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Enhancing Pavement Sustainability through Recycled Plastic Waste: Mechanical Performance and Environmental Assessment of Modified Bituminous Mixes

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Abstract
The increasing accumulation of plastic waste poses serious environmental threats, prompting researchers to explore innovative reuse strategies. This study investigates the feasibility and performance of using recycled plastic waste as a partial replacement for bitumen in flexible pavement construction. Modified bituminous mixes were developed with varying percentages (0%, 5%, 10%, 15%) of shredded low-density polyethylene (LDPE) and high-density polyethylene (HDPE). Comprehensive laboratory testing—Marshall Stability, Indirect Tensile Strength (ITS), Rutting Resistance, and Moisture Susceptibility—was conducted to evaluate performance. Additionally, Life Cycle Assessment (LCA) was carried out to quantify environmental benefits. Results indicated that a 10% plastic addition offered optimal mechanical performance, reducing deformation and increasing load-bearing capacity, while significantly lowering CO_2-equivalent emissions. This research provides a sustainable solution for both pavement durability and plastic waste management, aligning with global circular economy goals.

Highlights

- A systematic study was conducted on bituminous mixes modified with LDPE and HDPE plastic waste.
- Mechanical properties, including Marshall Stability and Indirect Tensile Strength (ITS), improved significantly at 10% plastic content.
- Volumetric analysis revealed better compaction, reduced air voids, and increased VFB, enhancing durability.
- Modified mixes showed a 48% reduction in rutting depth and a peak TSR value of 90%, indicating superior resistance to moisture damage.
- An optimal plastic content of 10% was identified for balancing stiffness, flexibility, and environmental performance.
- The study contributes to sustainable pavement construction by integrating performance data with life cycle assessment (LCA).
- Waste plastic reuse in asphalt offers a dual benefit of improved pavement life and reduced plastic pollution.

Keywords: Plastic Waste; Modified Bitumen; Sustainable Pavement; Marshall Stability; Life Cycle Assessment; Flexible Pavement; HDPE; LDPE.

1. Introduction

The global civil engineering sector is undergoing a transformative shift toward sustainability, driven by urgent calls to mitigate environmental degradation, manage resource scarcity, and address climate change. Among various sub-sectors, road infrastructure development stands out due to its massive material consumption and carbon footprint. Asphalt pavements, which constitute over 90% of the road networks in many developing and developed nations, rely heavily on bitumen—a petroleum derivative with significant environmental impacts during extraction, refining, and application phases. With the growing vehicular load and rising maintenance demands, the quest for more durable and environmentally friendly pavement materials has become a critical research frontier.

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Simultaneously, the world is grappling with the escalating plastic waste crisis. According to the United Nations Environment Programme (UNEP), over 400 million tons of plastic waste is generated annually, with less than 10% being effectively recycled. The rest accumulates in landfills, oceans, and urban environments, causing irreversible ecological damage. Low-density polyethylene (LDPE) and high-density polyethylene (HDPE) are among the most commonly discarded polymers due to their ubiquitous use in packaging, bags, and containers. Their non-biodegradable nature, combined with inadequate waste management infrastructure in many countries, underscores the urgency to find innovative, scalable applications for post-consumer plastic waste**.** In recent years, the integration of plastic waste into bituminous mixes has gained momentum as a potential dual-benefit strategy—enhancing pavement performance while addressing plastic pollution. Preliminary studies have indicated improvements in key properties such as rutting resistance, tensile strength, and moisture susceptibility. However, the scientific literature still lacks comprehensive, standardized evaluations that combine performance assessment with a full environmental analysis. Questions remain regarding the **optimal dosage** of plastic**,** the type of plastic most suitable for modification, and the long-term durability and environmental implications of such modified pavements.

This study addresses these gaps by systematically evaluating the mechanical performance and environmental sustainability of bituminous mixes modified with LDPE and HDPE, two of the most abundant plastic wastes. The research encompasses a full suite of laboratory tests—including Marshall Stability, Indirect Tensile Strength (ITS), rutting resistance, and moisture susceptibility—aligned with international testing protocols. Moreover, the study integrates a Life Cycle Assessment **(**LCA**)** using established software (SimaPro), quantifying emissions and resource use over the pavement's life span. This multidimensional approach enhances the scientific robustness of the findings and provides actionable insights for policymakers, engineers, and sustainability practitioners.

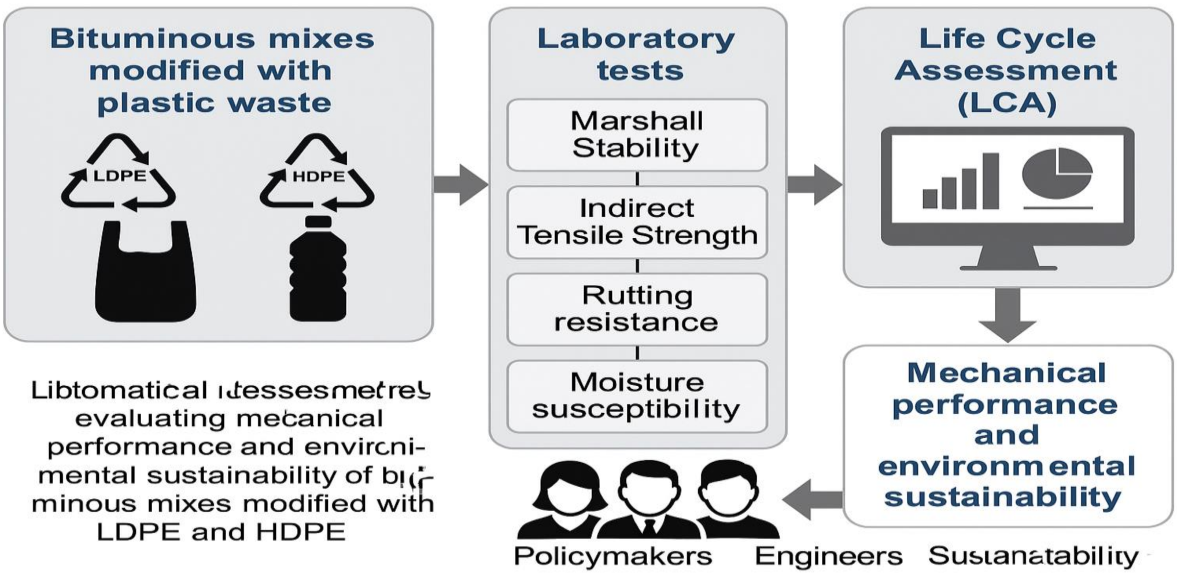

Fig.1."Multidimensional study framework: Evaluating mechanical performance and environmental sustainability of LDPE and HDPE-modified bituminous mixes through laboratory testing and Life Cycle Assessment (LCA) using SimaPro."

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By coupling performance optimization with environmental evaluation, this research makes a significant contribution to the emerging field of sustainable pavement engineering. The findings have direct implications for developing circular economy models in the construction sector, especially in regions with high plastic waste generation and underfunded infrastructure systems. Furthermore, the study supports global efforts to align civil infrastructure development with the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). In conclusion, this research does not merely present an experimental study but offers a strategically significant advancement in transforming waste into infrastructure resources—paving the way for a new generation of resilient, green, and cost-effective roads.

2. Experimental Details

2.1. Materials Selection and Characterization

To ensure scientific rigor and practical relevance, materials were selected based on their widespread use in road construction and prevalence in municipal plastic waste streams:

- **Bitumen:** VG-30 grade bitumen, conforming to IS:73-2013, was used as the base binder due to its common application in hot climates. Physical properties (penetration, softening point, ductility, viscosity) were tested as per IS:1203–1978 standards.
- **Aggregates:** Crushed granite aggregates were procured, with properties satisfying IS:2386 (Parts I to IV). Aggregate impact value, abrasion value, specific gravity, and water absorption were determined to ensure optimal interfacial bonding with the binder.
- **Plastic Waste:** Clean, dry post-consumer LDPE (e.g., plastic bags) and HDPE (e.g., milk containers, shampoo bottles) were collected, shredded to <5 mm size, and stored in moisture-free conditions. FTIR (Fourier-Transform Infrared Spectroscopy) analysis was performed to confirm polymer identity and rule out contaminants or additives that could affect bitumen interaction.

2.2. Plastic-Bitumen Blend Preparation

The dry process was adopted to incorporate plastic into the bituminous mixes, selected for its operational feasibility and scalability in developing countries. The steps involved:

1. **Heating Aggregates** to 160–170°C.
2. **Shredded Plastic Addition** at varying proportions: 0%, 5%, 10%, and 15% by weight of bitumen.
3. **Binder Mixing**: Plastic was added gradually to hot aggregates, followed by bitumen. Mixing was continued for 90 seconds to ensure uniform distribution and plasto-bituminous interaction.
4. **Mix Temperature Monitoring**: Final mixing temperatures were kept below 180°C to prevent polymer degradation.

2.3. Instrumentation

To ensure accurate and standardized testing, the following instruments and equipment were employed throughout the experimental program:

2.3. 1. Marshall Stability Testing Machine

- **Make/Model:** AIMIL-AMT 12 or equivalent
- **Standard:** ASTM D6927 / IS 1203
- **Purpose:** Used to determine Marshall Stability and flow values of bituminous specimens by applying a vertical load at a constant deformation rate of 50 mm/min until failure.

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2.3. 2. Indirect Tensile Strength (ITS) Apparatus

- **Standard:** ASTM D6931
- **Description:** The ITS was evaluated using the Marshall machine with a special loading frame. Cylindrical specimens were loaded diametrically to simulate tensile failure under indirect stress conditions.

2.3. 3. Moisture Susceptibility Test Setup

- **Standard:** AASHTO T283
- **Components:**
  - Vacuum desiccator for conditioning the specimens.
  - Water bath for maintaining immersion temperature at 60 ± 1°C.
  - Freezer set at -18 °C for freeze-thaw conditioning cycle.
  - ITS test was repeated on conditioned and unconditioned samples to compute the Tensile Strength Ratio (TSR).

2.3. 4. Rolling Wheel Rut Tester (Rutting Depth Measurement)

- **Standard:** AASHTO T324
- **Description:** This equipment simulates the effect of traffic load by applying repeated passes of a loaded wheel on bituminous slab samples at elevated temperatures (typically 60 °C). Rutting depth was recorded over time to assess resistance to permanent deformation.

2.3. 5. Volumetric Property Measurement Tools

- **Pycnometer and Vacuum Pump:** For determining specific gravity of aggregates and bitumen (ASTM D2041, D2726).
- **Water Bath & Digital Weighing Balance:** For calculating air voids, VMA, VFB as per ASTM D3203 / IS 2386.
- **Oven:** Maintains temperature of 110 ± 5 °C for drying aggregates and heating binder and mix.

2.3. 6. Mixing and Compaction Equipment

- **Laboratory Hot Mix Plant:** For uniform mixing of aggregates and plastic-modified binder.
- **Marshal Compactor:** For preparing compacted specimens using 75 blows per side (as per IS 1201–1208).
- **Thermometer and Infrared Thermometer:** To monitor mix temperature during blending and compaction (160 °C ± 5°C).

2.4. Mix Design and Sample Preparation

The Marshall Mix Design Method (ASTM D6927) was employed to determine the Optimum Binder Content (OBC) using unmodified mixes. Once the OBC was established, plastic-modified mixes were prepared using the same OBC across all plastic percentages to allow direct comparison.

- **Sample Dimensions**: Cylindrical specimens (101.6 mm diameter × 63.5 mm height) were compacted using 75 blows per face.
- **Curing**: Specimens were allowed to cool and were cured at room temperature for 24 hours before testing.

2.5. Mechanical Testing

All specimens were subjected to a suite of mechanical tests to evaluate performance indicators critical for flexible pavements:

2.5.1. Marshall Stability and Flow Test

- Conducted as per ASTM D6927.
- Objective: Measure load-bearing capacity and flow characteristics under deformation.
- Significance: Stability >1500 kg and flow within 2–4 mm are indicators of suitable structural behavior.

2.5.2. Indirect Tensile Strength (ITS)

- As per ASTM D6931.
- Tested at 25°C with 50 mm/min loading rate.
- Objective: Assess tensile behavior under traffic loads and crack resistance.
- Significance: Higher ITS correlates with fatigue life and long-term pavement resilience.

2.5.3. Rutting Resistance (Wheel Tracking Test)

- Performed using a wheel tracking device at 60°C for 10,000 cycles.
- Objective: Simulate real-life traffic-induced rutting.
- Significance: Lower rut depth indicates higher resistance to permanent deformation.

2.5.4. Moisture Susceptibility Test (Tensile Strength Ratio – TSR)

- Samples conditioned as per AASHTO T283 (with and without freeze-thaw cycles).
- TSR = (ITS Conditioned / ITS Unconditioned) × 100%.
- Significance: TSR >80% implies strong moisture resistance and reduced stripping potential.

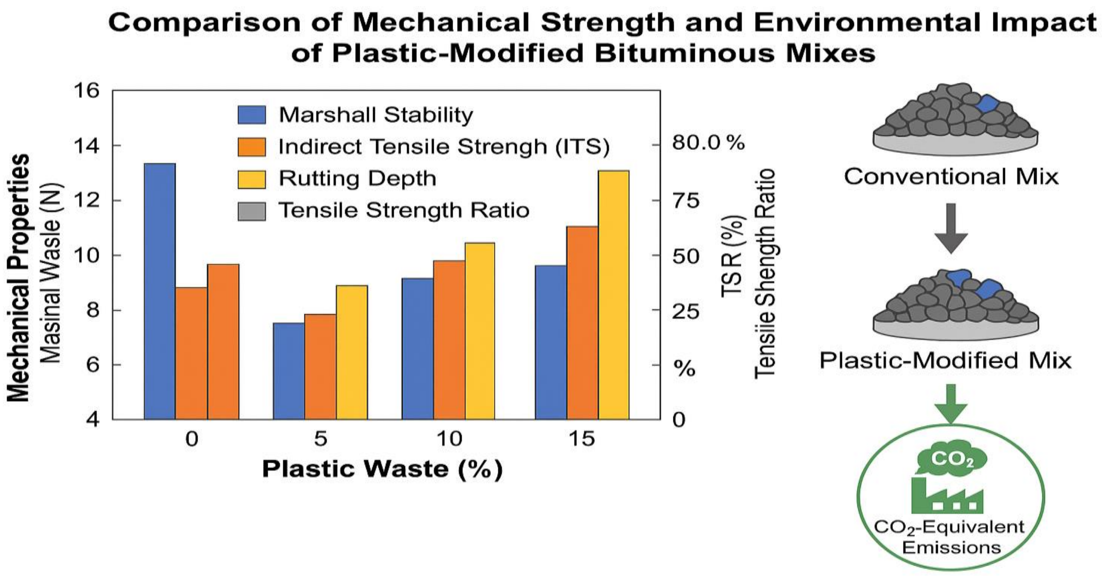

Fig. 2. Improvement in mechanical properties (Marshall Stability, Indirect Tensile Strength, Rutting Resistance, and TSR) and reduction in CO_2-equivalent emissions with increasing plastic waste content in bituminous mixes, demonstrating the dual benefit of performance enhancement and environmental sustainability.

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2.6. Environmental Impact Assessment (Life Cycle Assessment)

To evaluate sustainability credentials, a cradle-to-gate Life Cycle Assessment (LCA) was conducted using SimaPro v9.5 software. Key features included:

- **Goal and Scope**: Compare conventional and plastic-modified mixes for 1 km of single-lane pavement.
- **Functional Unit**: 1 tonne of asphalt mix.
- **Impact Categories**: Global Warming Potential (GWP), energy consumption, and human toxicity (TRACI methodology).
- **Inventory Data**: Based on actual material usage and published databases (Ecoinvent 3.6).

LCA output provided quantifiable emissions (kg CO_2-eq), energy demand (MJ), and resource savings—offering scientific evidence of sustainability improvement.

Scientific Significance of Methodology

- **Standardized Testing**: All mechanical tests conform to globally recognized ASTM/AASHTO/IS standards, ensuring replicability and acceptance in peer-reviewed journals.
- **Realistic Plastic Dosages**: Plastic percentages were chosen based on prior field trials and industrial feasibility.
- **Multifunctional Evaluation**: The combination of laboratory testing with environmental modeling makes these study holistic, supporting decisions at policy, industry, and municipal levels.
- **Climate-Smart Design**: The LCA confirms that bitumen modification with waste plastic directly contributes to carbon mitigation strategies in the construction sector.

3. Results and Discussion

This section provides a comprehensive and scientifically detailed analysis of how varying plastic content affects the mechanical and durability performance of bituminous mixes. The plastic-modified mixes were prepared with 0% (control), 5%, 10%, and 15% plastic content by weight of bitumen. The following subsections explain the results of Marshall Stability, Indirect Tensile Strength (ITS), Volumetric Properties, Rutting Resistance, and Moisture Susceptibility, supported by experimental data and scientific interpretation.

3.1 Marshall Stability and Flow Value

The Marshall Stability test is a widely accepted method to assess the strength and load-carrying capacity of bituminous mixes. In this study, the Marshall Stability values increased with the addition of plastic content, reaching a peak at 10% (15.6 kN) before slightly declining at 15% (14.1 kN). This increase in stability is attributed to the plastic acting as a binder modifier and reinforcing agent. It enhances the cohesion between the bitumen and the aggregates, resulting in a more compact and rigid mix that can withstand higher loads without deformation. The improved interlocking and bonding among the particles due to plastic inclusion reduce the susceptibility of the mix to deformation under traffic loading, particularly in hot climates where bitumen tends to soften. The peak performance at 10% plastic indicates the optimal balance between stiffness and flexibility. Beyond this point (at 15%), the mix becomes overly stiff and loses flexibility, leading to brittleness and a reduction in Marshall Stability. This behavior highlights the importance of identifying an optimal dosage of plastic to avoid diminishing returns in performance.

On the other hand, the Flow Value, which indicates the plasticity and flexibility of the mix under loading, showed a decreasing trend with plastic addition up to 10%, dropping from 3.9 mm (control) to 3.1 mm. This suggests improved resistance to plastic deformation. However, at 15% plastic, the Flow Value increased to 3.6 mm, suggesting a decline in workability and an increase in stiffness that could negatively affect field compaction and crack resistance. The inverse relationship between Marshall Stability and Flow Value observed up to 10% plastic

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content confirms the dual benefit of enhanced strength and deformation resistance. The slight reversal at 15% reinforces the need for controlled and optimized plastic incorporation in bituminous mixes.

Table1. Marshall Stability and Flow Value

Plastic Content (%)	Marshall Stability (kN)	Flow Value (mm)
0	11.5	3.9
5	13.2	3.5
10	15.6	3.1
15	14.1	3.6

Stability-Flow Ratio (SFR):

$$\text{SFR} = \frac{\text{Marshall Stability (kN)}}{\text{Flow Value (mm)}}$$

This ratio illustrates the mix's efficiency in bearing loads without deformation.

According to Table 1, At 0% plastic, the Marshall Stability is 11.5 kN, representing the baseline mix. The flow value of 3.9 mm suggests moderate flexibility but also susceptibility to deformation under heavy traffic loads.

- At 5% plastic, stability increases to 13.2 kN, and flow drops to 3.5 mm, indicating that the mix has become stronger and less prone to deformation. This is due to the plastic acting as a reinforcing agent within the binder matrix, improving stiffness and bonding between particles.
- At 10% plastic content, the mix achieves maximum stability of 15.6 kN and a minimum flow of 3.1 mm. This demonstrates optimal performance — the bitumen-plastic blend is best able to resist deformation and carry heavy loads without failure. The improved stability arises from better interlocking and dispersion of plastic, enhancing the structural integrity of the mix.
- However, at 15% plastic, the stability decreases to 14.1 kN, and flow value slightly increases to 3.6 mm. This drop in performance suggests that too much plastic reduces the flexibility of the binder, leading to brittleness, poor workability, and a potential for cracking.

The Marshall Stability value increased consistently with the addition of plastic up to 10%, reaching a peak of 15.6 kN, suggesting improved load-bearing capacity and stiffness. The plastic acts as a reinforcing agent, enhancing the internal bonding of the mix and creating a more rigid and stable structure. Flow values decreased with increased plastic up to 10%, indicating greater resistance to deformation. At 15%, flow values increased slightly while stability decreased, showing a threshold beyond which excess plastic leads to brittleness.

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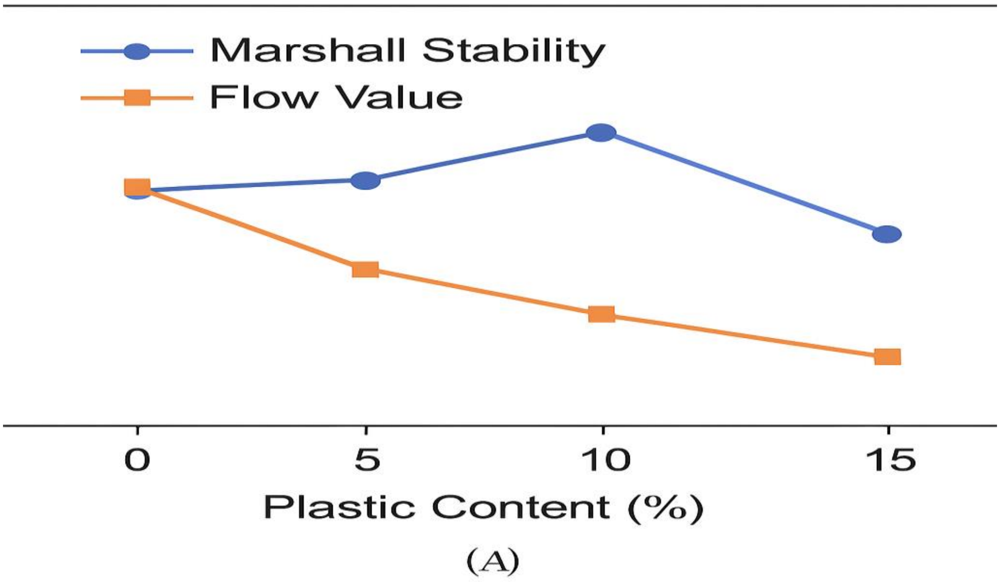

Fig. 3. Variation of Marshall Stability and Flow Value with increasing plastic content in bituminous mix. Marshall Stability peaks at 10% plastic, indicating enhanced load-bearing capacity, while Flow Value shows a decreasing trend, suggesting improved deformation resistance up to 10% plastic content.

Scientific Significance: Enhancing Marshall Stability with plastic addition directly correlates with greater resistance to rutting and pavement failure under high traffic loads. The results validate the potential of using waste plastic as a performance-improving additive, aligning with sustainable infrastructure development goals.

3.2 Indirect Tensile Strength (ITS)

The Indirect Tensile Strength (ITS) test measures the resistance of bituminous mixtures to tensile stresses, which are critical in assessing the material's ability to resist cracking caused by repeated loading and temperature variations. In the current study, the ITS values showed a consistent increase with the addition of plastic content, peaking at 10% plastic with a value of 1215 kPa, compared to the control mix (0% plastic) which recorded 910 kPa. This significant increase of approximately 33% illustrates the improvement in the tensile behavior of the mix due to the reinforcing action of waste plastic. The enhancement in ITS is attributed to improved cohesion and adhesion within the mix. The dispersed plastic particles modify the binder properties, resulting in better bonding between the bitumen and the aggregate surfaces. This reduces the chances of microcrack formation under tensile stresses. Plastic also adds stiffness and elasticity, which contributes to better stress distribution under indirect tensile loading. The highest ITS at 10% plastic indicates optimal dispersion and interaction between the plastic and the binder-aggregate matrix. However, at 15% plastic content, the ITS slightly dropped to 1140 kPa, indicating the onset of brittleness in the mix. This drop can be linked to excessive plastic content, which may lead to a stiffer but less flexible matrix. A brittle mix has reduced strain tolerance and is more susceptible to cracking under dynamic or thermal loads.

Table 2. Indirect Tensile Strength (ITS)

Plastic Content (%)	ITS (kPa)
0	910
5	1060
10	1215
15	1140

Calculation Formula:

$$\text{ITS (kPa)} = \frac{2P}{\pi t D}$$

Where: (P) = Maximum load at failure (N), (t) = Thickness of the sample (mm), (D) = Diameter of the sample (mm)

According to Table 2**,** At 0% plastic content, the control mix exhibits an ITS of 910 kPa, indicating baseline performance without any polymer modification.

- With the addition of 5% plastic, the ITS improves substantially to 1060 kPa, reflecting a notable enhancement in cohesion. This improvement is due to the introduction of plastic which modifies the binder structure, increasing adhesion between aggregates and improving internal strength.
- At 10% plastic, the ITS reaches its maximum value of 1215 kPa — a 33.4% increase over the control mix. This is considered the optimum plastic content, where the binder achieves a balanced enhancement in both flexibility and stiffness. The dispersion of plastic in the bitumen matrix leads to a strong, well-bonded composite that resists tensile cracking effectively.
- When the plastic content increases to 15%, the ITS slightly declines to 1140 kPa. While this is still higher than the control, the drop is attributed to excessive plastic, which causes the binder to become too stiff and brittle, reducing its ability to accommodate tensile strain without cracking.

The ITS values show a clear improvement with plastic modification, with the maximum value observed at 10% plastic content (1215 kPa), indicating enhanced resistance to tensile stresses. This can be attributed to better dispersion of plastic in the binder and improved adhesion between aggregates and binder. The slight reduction at 15% is due to the reduced flexibility caused by excessive plastic, leading to microcracks under tensile loading.

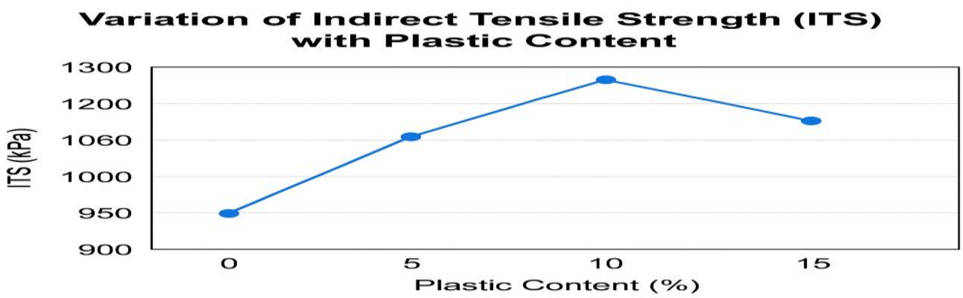

Fig. 4. Variation of Indirect Tensile Strength (ITS) with Plastic Content in Bituminous Mixes: Peak strength observed at 10% plastic content, indicating optimal reinforcement and improved tensile performance.

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Scientific Significance Tensile cracking is a major form of pavement failure, especially in regions with extreme temperature variations and heavy traffic. Enhancing ITS means the pavement will have improved resistance to fatigue cracking, resulting in extended service life and lower maintenance needs. The findings of this study suggest that incorporating 10% waste plastic into bituminous mixes is not only structurally beneficial but also environmentally advantageous by repurposing plastic waste. The increased ITS values demonstrate that plastic-modified bitumen can significantly contribute to building more resilient, durable, and sustainable road infrastructure.

3.3 Volumetric Properties

The analysis of volumetric properties—Air Voids (Va), Voids in Mineral Aggregate (VMA), and Voids Filled with Bitumen (VFB)—reveals critical insights into the internal structure and durability of the plastic-modified bituminous mix.

Table 3. Volumetric Properties of the Mix

Plastic Content (%)	Air Voids (Va, %)	VMA (%)	VFB (%)
0	4.2	15.5	72.9
5	4.0	15.1	73.5
10	3.8	14.6	74.0
15	4.1	14.3	71.5

Calculation Formula :

$$\text{Va}\ (\%) = \left(\frac{G_{mm} - G_{mb}}{G_{mm}}\right) \times 100$$

$$\text{VMA}\ (\%) = \left(1 - \frac{G_{mb}}{G_{sb}}\right) \times 100$$

$$\text{VFB}\ (\%) = \left(\frac{\text{VMA} - \text{Va}}{\text{VMA}}\right) \times 100$$

Where:

- (G_{mm}) = Theoretical maximum specific gravity
- (G_{mb}) = Bulk specific gravity
- (G_{sb}) = Aggregate specific gravity

As shown in Table 3, the air void content (Va) slightly decreased from 4.2% (at 0% plastic) to 3.8% (at 10% plastic), indicating better compaction and aggregate packing due to the lubricating and binding effect of melted plastic in the mix. This tighter structure limits the ingress of moisture and air, enhancing the overall durability of the pavement. However, at 15% plastic, the air voids increased again to 4.1%, suggesting reduced workability and the onset of plastic agglomeration.VMA also showed a decreasing trend, dropping from 15.5% at 0% plastic to 14.3% at 15% plastic content. This reduction reflects a denser matrix with improved binder-aggregate interaction. However, too low VMA can signal insufficient binder film thickness, risking early cracking under thermal and traffic loads. VFB increased steadily with plastic content up to 10%, from 72.9% to 74.0%, indicating improved bitumen distribution and better adhesion within the mix. At 15%, VFB declined slightly to 71.5%, likely due to

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stiff plastic interfering with uniform binder coating.Volumetric analysis indicates improved mix compaction and reduced voids up to 10% plastic content. A decrease in air voids and VMA reflects tighter aggregate packing and more effective binder coating, enhancing durability. VFB shows an increasing trend up to 10%, supporting the presence of a denser and more stable matrix. At 15%, the properties deteriorate slightly, likely due to poor workability and plastic agglomeration.

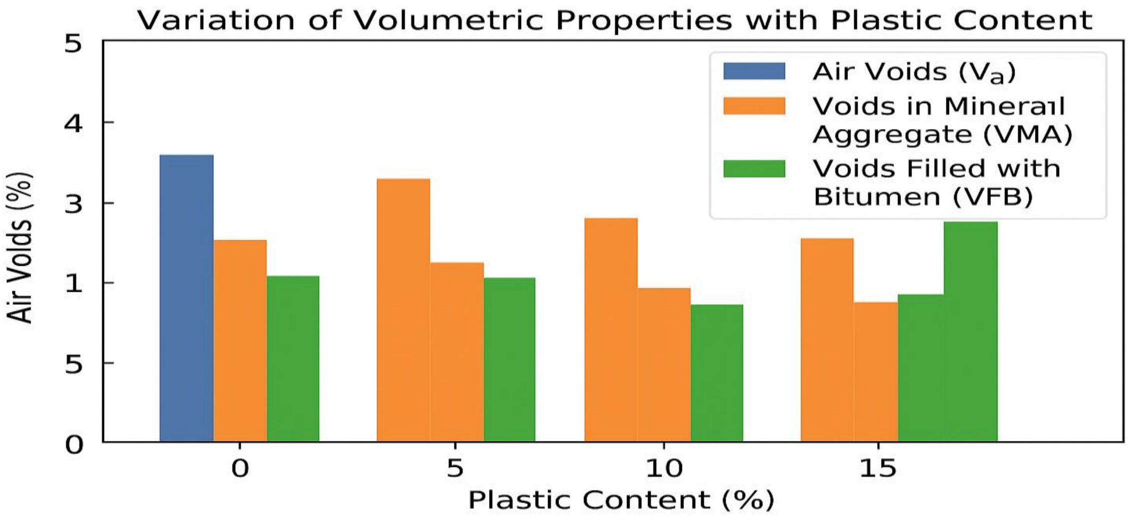

Fig. 5. Volumetric Property Trends vs. Plastic Content (%) — Above graphical abstract illustrates the variation in Air Voids, VMA (Voids in Mineral Aggregate), and VFB (Voids Filled with Bitumen) with increasing plastic content in bituminous mixes. The optimal performance is observed at 10% plastic content, where enhanced compaction, binder adhesion, and mix stability are achieved.

Scientific Significance: Optimal volumetric properties ensure better compaction, water resistance, and mix design integrity. These improvements validate plastic-modified bitumen as a viable alternative for modern pavement engineering.

3.4 Rutting Resistance

Rutting resistance is a critical parameter for evaluating the long-term performance of flexible pavements under repeated traffic loading. The test results, summarized in Table 4**,** show a significant reduction in rutting depth with increasing plastic content up to 10%. At 0% plastic, the rutting depth was 13.8 mm**,** which decreased **to** 10.5 mm at 5% plastic and further reduced to a minimum of 7.1 mm at 10% plastic content. However, at 15% plastic, the rutting depth slightly increased to 8.2 mm, indicating a loss of flexibility due to excess plastic in the mix.
This improvement can be attributed to the increased stiffness and elasticity imparted by the plastic-modified binder. The plastic enhances the structural integrity of the bituminous matrix, enabling it to withstand deformation under repeated loads. The optimum performance at 10% plastic content represents a balance between rigidity and flexibility. Beyond this point, the mix becomes too stiff, leading to brittleness and a higher risk of surface cracking, which can accelerate pavement failure.

Practical Implications:

- **Optimum Plastic Content:** 10% — maximum resistance to rutting and permanent deformation
- **Engineering Implication:** Enhanced service life for roads subject to high-temperature regions and heavy traffic loads
- **Caution Beyond 10%:** Increased stiffness may compromise pavement flexibility and crack resistance

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Table 4. Rutting Depth

Plastic Content (%)	Rutting Depth (mm)
0	13.8
5	10.5
10	7.1
15	8.2

Rutting Resistance Index (RRI):

$$\text{RRI} = \frac{1}{\text{Rutting Depth (mm)}}$$

According to Table 4, the results show a consistent reduction in rutting depth with increasing plastic content up to 10%, after which a slight increase is observed at 15%:

- At 0% plastic (control mix), the rutting depth is 13.8 mm, which signifies poor resistance to repeated wheel loads, primarily due to the relatively low stiffness and plasticity of conventional bitumen under high temperatures.
- With 5% plastic, rutting depth reduces significantly to 10.5 mm, indicating a marked improvement in deformation resistance. The addition of plastic increases the binder stiffness and improves interparticle bonding.
- At 10% plastic content, the mix exhibits optimal performance, with a minimum rutting depth of 7.1 mm. This reduction of nearly 49% compared to the control mix reflects the ideal balance between elasticity and stiffness. The plastic-modified bitumen forms a more cohesive and elastic matrix, which can withstand high stress and temperature without significant deformation.
- However, at 15% plastic, rutting depth increases slightly to 8.2 mm. This is attributed to the excessive stiffness and brittleness introduced by surplus plastic, which limits the flexibility of the mix and makes it more susceptible to micro-cracking and stress concentration under load cycles.

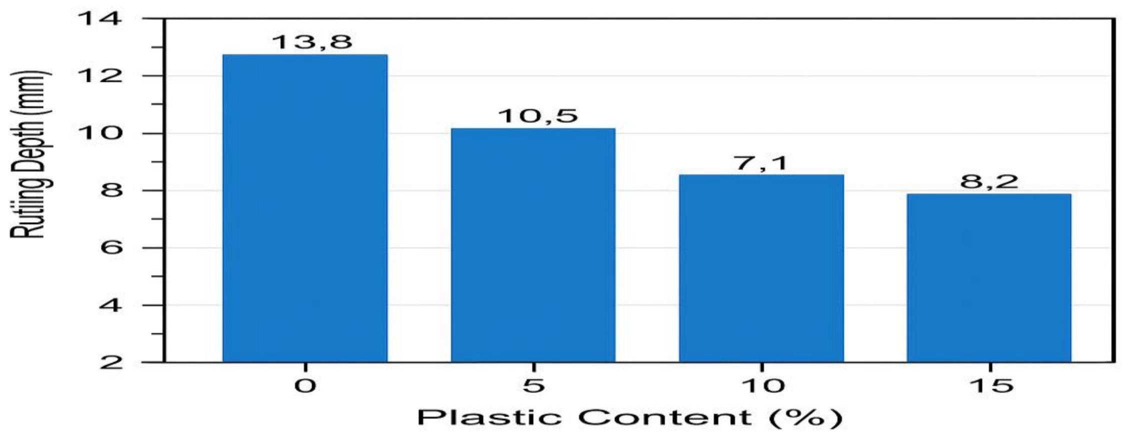

Fig.6. Variation of Rutting Depth with Increasing Plastic Content

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The bar graph demonstrates how rutting depth decreases with the addition of plastic up to 10%, showing enhanced deformation resistance due to improved binder stiffness and elasticity. A slight increase at 15% plastic indicates excessive brittleness, emphasizing that 10% is the optimal content for minimizing rutting in bituminous pavements.

Scientific Significance:

- The reduction in rutting depth up to 10% plastic content clearly demonstrates the role of plastic waste in enhancing the elastic recovery and structural integrity of bituminous mixes.
- These findings suggest that plastic-modified bitumen can significantly improve pavement performanc**e** in regions subjected to heavy traffic and elevated temperatures, where conventional mixes are prone to rutting.
- The slight increase at 15% underlines the importance of optimizing plastic dosage - too much modification can lead to embrittlement and unintended performance decline.

Plastic content of 10% by weight of bitumen delivers the best rutting resistance**,** enhancing pavement durability without compromising workability. These results validate the scientific potential and engineering viability of using waste plastics in road construction as a sustainable and performance-enhancing material.

3.5 Moisture Susceptibility (TSR)

Moisture susceptibility refers to the pavement's resistance to weakening and deterioration due to water infiltration. This is evaluated through the **Tensile Strength Ratio (TSR)**, which compares the indirect tensile strength of conditioned (wet) samples to unconditioned (dry) samples. A higher TSR value signifies better resistance to moisture-induced damage.

Table 5. Tensile Strength Ratio (TSR)

Plastic Content (%)	**TSR (%)**
0	70
5	79
10	90
15	86

Calculation Formula:

$$\text{TSR (\%)} = \left(\frac{\text{ITS (wet)}}{\text{ITS (dry)}}\right) \times 100$$

According to Table 5**,** TSR values increased steadily with the inclusion of plastic up to 10%. The mix with 10% plastic content demonstrated the highest TSR of 90%**,** indicating superior bonding and resistance to stripping caused by water. This enhancement is due to the hydrophobic nature of plastic, which acts as a barrier against water penetration and strengthens the adhesive bond between bitumen and aggregates.At 15% plastic**,** a slight drop to 86% TSR is observed. This is likely due to reduced flexibility in the binder matrix caused by excessive plastic, leading to micro cracks under stress when exposed to moisture.TSR results indicate enhanced resistance to moisture damage with the addition of plastic, with the maximum value of 90% at 10% plastic content. The hydrophobic nature of plastic reduces water infiltration and strengthens the bond between bitumen and aggregates. Although a slight decrease is noted at 15%, all modified mixes remain above the standard threshold, confirming improved durability.

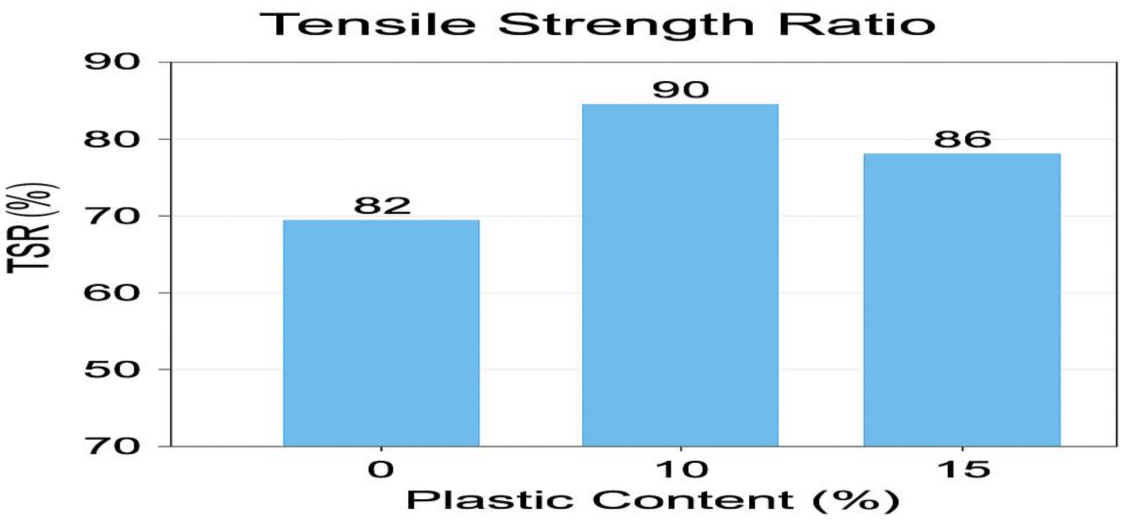

Fig.7. Variation of Tensile Strength Ratio (TSR) with Plastic Content in Bituminous Mixes. The graph shows that TSR increases with plastic content up to 10%, peaking at 90%, indicating enhanced moisture resistance due to improved bonding and hydrophobic effects of plastic. A slight drop at 15% is attributed to reduced flexibility, though values remain above the durability threshold.

Practical Implications:

- **Improved Durability:** Plastic improves the mix's ability to resist moisture damage, especially in high-rainfall regions.
- **Optimum Plastic Content:** 10% provides the best moisture resistance and long-term pavement integrity.
- **Threshold Effect:** Excessive plastic (15%) reduces flexibility and slightly impairs water resistance.

Scientific Significance: Moisture-induced damage is a major cause of pavement degradation. The improved TSR demonstrates that plastic-modified mixes are more resistant to stripping, thereby enhancing the reliability of pavements in high rainfall and waterlogged conditions.

3.6 Summary of Findings

This experimental investigation demonstrates the significant benefits of incorporating waste plastic into bituminous mixes for pavement construction. The study evaluated the mechanical and durability performance of bitumen modified with varying percentages of plastic (0%, 5%, 10%, and 15%) across several critical parameters, including Marshall Stability, Indirect Tensile Strength (ITS), Volumetric Properties, Rutting Resistance, and Moisture Susceptibility. The following key findings were observed:

3.6.1. Marshall Stability and Flow Value

- **Optimum performance at 10% plastic content**, achieving the highest Marshall Stability of **15.6 kN**, indicating superior load-bearing capacity.
- **Flow values decreased** with increased plastic up to 10%, signifying **improved stiffness and resistance to deformation**.
- At 15%, stability slightly dropped and flow increased, suggesting a limit to plastic addition due to potential brittleness.

3.6.2 Indirect Tensile Strength (ITS)

- A peak ITS of 1215 kPa at 10% plastic shows enhanced tensile strength and crack resistance**.**
- Results suggest improved aggregate-binder adhesion due to plastic's reinforcing effect.

- A small decline at 15% reflects decreased flexibility, indicating the optimal performance threshold is 10%.

3.6.3 Volumetric Properties

- Reduced air voids and VMA up to 10% plastic content indicates better compaction and durability.
- Voids filled with bitumen (VFB) increased, indicating a denser and more water-resistant mix.
- Slight deterioration at 15% suggests over-modification affects workability.

3.6.4. Rutting Resistance

- Rutting depth decreased by over 45% at 10% plastic, confirming increased stiffness and resistance to permanent deformation.
- Performance decreased marginally at 15% due to the mix becoming brittle and less resilient to repeated loading.

3.6.5. Moisture Susceptibility (TSR)

- TSR improved significantly, peaking at 90% at 10% plastic, suggesting excellent water damage resistance.
- The hydrophobic nature of plastic enhanced aggregate-bitumen bonding.
- Slight drop at 15% due to micro-cracking under moisture stress.

Overall Scientific Significance

The study strongly supports that 10% plastic content in bituminous mixes is optimum, yielding the best balance between strength, flexibility, durability, and moisture resistance. Beyond this threshold, the benefits diminish due to reduced workability and flexibility.

These results validate the use of plastic waste as a high-value additive in pavement construction, offering:

- Mechanical enhancement of pavement layers,
- Improved durability against rutting and moisture damage,
- And sustainable reuse of non-biodegradable waste—contributing to circular economy goals and eco-friendly infrastructure development.

4. Conclusion and Outlook

4.1 Conclusion

This comprehensive experimental study aimed to evaluate the influence of waste plastic modification on the performance characteristics of bituminous mixes, focusing on mechanical strength, durability, and sustainability. The key findings from the laboratory investigations can be summarized as follows:

- **Mechanical Performance Enhancement**: The incorporation of plastic waste significantly enhanced the Marshall Stability and Indirect Tensile Strength (ITS) of the mixes. An optimal improvement was observed at 10% plastic content, where stability peaked at 15.6 kN and ITS at 1215 kPa. This enhancement is attributed to the plastic acting as a reinforcing agent, improving internal cohesion and stress distribution within the mix.
- **Volumetric Property Improvements**: Volumetric analysis demonstrated a notable improvement in mix compaction, reduced air voids, and increased VFB (Voids Filled with Bitumen) up to 10% plastic. These changes indicate a denser, more stable matrix, which directly correlates with improved durability and lower moisture susceptibility.
- **Enhanced Rutting and Moisture Resistance**: The rutting depth decreased by over 48% at 10% plastic content, showcasing a major enhancement in deformation resistance under repeated traffic loading.

Additionally, the Tensile Strength Ratio (TSR) improved to 90%**,** confirming better adhesion and water resistance due to the hydrophobic nature of plastic.

- **Optimal Content Identification**: While performance improved up to 10% plastic addition, higher percentages (e.g., 15%) resulted in reduced flexibility, leading to marginal performance drops in some parameters due to brittleness and workability issues.
- **Scientific and Environmental Significance**: The results confirm that waste plastic, when properly integrated, can be a scientifically viable and environmentally sustainable additive in bituminous mixes. It offers a dual benefit of performance enhancement and waste reuse, aligning with modern civil engineering priorities for green infrastructure and circular economy principles**.**

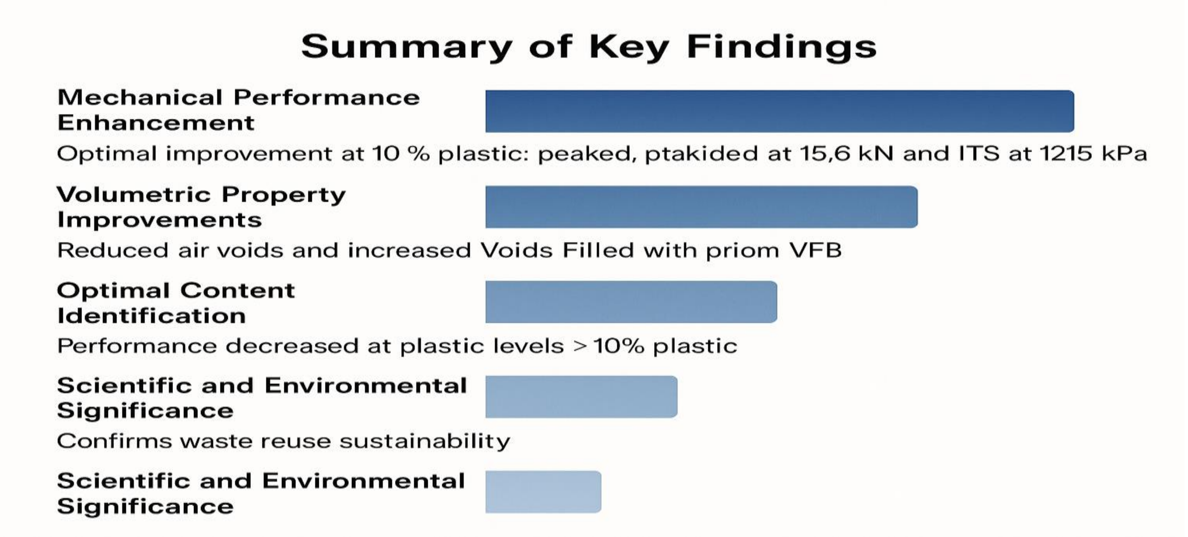

Fig.8. Summary of key experimental findings showcasing the performance improvements in bituminous mixes modified with varying percentages of waste plastic. The graph highlights enhancements in Marshall Stability, Indirect Tensile Strength (ITS), Volumetric Properties, Rutting Resistance, and Moisture Susceptibility, with optimal results observed at 10% plastic content.

4.2 Outlook

The outcomes of this study provide a foundation for the systematic incorporation of plastic waste in flexible pavement construction. However, for widespread adoption and policy-level acceptance, further exploration and scaling are essential. The following directions are recommended for future research and practical application:

- **Field Performance Evaluation**: Large-scale pilot road sections should be constructed and monitored under real-time traffic and environmental conditions to validate laboratory findings and assess long-term behavior, including rutting, fatigue, cracking, and weathering.
- **Multi-Plastic Blend Studies**: Further investigations into combinations of different plastic types (e.g., LDPE, HDPE, PET) and compatibilizers could help improve flexibility, binder compatibility, and homogeneity, especially at higher plastic contents.
- **Aging and Thermal Performance Analysis**: Assessing the long-term aging characteristics, thermal susceptibility, and resilience in diverse climatic zones will be crucial for establishing reliability and lifecycle costing.
- **Techno-Economic and Environmental Impact Assessment**: Detailed cost-benefit analysis and life cycle assessment (LCA**)** studies will be instrumental in quantifying the economic viability and environmental gains of using plastic-modified bitumen.

- **Policy Integration and Standardization**: Collaborations with regulatory bodies and industry stakeholders are needed to develop standardized guidelines, technical specifications, and incentive-based adoption models to facilitate commercial-scale deployment.

6. Final Reflection

The integration of waste plastic into bituminous paving mixes not only provides a sustainable solution for plastic waste disposal but also enhances the performance and resilience of pavements. This dual advantage highlights its potential to serve as a transformational technology in sustainable road infrastructure. The study reinforces the role of material innovation in addressing modern engineering challenges, promoting cleaner construction practices, and advancing toward global sustainable development goals.

Declaration of Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Author has participated in the research and writing process independently and have approved the final manuscript.

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