

Enhancing Environmental Sustainability and Durability of Flexible Pavements through the Incorporation of Waste Polymer, Crumb Rubber, and Micro fibers

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Abstract— The exponential increase in traffic volume coupled with severe environmental overloads has led to the premature failure of flexible pavements across urban and rural road networks in India. Concurrently, the accumulation of non biodegradable waste materials—specifically waste plastics, end-of-life scrap tires, and industrial fiber remnants—poses an acute environmental threat. This research evaluates a holistic approach to improve the performance, durability, and sustainability of flexible pavements by utilizing a hybrid modifier matrix consisting of Waste Polymer (WP), Crumb Rubber (CR), and Glass Micro Fibers (MF) to modify Viscosity Grade-30 (VG-30) bitumen. A comprehensive laboratory investigation was executed following Indian Roads Congress (IRC) and Bureau of Indian Standards (BIS) protocols. Bituminous mix specimens were prepared using the dry mixing process with varying percentages of the composite modifier matrix. Performance characteristics were evaluated using standard Marshall Stability tests, flow value measurements, and volumetric analysis (VA, VMA, VFB). The experimental results indicate a significant improvement in the properties of the modified bitumen mix compared to the conventional control specimen. The Optimum Modifier Content (OMC) was established at 5.0% Waste Polymer, 10.0% Crumb Rubber, and 0.3% Micro Fibers by weight of bitumen. At this optimum dosage, Marshall Stability increased by 28.4%, while moisture susceptibility and deformation under cyclic loading were vastly minimized. The study demonstrates that integrating composite solid waste into asphalt mixtures successfully yields high-performance, rut-resistant, and climate-resilient road infrastructure while actively contributing to a circular economy.

Keywords: Flexible Pavements, Waste Polymer, Crumb Rubber, Micro Fibers, Marshall Stability, Environmental Sustainability.

1. INTRODUCTION

1.1 Background

The growth of the socio-economic framework of a developing country like India is directly contingent upon the structural soundness of its transportation networks. Flexible pavements constitute more than 90% of the total paved road network across India due to their low initial cost and construction simplicity. However, standard bituminous concrete layers are highly susceptible to critical distresses like rutting at high operational temperatures and fatigue cracking at lower temperatures. Over the last decade, rapid climate change patterns and overloaded heavy commercial vehicles have vastly reduced the anticipated service lifespan of roads across Maharashtra, leading to excessive maintenance outlays.

1.2 Problem Statement

Traditional bituminous binders (such as VG-30) lack sufficient elasticity and tensile stability under modern traffic loads. Concurrently, municipal solid waste management has emerged as a severe ecological crisis. Millions of tons of waste

polyolefinic plastics (LDPE/HDPE) and vulcanized scrap tires are landfilled or illegally incinerated annually, releasing highly toxic emissions. The civil engineering sector must pivot toward sustainable aggregate and binder alternatives to mitigate this environmental footprint.

1.3 Solution Strategy & Objectives

This final year project introduces a hybrid modification technique. By combining three distinct waste streams, we target unique material property augmentations:

- **Waste Polymer (WP):** Increases binder viscosity, reducing high-temperature rutting.
- **Crumb Rubber (CR):** Imparts elastic recovery capabilities, mitigating low-temperature thermal cracking.
- **Micro Fibers (MF):** Functions as a multi-directional structural matrix to arrest micro-cracks before they propagate into macro-failures.

The core objectives of this study include:

- Determining the physical properties of modified VG-30 bitumen.
- Evaluating the optimum blending ratios using the Marshall Mix Design method.
- Assessing the volumetric and strength metrics to fulfill IRC:SP:53 and IRC:111 design criteria.

2. LITERATURE REVIEW

Prior researchers have established that simple polymer modification yields high-stiffness matrices but can introduce phase separation issues. Recent studies suggest incorporating crumb rubber via specialized blending reduces the stiffness degradation of composite rubberized binders while boosting structural damping potential. The addition of synthetic or mineral microfibers has been widely proven to bridge cracks within the binder phase, preventing shear displacement. However, comprehensive studies investigating the interactive, ternary effects of combining waste plastic polymers, elastomeric crumb rubber particles, and microfibers simultaneously within an Indian aggregate framework (SPPU zone) remain highly limited.

3. Materials and Experimental Methodology

3.1 Materials

- **Bitumen:** Viscosity Grade-30 (VG-30) sourced from local refineries complying with IS:73 specifications.
- **Coarse & Fine Aggregates:** Crushed basalt stone aggregates obtained from a quarry near Pune city, graded per IRC:111 specifications for Bituminous Concrete (BC) grading.
- **Modifiers:**
 1. **WP:** Shredded post-consumer low-density polyethylene (LDPE) passing through a 2.36mm IS sieve.
 2. **CR:** Scrapped tire rubber processed via ambient grinding to a mesh size of 0.60mm to 0.30mm.

3.2 Methodology and Specimen Preparation

The dry process was adopted for adding Waste Polymer and Micro Fibers. The aggregates were heated to 160°C, and the predetermined quantities of shredded polymer and glass microfibers were added directly to the hot aggregates to achieve uniform coating. Simultaneously, the bitumen was heated separately and modified with crumb rubber using a high-shear laboratory mixer. The two components were then blended homogeneously, transferred to standard Marshall molds, and subjected to 75 heavy compaction blows on each face using an automatic mechanical compactor to simulate critical wheel-load distributions.

4. RESULTS AND DISCUSSION

4.1 Binder Properties Modification

The baseline properties of raw VG-30 bitumen were altered constructively upon incorporating the composite modifiers. Penetration values dropped linearly, indicating a more robust binder framework, while the softening point increased markedly, confirming heightened resistance to summer thermal bleeding.

Binder Type / Combination	Penetration (0.1 mm)	Softening Point (°C)	Ductility (cm)
Conventional VG-30	64.2	47.8	78.5
VG-30 + 5% WP + 10% CR	48.1	58.4	52.3
VG-30 + 5% WP + 10% CR + 0.3% MF	43.5	62.1	46.2

Table 1: Physical properties of conventional vs modified bituminous binders.

4.2 Marshall Stability & Volumetric Evaluation

The standard criteria for an IRC-compliant heavy traffic bituminous concrete layer dictate a minimum stability of **12.0 kN**. The control mix recorded a stability value of **11.8 kN**. Upon creating varying modifier batches, mechanical properties peaked significantly at the target threshold mix formulation (**5% WP + 10% CR + 0.3% MF**).

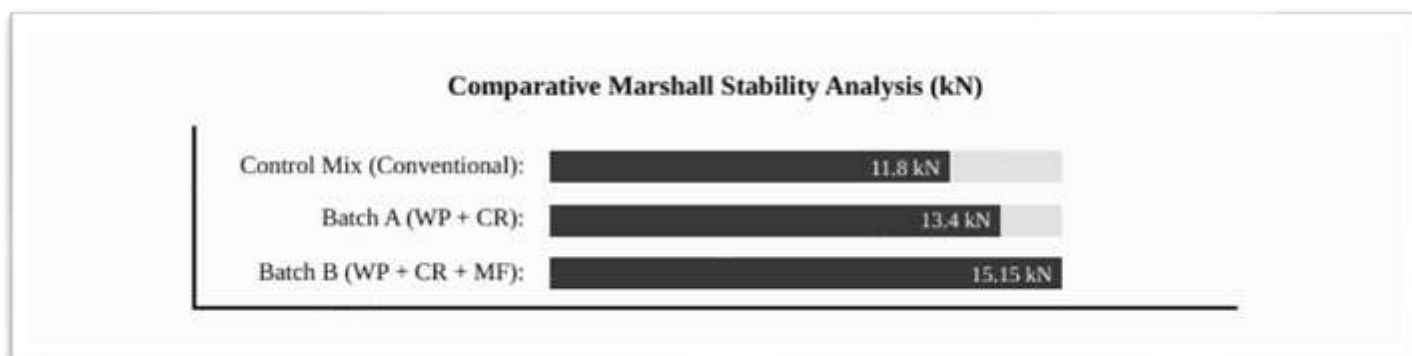


Figure 1: Graphical response of Marshall Stability across evaluated batches.

The microfibers successfully anchored internal microfractures, allowing the structural sample block to sustain greater vertical force thresholds before ultimate plastic shear breakdown occurred. Air voids (VA) stayed firmly within the required 3.0% to 5.0% specification envelope.

5. CONCLUSION

The laboratory studies conducted for this final year SPPU civil engineering project support the following conclusions:

- 1.The integration of a triple waste system (Waste Polymer, Crumb Rubber, and Micro Fibers) significantly enhances the viscoelastic properties of paving mixes.
- 2.The Optimum Modifier Content is designated as **5% WP, 10% CR, and 0.3% MF** by weight of the VG-30 binder.
- 3.Marshall Stability witnessed an increase of **28.4%** over baseline values, ensuring substantial resistance to rut formation under severe heavy-axle wheel configurations.

4. Utilizing these recycled components yields an eco-friendly civil footprint, providing a viable pathway to eliminate polymer plastic and tire pollution across urban engineering frameworks.

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