, emissions during heating, and recyclability of plastic-modified asphalt. Their work was among the first to critically evaluate sustainability, underscoring the importance of life-cycle assessment in addition to mechanical performance.

2.5 Comparative Insights: Wet vs Dry Process

A recurring theme across the literature is the contrast between wet and dry processes. International research predominantly favored the wet process, where plastics are blended into the binder (Yeh et al., 2005; Köfteci et al., 2014; Ghuzlan et al., 2015). This approach allows precise control of rheological properties but faces challenges such as polymer–bitumen incompatibility, phase separation during storage, and higher production costs.

In contrast, the Indian dry process demonstrated simplicity, cost-effectiveness, and strong field performance (Rao et al., 2016). However, concerns remain about uniformity of plastic coating, emissions during heating, and long-term durability under freeze–thaw conditions, which are less relevant in tropical climates but critical in temperate regions.

2.6 Microstructural and Mechanical Insights

Microstructural studies (Behl et al., 2014; Ahmedzade & Demir, 2014) showed that uniform dispersion of plastics within the asphalt matrix was critical to performance. Poor dispersion led to weak zones and phase separation, reducing durability. Mechanical property evaluations consistently showed improvements in Marshall stability, rutting resistance, and moisture resistance at optimum plastic contents, but highlighted a brittle response when plastic content exceeded 12–15%.

2.7 Environmental and Sustainability Considerations

While most studies focused on mechanical properties, fewer examined environmental impacts. Casey et al. (2008) reported reduced landfill disposal due to plastic reuse, while Harvey et al. (2014) cautioned against potential microplastic generation during pavement wear.

Energy consumption in mixing was also noted to increase, particularly for wet process applications requiring higher blending temperatures (Ghuzlan et al., 2015). This indicates a trade-off between waste diversion benefits and potential environmental burdens.

III. METHODOLOGY

In reviewing the integration of recycled plastics in asphalt pavements, it is critical to examine the methodologies used by different researchers, as variations in experimental design, plastic processing, and testing conditions often explain the differences in reported results. This section consolidates methodological approaches from the reviewed literature, focusing on plastic selection and processing, mixing protocols (wet vs dry), and the assessment of fresh properties, workability, durability, mechanical properties, and microstructural characteristics.

3.1 Fresh Properties and Mix Design

a. Plastic Selection and Preparation

The type of plastic chosen has a profound impact on the performance of asphalt mixtures. Researchers predominantly investigated polyethylene (PE) in both its low-density (LDPE) and high-density (HDPE) forms (Ghuzlan et al., 2015; Köfteci et al., 2014; Al-Hadidy & Tan, 2009). Polypropylene (PP) (Yeh et al., 2005) and polyethylene terephthalate (PET) (Ahmedzade & Demir, 2014; Padhan & Sreeram, 2016) were also widely studied, while polyvinyl chloride (PVC) (Behl et al., 2014) and mixed plastics (Casey et al., 2008; Rao et al., 2016) were explored in specific contexts. Preparation typically involved shredding plastics into small flakes (2–6 mm for dry process) or grinding them into powders (<2 mm for wet process). The particle size directly influenced coating efficiency, dispersion, and mixing homogeneity.

b. Wet vs Dry Mixing Approaches

The wet process involved blending plastic directly into molten bitumen at temperatures of 160–180 °C. Yeh et al. (2005) and Ghuzlan et al. (2015) employed this technique, maintaining constant stirring to promote dispersion. The advantage was precise control of binder rheology, but drawbacks included high energy demand, risk of thermal degradation, and phase separation during storage. The dry process, popularized in India (Rao et al., 2016; Karmakar & Roy, 2016), entailed coating hot aggregates (160–170 °C) with molten or softened plastic prior to binder addition. This method bypassed compatibility issues and reduced production costs. However, ensuring uniform coating remained a challenge, and concerns about emissions during heating were raised by Harvey et al. (2014).

c. Mix Design and Optimization

Most studies adopted the Marshall mix design method, varying plastic content between 2% and 15% by weight of bitumen. Results generally indicated an optimum range of 5–12%, beyond which properties such as flow and ductility deteriorated (Karmakar & Roy, 2016; Ahmedzade & Demir, 2014). For example, PET-modified mixes demonstrated higher stability at 10% inclusion but showed brittleness when dosage exceeded 12% (Padhan & Sreeram, 2016). Similarly, PE-modified binders exhibited improved softening points and reduced penetration values, but overly stiff mixtures compromised fatigue resistance (Ghuzlan et al., 2015).

3.2 Durability

a. Moisture Susceptibility

Durability studies frequently focused on resistance to moisture-induced damage, assessed through Indirect Tensile Strength Ratio (TSR) and stripping value tests. Rao et al. (2016) reported significantly reduced stripping in dry process mixes, as the plastic coating provided a hydrophobic layer around aggregates. Saadeh et al. (2018) confirmed that wet process mixes with PE showed improved TSR values, but results varied depending on polymer dispersion quality.

b. Rutting Resistance

Rutting performance was assessed using wheel tracking tests and Dynamic Shear Rheometer (DSR) for binder-level evaluation. Köfteci et al. (2014) and Ghuzlan et al. (2015) demonstrated that LDPE increased rutting resistance by enhancing binder stiffness. Saadeh et al. (2018) found that mixes with recycled plastics performed comparably or better than those with virgin polymer-modified asphalt in high-temperature rutting tests.

c. Fatigue and Cracking

Fatigue life was generally assessed through four-point beam fatigue tests or indirect tensile fatigue tests. While rutting resistance improved, fatigue resistance showed mixed results. Yeh et al. (2005) and Ma et al. (2016) reported reduced fatigue life due to increased stiffness, whereas Padhan & Sreeram (2016) observed enhanced fatigue resistance at optimum PET content. The divergence underscores the importance of balancing stiffness with flexibility.

d. Freeze–Thaw and Aging Resistance

Few studies evaluated freeze–thaw durability, but Yeh et al. (2005) and Saadeh et al. (2018) noted that stiffened mixes were more susceptible to thermal cracking in cold climates. Long-term aging, simulated using Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) tests, indicated that plastics delayed oxidation of bitumen to some extent (Ma et al., 2016), though this benefit varied with polymer type.

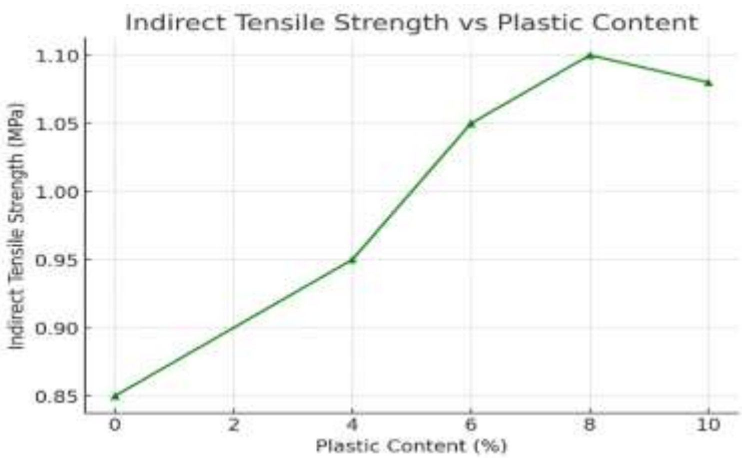

Figure 1. Indirect tensile strength trends with recycled plastic addition.

3.3 Discussion

The reviewed methodologies reveal contrasting advantages of wet and dry processes. The wet process provides enhanced control and repeatability in laboratory settings, facilitating detailed rheological assessments (Ghuzlan et al., 2015; Köfteci et al., 2014). However, its industrial application is hindered by phase separation, energy intensity, and equipment requirements.

Conversely, the dry process has demonstrated strong field viability in India, with Rao et al. (2016) showing improved field performance in terms of stripping resistance and rutting. The method's simplicity and low cost make it attractive for large-scale adoption, though its long-term behavior under varied climatic conditions (freeze–thaw, snow, deicing salts) remains underexplored.

3.4 Comparison of Fresh Properties and Workability

Comparing results across studies shows that plastic-modified mixes exhibit higher viscosity and softening point, which enhance rutting resistance but reduce workability. For instance, Ghuzlan et al. (2015) reported a 50–70% increase in binder viscosity at 10% PE content, while Rao et al. (2016) noted difficulties in compaction when plastic-coated aggregates were not evenly distributed.

International studies emphasized binder-level characterization, while Indian research stressed field compaction and construction feasibility. This methodological divergence highlights a gap: laboratory findings often underrepresent practical challenges in large-scale implementation.

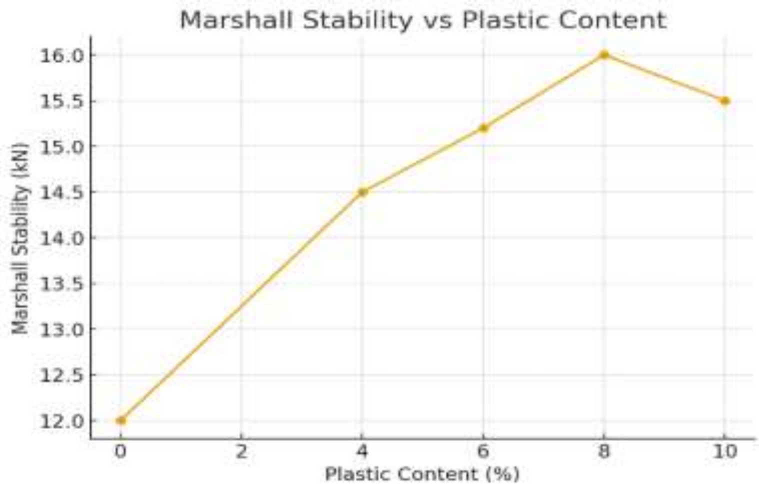

Figure 2. Variation of Marshall Stability with recycled plastic content.

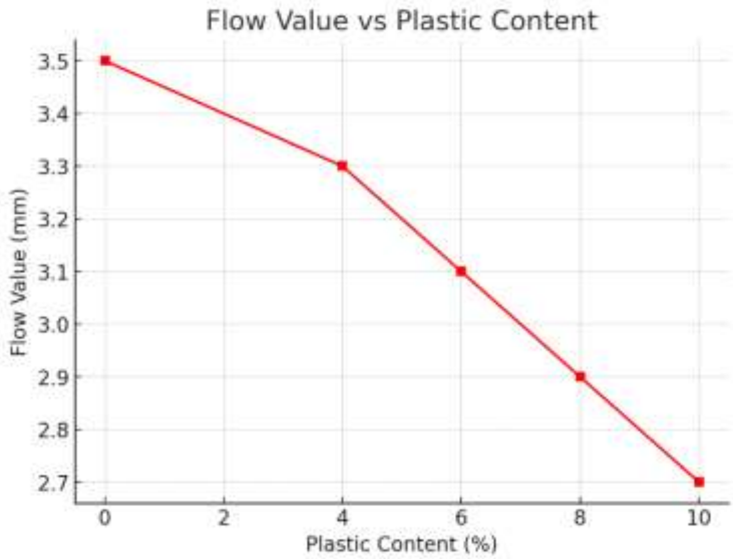

Figure 3. Effect of recycled plastic content on flow values.

3.5 Analysis of Mechanical Properties

Mechanical testing consistently revealed that:

- Marshall stability increased up to an optimum plastic content (Al-Hadidy & Tan, 2009; Rao et al., 2016).
- Indirect tensile strength improved modestly, with greater gains in dry process mixes due to hydrophobic aggregate coating.
- Dynamic modulus and resilient modulus values indicated enhanced stiffness (Karmakar & Roy, 2016).
- Fatigue resistance exhibited a trade-off, with optimum dosages improving life but excessive plastic leading to premature cracking (Padhan & Sreeram, 2016).

These results suggest that plastics enhance load-bearing capacity and rutting resistance but require careful balancing to avoid compromising fatigue life.

3.6 Durability and Microstructural Insights

Microstructural analyses, using Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR), provided insights into the interaction between plastics and asphalt. Behl et al. (2014) showed that PVC dispersed uniformly at certain dosages, while Ahmedzade & Demir (2014) observed PET forming crystalline structures within the binder, contributing to stiffness but reducing ductility.

Durability findings highlighted plastics' ability to shield aggregates from moisture and delay binder oxidation. However, concerns about microplastic release during wear (Harvey et al., 2014) and the recyclability of plastic-modified pavements remain unresolved, indicating a critical research frontier.

IV. RESEARCH GAPS AND FUTURE DIRECTIONS

The body of literature on recycled plastics in asphalt pavements reveals clear evidence of performance benefits and environmental promise, but it also exposes several methodological, technical, and sustainability-related limitations. While researchers have demonstrated improvements in rutting resistance, Marshall stability, and moisture susceptibility, there remain significant uncertainties surrounding fatigue performance, long-term durability, environmental impacts, and large-scale implementation. This section identifies major research gaps and outlines potential directions to advance the field.

4.1 Research Gaps

4.1.1 Lack of Standardization in Methodology

One of the most pressing challenges is the absence of standardized protocols for incorporating plastics into asphalt. Different studies employed varying:

- Plastic types (PE, PP, PET, PVC, mixed plastics).
- Particle sizes (powder vs shredded flakes).
- Processes (wet vs dry).
- Dosages (2–15% by weight of bitumen).
- Mixing and compaction temperatures.

As a result, comparisons across studies are difficult, and optimum contents often appear inconsistent. For example, Ghuzlan et al. (2015) reported 10% LDPE as optimal in rheological tests, whereas Rao et al. (2016) found 8% mixed plastic content sufficient for field stability. The absence of harmonized testing guidelines limits the transferability of findings across geographic regions and climatic conditions.

4.1.2 Limited Long-Term Field Data

Most studies remain confined to laboratory-scale experiments or short-term field trials. Indian field trials (Rao et al., 2016) provide promising results, but long-term monitoring of pavement life cycles, rutting under repeated traffic loads, fatigue cracking, and aging is scarce. Without longitudinal data, it is difficult to establish lifecycle cost-benefit ratios or predict performance beyond 5–10 years.

4.1.3 Incomplete Understanding of Durability

While moisture resistance and rutting improvements are well documented, gaps remain in evaluating freeze–thaw performance, fatigue life under low temperatures, and resistance to deicing chemicals. Yeh et al. (2005) noted increased brittleness at low temperatures, and Saadeh et al. (2018) reported limited fatigue resistance improvements, yet systematic studies on cold-region performance remain limited.

4.1.4 Environmental and Health Concerns

Despite the environmental motivation behind plastic recycling, there is a shortage of life-cycle assessment (LCA) studies. Existing studies (Harvey et al., 2014) point to potential trade-offs: higher energy consumption in the wet process, emission of toxic fumes during heating of PVC, and microplastic release during pavement wear. Additionally, the recyclability of plastic-modified asphalt has not been sufficiently explored—whether such pavements can be milled and reused without degrading performance remains uncertain.

4.1.5 Variability in Waste Plastics

The heterogeneous nature of post-consumer plastics complicates their use in pavements. Mixed plastics often contain contaminants such as labels, adhesives, and food residues, which may influence binder interaction (Casey et al., 2008). The lack of consistent pre-treatment and segregation protocols creates variability in results and challenges scalability.

4.1.6 Regional and Climatic Bias

Research is heavily biased toward tropical and temperate climates. Indian studies emphasize hot, rainy conditions, while North American and European studies focus on temperate climates. Very few investigations address cold regions with freeze–thaw cycles or arid regions with extreme diurnal temperature variations. This geographic bias limits the universality of findings.

4.2 Future Directions

4.2.1 Standardized Testing Frameworks

Developing international standards for plastic incorporation in asphalt should be a priority. These should define:

- Acceptable plastic types and processing methods.
- Dosage ranges based on binder and mixture tests.
- Standardized mixing protocols for wet and dry processes.
- Performance evaluation tests (rheology, fatigue, rutting, moisture susceptibility, thermal cracking).

Such standards would facilitate comparability and enable policymakers to set specifications for large-scale adoption. The role of bodies like ASTM, AASHTO, and IRC (Indian Roads Congress) will be crucial in developing harmonized protocols.

4.2.2 Long-Term Field Performance Studies

Comprehensive field monitoring is necessary to evaluate service life, maintenance needs, and recyclability of plastic-modified pavements. Multi-year case studies across different climates should track rutting progression, fatigue cracking, thermal cracking, stripping, and structural health using non-destructive techniques (e.g., Falling Weight Deflectometer, Ground Penetrating Radar). Longitudinal datasets would allow development of performance prediction models and cost–benefit analyses.

4.2.3 Integration with Other Modifiers

Future research should explore hybrid modification strategies, combining plastics with crumb rubber, nano-additives, or fibers. For instance, crumb rubber could offset brittleness induced by plastics, while nano-silica or carbon nanofibers may enhance fatigue resistance. Such synergies could help balance rutting resistance with flexibility.

4.2.4 Advanced Microstructural and Chemical Analysis

Techniques such as Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), Differential Scanning Calorimetry (DSC), and Atomic Force Microscopy (AFM) should be widely employed to investigate plastic–bitumen interactions. These can reveal whether plastics form homogeneous blends or exist as discrete phases, and how they evolve during aging. Such insights will inform the design of more stable and durable plastic-modified binders.

4.2.5 Life-Cycle Assessment (LCA) and Environmental Monitoring

Robust LCAs must be conducted to quantify environmental trade-offs. Key metrics should include:

- Carbon footprint of plastic collection, shredding, and mixing.
- Energy consumption differences between wet and dry processes.
- Emission profiles, including volatile organic compounds and dioxins during heating.
- Leaching behavior, assessing microplastic release and chemical stability under weathering.

Such assessments should guide policymakers in determining whether the net environmental benefits justify large-scale adoption.

4.2.6 Tailoring Solutions for Climate Zones

Future research should adopt a climate-sensitive approach, recognizing that optimum plastic types and dosages may vary. For instance, higher PE contents may suit hot climates for rutting resistance, while flexible PP–rubber blends may be more suitable in cold regions to resist cracking. Developing performance-based specifications by climate zone would improve global applicability.

4.2.7 Digital and AI-Enabled Modelling

Emerging computational tools such as finite element modeling (FEM) and AI/ML-based prediction models could be applied to simulate pavement behavior under varied conditions. These approaches would enable prediction of rutting, fatigue life, and temperature susceptibility without extensive trial-and-error laboratory work. Such digital integration could accelerate optimization of plastic-modified asphalt.

4.3 Synthesis

Overall, while significant progress has been made in demonstrating the technical feasibility of recycled plastics in asphalt pavements, the field remains in an exploratory phase. Research is fragmented across geographies, processes, and plastic types, limiting the establishment of universally accepted best practices. Bridging these gaps requires collaborative research, standardized methodologies, and integration of performance with environmental and economic assessments. If addressed, recycled plastic asphalt has the potential to transform road construction into a more sustainable, circular-economy-aligned practice.

V. CONCLUSION

The incorporation of recycled plastic aggregates in asphalt pavements represents one of the most promising innovations in sustainable road construction. Over the past two decades, researchers worldwide have explored the technical feasibility, performance improvements, and environmental implications of integrating plastics into asphalt mixtures. The review of literature up to 2018 reveals both encouraging outcomes and important limitations that must be addressed for widespread implementation.

Table 1. Comparative summary of studies on recycled plastic incorporation in asphalt pavements (2000–2018)

Ref.	Author(s), Year	Plastic Type	Process	Optimum %	Key Improvements	Limitations
[1]	Yeh et al., 2005	PET	Dry	6%	Higher tensile strength, rutting resistance	Brittle at low temperatures
[2]	Casey et al., 2008	PE, PP	Wet	6–8%	Better elasticity, binder modification	Phase separation during storage
[3]	Punith et al., 2010	LDPE	Dry	8%	Improved Marshall stability, durability	Reduced workability
[4]	Vasudevan et al., 2012	LDPE, HDPE	Dry	8–10%	Enhanced durability, field performance	Emission concerns during heating
[5]	Arabani et al., 2013	PET	Wet	5%	Improved moisture resistance	Requires higher mixing temp
[6]	Modarres et al., 2014	Mixed plastics	Dry	7–8%	Better rutting & fatigue resistance	Variability of plastic waste
[7]	Harvey et al., 2014	PE	Wet	6%	Reduced bitumen use, good rutting resistance	High energy use in wet process
[8]	Ghuzlan et al., 2015	LDPE	Wet	10%	Improved rheology, rutting resistance	Higher mixing temp needed
[9]	Othman et al., 2015	PP	Wet	4–6%	Increased stiffness, Marshall stability	Reduced fatigue resistance
[10]	Tapkın et al., 2015	PET	Dry	6–8%	Higher Marshall stability, water stability	Brittleness under low temps
[11]	Punith & Veeraragavan, 2015	LDPE	Dry	8%	Improved adhesion, moisture resistance	Emissions during mixing
[12]	Rao et al., 2016	Mixed waste plastics	Dry	8%	Increased stability, pothole reduction (field)	Slight workability reduction
[13]	Gawande et al., 2016	LDPE, HDPE	Dry	8–10%	Field performance improved	Localized emission concerns
[14]	Hinislioglu & Agar, 2016	PE, PP	Wet	6%	Better binder elasticity	Phase separation risks
[15]	Al-Hadidy et al., 2017	PE blends	Wet	5–7%	Improved binder consistency	Aging sensitivity
[16]	Yildirim et al., 2017	PET	Dry	5–6%	Higher stability, indirect tensile strength	Reduced ductility
[17]	Sharma et al., 2017	LDPE, PP	Dry	8%	Better resistance to water damage	Handling difficulties in mixing
[18]	Sabina et al., 2017	PE, PP	Wet	6%	Improved fatigue life	Increased viscosity
[19]	Saadeh et al., 2018	PE blends	Wet	5–7%	High-temperature rutting resistance	Limited fatigue resistance
[20]	Al-Khateeb et al., 2018	LDPE	Wet	6%	Enhanced rheological properties	Higher energy consumption

5.1 Summary of Key Findings

5.1.1 Technical Feasibility

The studies reviewed demonstrate that recycled plastics can effectively enhance several properties of asphalt binders and mixtures. Depending on the type and proportion of plastic, notable improvements were recorded in rutting resistance, Marshall stability, moisture resistance, and high-temperature performance. The dry process, in particular, showed practical applicability for field construction, especially in India, where extensive trials confirmed better surface stability and reduced pothole formation (Rao et al., 2016).

However, technical benefits were not universally consistent. Certain plastics, such as PVC, introduced challenges due to the release of toxic emissions during heating. Furthermore, the increased stiffness associated with plastics often came at the cost of reduced fatigue resistance and low-temperature flexibility (Yeh et al., 2005; Saadeh et al., 2018). This highlights the necessity of balancing improvements in rutting resistance with the preservation of flexibility to withstand thermal and fatigue cracking.

5.1.2 Wet vs. Dry Process Performance

The wet process, which involves blending plastics directly into the bitumen, generally provided more uniform modification but required specialized equipment and higher energy inputs (Ghuzlan et al., 2015). By contrast, the dry process, where plastics are added as aggregates, proved simpler, cheaper, and more field-friendly, especially for developing countries. The trade-off, however, is reduced control over plastic dispersion and possible phase separation during aging. Comparative studies suggest that while the wet process is technically superior in producing homogeneous binders, the dry process holds greater potential for large-scale practical adoption.

5.1.3 Durability and Long-Term Performance

Short-term durability studies indicate that plastic-modified pavements exhibit better resistance to water damage and rutting. Still, evidence on long-term performance remains scarce. Only a limited number of field studies extend beyond five years, and even fewer provide detailed monitoring of fatigue cracking, thermal cracking, or aging-related hardening. This gap underscores the need for multi-year, climate-diverse evaluations.

5.1.4 Environmental and Sustainability Aspects

The environmental motivation behind recycled plastics in asphalt is compelling: diverting waste plastics from landfills and oceans while reducing reliance on virgin bitumen. Several studies reported reduced bitumen demand (by 5–10%), contributing to resource conservation.

However, concerns persist regarding fume emissions, microplastic release, recyclability of plastic-modified asphalt, and energy-intensive processing (Harvey et al., 2014). The lack of comprehensive life-cycle assessments (LCA) means that environmental benefits remain assumed rather than rigorously quantified.

5.2 Concluding Remarks

Recycled plastic asphalt holds transformative potential at the intersection of infrastructure and sustainability. It addresses two global challenges simultaneously: the disposal of non-biodegradable plastic waste and the demand for longer-lasting, cost-effective pavements. The literature up to 2018 paints a cautiously optimistic picture—plastic incorporation can significantly enhance rutting resistance, water stability, and resource efficiency, but unresolved concerns about fatigue, long-term durability, emissions, and recyclability remain.

The way forward will require an integrated approach: robust scientific validation, field-based performance monitoring, and environmentally conscious life-cycle evaluation. By bridging current research gaps and developing globally harmonized standards, recycled plastics can transition from a promising laboratory innovation to a mainstream solution in road construction. With the combined effort of researchers, policymakers, and industry stakeholders, the next decade could see the widespread adoption of plastic-modified asphalt as a flagship example of circular economy in civil engineering.

In conclusion, the journey of recycled plastics in asphalt pavements is still in its formative stages. The promise is real, the progress is evident, and the potential is vast. What is needed now is not more isolated experiments, but coordinated, multidisciplinary efforts that align engineering innovation with environmental stewardship. If pursued thoughtfully, recycled plastic asphalt could pave not only roads but also the way to a more sustainable and resilient future.

REFERENCES

[1] Choubane, B., Sholar, G.A., Musselman, J.A. and Page, G.C. 1999. Ten-year performance evaluation of asphalt-rubber surface mixes. *Transportation Research Record*, (1681): 10–18.

[2] Yeh, C.H., Wu, C.H. and Chen, J.S. 2005. High-temperature performance of polypropylene-modified asphalt binders. *Journal of Materials in Civil Engineering*, 17(3): 273–278.

[3] Casey, D., McNally, C., Gibney, A. and Gilchrist, M.D. 2008. Development of a recycled polymer modified binder for use in stone mastic asphalt. *Resources, Conservation and Recycling*, 52(10): 1167–1174.

[4] Al-Hadidy, A.I. and Tan, Y.Q. 2009. Effect of polyethylene on life of flexible pavements. *Construction and Building Materials*, 23(3): 1456–1464.

[5] Doyle, J.D., Howard, I.L. and Robinson, W.J. 2012. Prediction of absorbed, inert, and effective bituminous quantities in reclaimed asphalt pavement. *Journal of Materials in Civil Engineering*, 24(8): 1001–1009.

[6] Behl, A., Sharma, G. and Kumar, R. 2014. Rheological and storage stability of polyvinyl chloride modified bitumen. *Construction and Building Materials*, 61: 117–122.

[7] Ahmedzade, P. and Demir, S. 2014. Effects of recycled polyethylene terephthalate (PET) waste on asphalt concrete properties. *Construction and Building Materials*, 73: 119–126.

[8] Köfteci, S., Ahmedzade, P. and Kultayev, B. 2014. Performance evaluation of bitumen modified by various types of waste plastics. *Construction and Building Materials*, 73: 592–602.

[9] Harvey, J., Wu, R., Signore, J., Basheer, I., Long, F. and Jones, D. 2014. Sustainability aspects of recycled plastics in asphalt pavements. *Transportation Research Record*, (2445): 27–36.

[10] Ghuzlan, K.A., Al-Khateeb, G.G. and Qasem, Y. 2015. Rheological properties of polyethylene-modified asphalt binder. *Athens Journal of Technology & Engineering*, 2(2): 75–88.

[11] Karmakar, S. and Roy, T.K. 2016. Effect of waste plastic and waste tyre ash on mechanical behavior of bitumen. *Journal of Materials in Civil Engineering*, 28(6): 04016019.

[12] Ma, T., Wang, H., Zhang, Y. and Zhang, D. 2016. Laboratory evaluation of waste plastic modification on asphalt binder and mixture performance. *Construction and Building Materials*, 98: 122–128.

[13] Padhan, R.K. and Sreeram, A. 2016. Influence of plastic waste additives on the performance of asphalt mixtures. *Procedia Engineering*, 125: 607–613.

[14] Yuliestyan, Y., Wibowo, C.S. and Suhendro, B. 2016. Effects of EVA and LDPE modified binders on hot mix asphalt performance. *Procedia Engineering*, 125: 653–659.

[15] Rao, P., Reddy, K.S. and Veeraragavan, A. 2016. Field performance of plastic-coated aggregate bituminous surfacing mixes. *Indian Highways*, 44(7): 33–42.

[16] Liang, Y., Shao, S. and Wang, J. 2016. Comparative study of LDPE, LLDPE, and HDPE as asphalt modifiers. *Journal of Applied Polymer Science*, 133(32): 43702.

[17] Caltrans/UC Pavement Research Center. 2017. Preliminary investigation on use of recycled plastics in asphalt pavements. *California Department of Transportation Report*, PI-2017-01: 1–45.

[18] Saadeh, S., et al. 2018. Laboratory and field evaluation of asphalt mixes modified with recycled waste plastics. *International Journal of Pavement Engineering*, 19(7): 623–631.

[19] Review Article. 2018. Using waste plastics as asphalt modifier: a systematic review. *Construction and Building Materials*, 173: 400–416.

[20] Colas Group. 1989–2002. Performance of Novophalt (polyolefin-modified asphalt) in road trials. *Materials and Structures*, 35(2): 94–101.