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Characterization and Performance Evaluation of Polymer-Modified Flexible Pavement Incorporating Waste Plastics

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Abstract - This study investigates the characterization and performance of polymer-modified flexible pavement mixes incorporating waste plastic and crumb rubber. VG-30 bitumen was modified using two approaches: (i) a dry-mix plastic coating process and (ii) crumb rubber addition to produce CRMB. A control mix and six modified mixes—P5, P10, R10, R15, P5+R10, and P10+R15 (numbers indicating percentage by weight of bitumen)—were designed using the Marshall method. Performance evaluation included Marshall Stability and Flow, Indirect Tensile Strength (ITS), Moisture Susceptibility (TSR), Wheel-Tracking Rutting, and Fatigue Life. Results showed that all modified mixes performed better than the control. After converting stability values from kgf to kN, stability increased from 11.60 kN (Control) to 14.91 kN (P10+R15), while maintaining acceptable flow values (2.9–3.8 mm). ITS improved from 0.95 MPa to 1.82 MPa, and TSR values exceeded the 80% durability threshold, reaching a maximum of 87% for P10+R15. Rutting depth decreased from 4.8 mm to 2.5 mm, and fatigue life increased significantly from 14,000 to 23,000 cycles. The combined modification enhanced stiffness through plastic and elasticity through rubber, resulting in superior overall performance and promoting effective solid-waste utilization. The mix P10+R15 is recommended for heavy-traffic corridors in warm and wet regions, subject to field validation and compliance with IS/IRC/AASHTO specifications. Environmental benefits include reduced waste disposal and lower binder consumption.

Keywords: Polymer-modified bitumen; Waste plastic; Crumb rubber; Dry-mix coating

1.INTRODUCTION

The rapid accumulation of plastic waste and discarded rubber tyres has become a major environmental concern due to their non-biodegradable nature. To address this issue, researchers have explored incorporating waste plastic and crumb rubber into flexible pavement construction. Flexible pavements, widely used worldwide, often suffer from cracking, rutting, and pothole formation under increasing traffic loads and temperature variations. Modifying bitumen with waste plastic and crumb rubber significantly enhances pavement durability. Plastic modification improves stiffness and temperature resistance, while crumb rubber increases elasticity and fatigue performance. This approach offers environmental benefits by reducing waste destined for landfills, economic benefits through longer pavement life and reduced maintenance, and technical advantages such as improved moisture and thermal resistance. In India, states like Tamil Nadu, Kerala, and Maharashtra have successfully implemented plastic-modified roads. International studies also confirm improved tensile strength and stability in polymer-modified asphalt. Overall, this technique supports sustainable development and promotes circular economy practices.

1.2 RESEARCH SIGNIFICANCE

The growing accumulation of plastic waste and discarded tyres has intensified global environmental concerns, making sustainable waste management a critical need. Integrating waste plastic and crumb rubber into flexible pavement construction offers a practical and high-impact solution. Plastic enhances bitumen stiffness, water resistance, and temperature stability, while crumb rubber improves elasticity, fatigue resistance, skid resistance, and thermal flexibility. These improvements significantly enhance pavement durability under heavy traffic and varying climatic conditions. Environmentally, this approach diverts large volumes of non-biodegradable waste from landfills and reduces pollution. Economically, longer-lasting roads reduce maintenance costs and conserve natural resources by lowering bitumen demand. The reuse of waste materials also promotes circular economy principles and supports local recycling industries. This research is significant as it demonstrates a sustainable, cost-effective method for improving pavement performance while addressing major environmental challenges, making it a promising strategy for future resilient and eco-friendly road infrastructure.

1.3 Objectives of the Present Study

This study examines the effectiveness of using waste plastic and crumb rubber as modifiers in flexible pavement materials to improve performance and promote sustainability. The investigation is limited to laboratory experiments but provides essential insights that can inform real-world road construction. Modified bituminous mixes are evaluated for strength, durability, flexibility, deformation resistance, and moisture susceptibility using tests such as Marshall Stability, Flow Value, Indirect Tensile Strength, Rutting Resistance, and TSR. The research focuses on determining the optimum proportions of waste plastic and crumb rubber that yield the best pavement performance. Locally sourced LDPE, HDPE, PP, and tyre-derived crumb rubber are used to ensure regional relevance. Environmental and economic benefits—including reduced landfill waste, lower bitumen consumption, and decreased maintenance requirements—are also considered. Challenges related to material handling, compatibility, and mixing are identified, laying the foundation for future field trials and large-scale implementation.

2. LITERATURE REVIEW

Vasudevan et al. (2007) reported that incorporating polyethylene waste plastic into hot aggregates before adding bitumen significantly enhances the performance of flexible pavements. Their study demonstrated that when plastic-coated aggregates are mixed at high temperatures, the melted plastic forms a thin, uniform film around the aggregate surface, improving binding and reducing voids in the mix. This leads to stronger interlocking, higher stability, and improved load-carrying capacity. The plastic coating also increases resistance to water infiltration, reducing stripping and pothole formation. Overall, their research highlighted that waste plastic serves as an effective modifier, enhancing road durability while simultaneously addressing plastic waste disposal challenges.

Hinislioglu et al. (2004) found that incorporating plastic polymers into asphalt binders significantly improves the mechanical and durability characteristics of flexible pavements. Their study showed that the addition of polymers increases the tensile strength of the mix by enhancing the cohesion between binder and aggregates. The modified asphalt also exhibited superior resistance to water-induced damage, reducing stripping and moisture susceptibility. This improvement is attributed to the reduced permeability and stronger bonding created by the polymer-modified binder. Overall, their findings demonstrated that plastic polymers can effectively enhance pavement durability, making the mix more reliable under varying environmental and traffic conditions.

3.MATERIAL AND METHODOLOGY

3.1 Materials Used

3.1.1 Bitumen

The primary binding agent used in this study is VG-30 grade bitumen, commonly employed in flexible pavement construction. The bitumen conforms to IS:73 standards and possesses adequate viscosity and temperature susceptibility for modification.

3.1.2 Waste Plastic

The waste plastic used in this study was collected from municipal solid waste (MSW), including common household items such as carry bags, wrappers, milk packets, and food packaging made mainly of polyethylene (PE) and polypropylene (PP). The plastic was manually segregated to remove contaminants, washed with water and mild detergent, and air-dried for 24–48 hours to eliminate moisture. It was then shredded into 2–4 mm flakes, ensuring uniform size suitable for effective coating of hot aggregates. The processed flakes were stored in dry, sealed containers until mixing. Using such recycled plastic improves binder adhesion, rutting resistance, and overall pavement durability while addressing waste management challenges.

3.1.3 Crumb Rubber

In this study, crumb rubber was used as a partial replacement for fine aggregates, sourced from waste automobile tyres shredded into 1–3 mm particles. The selected size ensured compatibility with fine aggregates and uniform mixing. The rubber granules were thoroughly cleaned and free from steel wires or textile fibres, meeting ASTM D5603 requirements for reclaimed rubber. Before use, the material was inspected to ensure it was dry and free from impurities to promote proper bonding with cement paste. Incorporating crumb rubber reduces natural sand consumption, supports recycling, and enhances flexibility and shock absorption in concrete, making it an eco-friendly and sustainable construction material.

3.1.4 Aggregates

The coarse and fine aggregates used in this study were sourced from a nearby quarry to ensure consistent quality and availability. Their selection followed IS: 2386 standards for testing aggregate properties. Both aggregates were clean, free from dust, clay, and organic impurities, ensuring suitability for concrete production. The angular shape of the coarse aggregates provided superior interlocking and strength, while the fine aggregates, obtained as river sand or quarry dust, were properly graded as per IS: 383. Tests such as specific gravity, water absorption, bulk density, and sieve analysis confirmed that the aggregates met the required standards for strength, durability, and workability in concrete.

4. ANALYSIS OF RESULTS AND DISCUSSION

This chapter presents the experimental results obtained from evaluating bituminous mixes modified with varying proportions of waste plastic and crumb rubber. A comparative assessment is carried out using the conventional (unmodified) bitumen mix as the control. The performance of each modified mix is analysed with respect to five critical parameters that influence pavement quality and durability:

- Marshall Stability
- Indirect Tensile Strength (ITS)
- Tensile Strength Ratio (TSR)
- Rutting Resistance
- Fatigue Life

These indicators collectively provide a comprehensive understanding of the structural, mechanical, and durability improvements achieved through polymer modification.

4.1 Marshall Stability Test (kg)

Marshall Stability results show a clear improvement in load-bearing capacity when waste plastic and crumb rubber are added to bituminous mixes. Plastic enhances stiffness and binder–aggregate bonding, while rubber increases elasticity and deformation resistance. Compared to the control mix (1180 kg), all modified mixes achieved higher stability. The combined mixes performed even better, with the highest value of 1520 kg recorded for 10% plastic + 15% rubber, representing an improvement of nearly 28.8%. This demonstrates the synergistic effect of using both modifiers together, resulting in superior strength, better load resistance, and improved performance under traffic loading.

4.2 Indirect Tensile Strength (ITS, MPa)

Indirect Tensile Strength results show a clear improvement in cracking resistance with the addition of waste plastic and crumb rubber. The control mix recorded the lowest ITS of 1.15 MPa, indicating poor tensile performance. Plastic modification increased ITS to 1.28 MPa at 5% and 1.42 MPa at 10%, due to enhanced binder–aggregate bonding and reduced micro-crack formation. Rubber-modified mixes performed even better, reaching 1.58 MPa at 15% rubber because of improved flexibility. The highest ITS value of 1.82 MPa was achieved by the combined mix with 10% plastic and 15% rubber, demonstrating a strong synergistic effect and superior resistance to thermal and traffic-induced cracking.

4.3 Tensile Strength Ratio (TSR, %)

Tensile Strength Ratio (TSR) results show that moisture resistance improved consistently with the addition of waste plastic and crumb rubber. The control mix recorded the lowest TSR of 68%, indicating high susceptibility to stripping. Plastic-modified mixes performed better, reaching 72% at 5% and 76% at 10% plastic. Rubber further enhanced moisture resistance, with TSR increasing to 78% at 10% and 80% at 15% rubber. The combined mixes showed the highest improvement: 5% plastic + 10% rubber achieved 83%, while 10% plastic + 15% rubber reached 87%. This demonstrates strong adhesion, reduced moisture damage, and excellent suitability for wet-climate pavements.

4.4 Rutting Resistance (mm)

Rutting resistance improved significantly with the addition of waste plastic and crumb rubber. The control mix showed the highest rut depth of 4.80 mm, while plastic-modified mixes reduced rutting to 4.00 mm at 5% and 3.40 mm at 10% plastic due to increased stiffness and better thermal stability. Rubber-modified mixes performed similarly well, decreasing rutting to 3.20 mm at 10% rubber and 3.00 mm at 15% rubber because of enhanced elasticity and load redistribution. The best performance was achieved by combined mixes, especially 10% plastic + 15% rubber, which showed the lowest rut depth of 2.50 mm, indicating excellent deformation resistance under traffic loading.

5. CONCLUSIONS

1. The study confirms that modifying flexible pavement mixes with waste plastic and crumb rubber significantly enhances their structural and mechanical performance. Plastic increases stiffness and improves aggregate–binder bonding, while rubber contributes elasticity and flexibility.
2. Marshall Stability and Flow results showed that modified mixes exhibit higher strength compared to conventional mixes, with the combined modification outperforming individual additives. This indicates a balanced improvement in load-bearing capacity and deformation resistance.
3. Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR) values were consistently higher for modified mixes, demonstrating superior resistance to moisture damage and improved dry and wet strength.
4. Wheel tracking tests showed reduced rut depth, especially in mixes containing both plastic and rubber, highlighting better resistance to permanent deformation under repeated traffic loading.
5. Overall, the use of waste plastic and crumb rubber supports sustainable pavement construction by improving performance, reducing maintenance needs, and effectively utilizing waste materials that would otherwise contribute to environmental pollution.

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