Study on Bitumen Modified with Crumb Rubber

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Abstract - The primary objective of this research is to develop a cost-effective and storage-stable crumb rubber modified bitumen (CRMB) using waste-derived materials, thereby offering an environmentally sustainable alternative for rubber waste disposal. The study focuses on improving the compatibility, dispersion, and long-term stability of crumb rubber within bitumen through novel chemical additives. Long-chain amine compounds were explored to enhance storage stability, while the synergistic interaction between polyamines and fatty acids was examined for improved modification efficiency. Additionally, a synthesized PET-based waste derivative combined with a bifunctional anchoring compound was investigated to promote chemical bonding within the CRMB matrix. The developed formulations aim to reduce phase separation, enhance performance characteristics, and provide a practical, eco-friendly solution for the bitumen industry. Overall, this work contributes to sustainable pavement technologies while minimizing the environmental impact of waste rubber and plastic materials.

Key Words**:** Crumb Rubber Modified Bitumen (CRMB); Storage Stability; Waste PET Derivatives; Long-Chain Amines; Polyamine–Fatty Acid Interaction; Bifunctional Anchoring Compounds; Sustainable Pavement Materials; Waste Rubber Utilization; Eco-friendly Bitumen Modification; Phase Separation Reduction.

1. INTRODUCTION

The rapid expansion of road infrastructure in India, which holds the world's second-largest road network, demands high-performance and durable pavement materials. Conventional bitumen, widely used in flexible pavements, often suffers from premature distresses such as rutting, fatigue cracking, and thermal susceptibility under increasing traffic loads and extreme climatic variations. At the same time, the accumulation of waste tires and plastic materials—particularly crumb rubber from automotive tires and polyethylene terephthalate (PET) from packaging industries—poses major environmental challenges due to their non-biodegradable nature and unsafe disposal practices. Incorporating these waste materials into bitumen provides a sustainable solution that not only enhances pavement performance but also minimizes landfill pollution.

Crumb Rubber Modified Bitumen (CRMB) offers improved elasticity, durability, and resistance to deformation; however, its widespread application is limited by poor storage stability arising from phase separation between rubber particles and bitumen. This research aims to address these limitations by developing cost-effective and storage-stable CRMB using novel waste-derived chemical additives. Long-chain amines, polyamine–fatty acid blends, and synthesized PET-based derivatives combined with bifunctional anchoring compounds are explored to enhance compatibility and reduce phase separation. The study includes chemical characterization, synthesis of additives, rheological evaluation, and performance assessment to develop an environmentally friendly and economically viable modified bitumen for advanced pavement applications.

1.4 Need for the Study

Understanding heterogeneous traffic behavior is essential for planning and optimizing urban road networks. Speed–flow relationships are vital tools used in capacity estimation, level-of-service analysis, and travel-cost evaluation. Developing models tailored to mixed traffic conditions provides a better understanding of roadway performance.

1.2 Objectives of the Study

1. To develop a cost-effective and storage-stable crumb rubber modified bitumen (CRMB) **using waste-derived materials, thereby reducing environmental pollution and offering a sustainable disposal route for waste rubber.**

2. To formulate storage-stable CRMB using long-chain amine compounds **that enhance compatibility and minimize phase separation between crumb rubber and bitumen.**

3. To investigate the synergistic effect of polyamines and fatty acids **in improving the interaction, dispersion, and performance properties of crumb rubber modified bitumen.**

4. To utilize synthesized waste PET-based derivatives combined with a bifunctional anchoring compound **for strengthening the bonding mechanism within CRMB and improving its long-term storage stability.**

5.To evaluate the performance properties of the modified binders and mixes **using standard rheological and mechanical tests, including the** Marshall Stability Test **for assessing stability and flow characteristics of CRMB mixes.**

2. LITERATURE REVIEW

Crumb Rubber Modified Bitumen (CRMB) has been widely studied as a sustainable alternative to conventional binders for flexible pavements. Researchers such as Farina et al. and Zhang et al. highlighted that incorporating crumb rubber from waste tires enhances elasticity, rutting resistance, and fatigue performance while simultaneously addressing environmental challenges related to tire disposal. In the wet process, rubber interacts with hot bitumen, and its performance depends on blending temperature, mixing time, particle size, and shear rate. Studies by Li et al. and Nejad et al. showed that CRMB exhibits higher stiffness, improved softening point, and better deflection tolerance compared to unmodified binders. Kök et al. confirmed that fine rubber particles can match the performance of SBS-modified binders, emphasizing the importance of rubber size and swelling behavior.

Despite these advantages, storage stability at elevated temperatures remains a major issue, as reported by Pang et al., Wu et al., and Çelik et al., who observed phase separation between rubber and bitumen during storage. To improve this, several researchers explored additives such as SBS (Gonzalez et al.), SBR/MMT composites (Zhang et al.), HDPE extrusion (Wang et al.), LDPE with copolymers (Oyuang et al.), acrylic acid–treated rubber (Kocevski et al.), and desulfurized rubber (Ma et al.). These modifications improved viscosity, elasticity, aging resistance, and softening point, though they often required complex chemical treatments and did not fully eliminate separation issues.

Recent reviews, including those by Navarro et al., emphasized that limited research exists on chemically anchoring crumb rubber within the bitumen matrix. Therefore, the present study focuses on long-chain amines, polyamines with fatty acids, and PET-derived amide additives to develop chemically anchored, storage-stable CRMB with enhanced rheological and performance properties.

3. METHODOLOGY

Figure 1. Flow chart showing study methodology

This study investigates the physical, rheological, and performance characteristics of bitumen and Crumb Rubber Modified Bitumen (CRMB) using standard test protocols. The materials used include conventional paving-grade bitumen and processed crumb rubber obtained from waste tires. Bitumen is a black, thermoplastic hydrocarbon binder composed of saturates, aromatics, resins, and asphaltenes, whose proportions influence stiffness, flow behavior, and durability. Crumb rubber was produced through ambient and cryogenic grinding processes to obtain uniform rubber particles suitable for binder modification.

CRMB samples were prepared by blending bitumen with crumb rubber under controlled temperature and mixing conditions. The physical properties of both base and modified binders were evaluated through penetration, softening point, elastic recovery, viscosity, and aging tests using ASTM and AASHTO standards. Short-term and long-term aging characteristics were assessed using the Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) methods. Rheological behavior was examined using a Dynamic Shear Rheometer (DSR) to determine complex modulus, phase angle, and rutting resistance, while low-temperature performance was assessed using the Bending Beam Rheometer (BBR). The Multiple Stress Creep Recovery (MSCR) test was performed to quantify permanent deformation resistance.

Performance evaluation of CRMB–aggregate mixtures was conducted using the Marshall Stability method and wheel-tracking assessments to determine strength, flow, and rutting resistance under simulated field conditions.

4. Results and Discussion

The Marshall Stability and flow characteristics of neat bitumen, CRDS-1, and CRDS-4 mixtures were evaluated to assess the influence of crumb rubber modifiers and chemical additives on the performance of the bituminous mix. The results presented in Table 4.1 show a clear improvement in strength and durability with the incorporation of CRMB blends.

The Marshall Stability values before conditioning were 14.84 kN for neat bitumen, 19.76 kN for CRDS-1, and 22.92 kN for CRDS-4. After conditioning, the values decreased to 10.16 kN, 15.13 kN, and 19.85 kN, respectively. The reduction in stability after conditioning is expected due to moisture exposure; however, the modified binders exhibited substantially lower loss compared to neat bitumen. Among the samples, CRDS-4 demonstrated the highest retained strength, indicating superior resistance to moisture-induced damage.

Flow values remained within acceptable limits for all samples, ranging from 3.29–3.41 mm before conditioning and 3.30–3.66 mm after conditioning, indicating that the deformation characteristics of the mixtures were not adversely affected by modification.

The Retained Marshall Stability (RMS) values further highlight the enhanced durability of CRDS-4. While neat bitumen exhibited an RMS of 68%, CRDS-1 improved to 76%, and CRDS-4 achieved the highest RMS of 87%. The superior performance of CRDS-4 can be attributed to its improved storage stability, higher rutting resistance (high G*/sinδ), lower creep stiffness, and better resistance to thermal cracking compared to other CRMB blends.

Overall, the results confirm that CRDS-4 provides the most resilient mix, demonstrating enhanced strength, improved moisture resistance, and stable deformation behavior, making it the most suitable binder formulation among the tested samples.

Table1: Retained Marshall Stability of bituminous mixes

Sample code	Marshall Strength (kN) before conditioning (S1)	Flow value (cm) before conditioning	Marshall Strength (kN) after conditioning (S2)	Flow value (cm) after conditioning	Retained Marshall Stability (%) =(S2/S1)×100
Neat Bitumen	14.84	3.29	10.16	3.66	68.46
CRDS-1	19.76	3.35	15.13	3.30	76.56
CRDS-4	22.92	3.41	19.85	3.34	86.60

The rutting resistance test was conducted using the Wheel Tracking apparatus as per EN 12697–22:2003+A1. Mix slabs of size 300 × 300 × 40 mm were prepared and tested to evaluate permanent deformation under repeated loading. The rut depths after 10,000 cycles were **6.18 mm** for neat bitumen, **2.92 mm** for CRDS-1, and **2.24 mm** for CRDS-4. The significantly lower rut depth of CRDS-4 demonstrates its superior resistance to permanent deformation. Compared with

neat bitumen and CRDS-1, CRDS-4 exhibited the best rutting resistance throughout all loading cycles, confirming its enhanced high-temperature performance and structural stability.

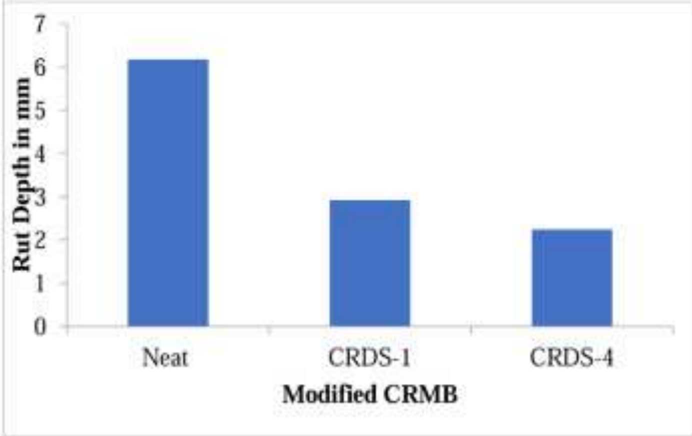

Figure 2: Rut depth different CRMB blends

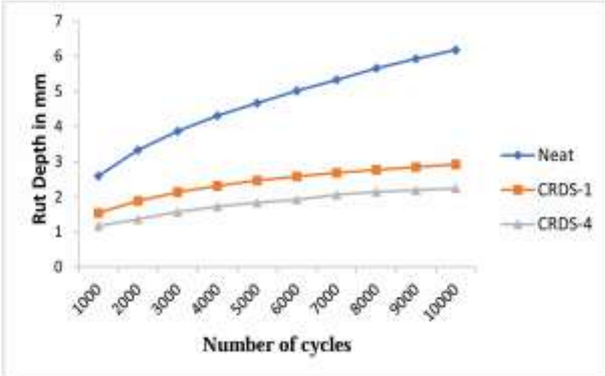

Figure 3: Rut depth of CRMB blends at different cycle

The Marshall Stability test was conducted to evaluate the strength and deformation characteristics of bituminous mixtures prepared according to ASTM D6926 and ASTM D6927. Specimens were conditioned in a water bath at 60 ± 1 °C for 30 minutes and 24 hours to assess stability before and after moisture exposure. Marshall Stability reflects the maximum load a specimen can withstand, while the flow value represents its total deformation at failure. Among all blends, CRMB-7 exhibited superior performance due to its excellent storage stability, high G*/Sinδ value, strong rutting resistance, low creep stiffness, and improved thermal cracking resistance. Its results were compared with CRMB-1 and neat bitumen to assess overall improvement.

Sample code	Marshall Strength (kN) before conditioning (S_1)	Flow value (cm) before conditioning	Marshall Strength (kN) after conditioning (S_2)	Flow value (cm) after conditioning	Retained Marshall Stability (%) = (S_2/ S_1)×100
Neat	14.84	3.29	10.16	3.66	68
CRMB-1	19.76	3.35	15.13	3.30	76

CRMB-7	23.32	3.40	20.15	3.34	86

Marshall Strength of neat bitumen, CRMB-1, CRMB-7 before conditioning was found to be 14.84, 19.76, 23.32 kN and after conditioning was found out to be 10.16, 15.13, 20.15 kN respectively (Table 6.2). Flow value before and after conditioning of sample was found to be 3.29, 3.35, 3.40 and 3.66, 3.30, and 3.34 mm respectively. After observing Marshall Strength and flow value before and after conditioning of the samples, it has been observed that percentage of Retained Marshall Stability for CRMB-7 was better (86%) than CRMB-1 (76%) and neat bitumen (68%).

The rutting resistance test was conducted using the wheel tracking method as per EN 12697–22:2003+A1. Mix slabs of 300 × 300 × 40 mm were prepared and tested to evaluate permanent deformation under repeated loading. Since CRMB-7 exhibited superior physical and rheological properties among all blends, it was selected for detailed rutting evaluation and compared with CRMB-1 and neat bitumen. The rut depths after 10,000 cycles were 6.18 mm for neat bitumen, 2.92 mm for CRMB-1, and 2.11 mm for CRMB-7. The consistently lower rut depth of CRMB-7 across loading cycles confirms its enhanced high-temperature performance, improved resistance to permanent deformation, and better overall rutting resistance compared to the other binders.

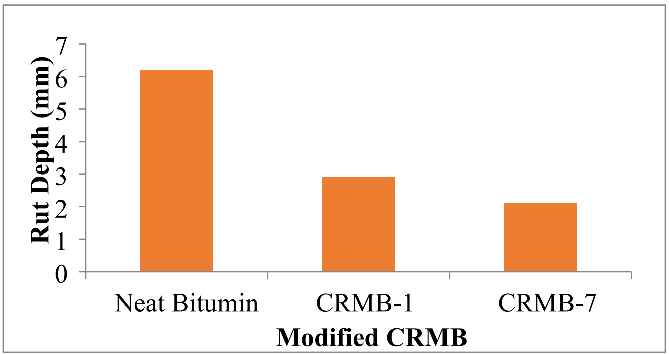

Figure 4 Rut Depth of different CRMB blends

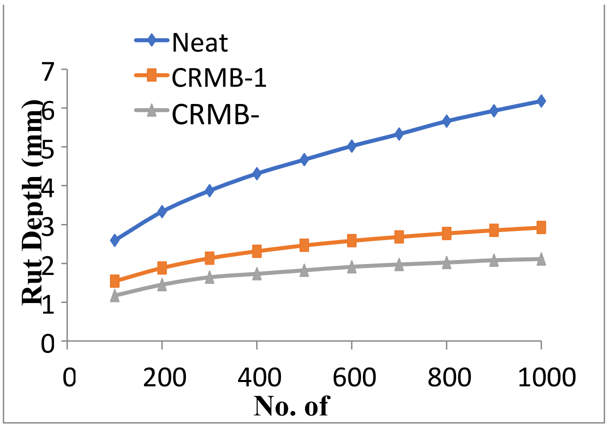

Figure 5 Rut Depth of CRMB blends at different cycles .

5.Conclusion

This study presents a novel approach for anchoring crumb rubber within bitumen using different chemical additives to enhance the performance and storage stability of Crumb Rubber Modified Bitumen (CRMB). The method eliminates the need for milling operations, making the process more energy-efficient and cost-effective while simultaneously supporting sustainable waste management through the utilization of waste plastics and discarded tire rubber.

Results showed that CRMB doped with long-chain amines exhibited a marked improvement in storage stability. Enhanced absorption of the bitumen's oil fraction by the crumb rubber increased viscosity, and the presence of long-chain amines further promoted interaction by increasing the saturated component of the binder. CRMB modified with polyamines and fatty acids also demonstrated improved stability and enhanced rheological and performance characteristics due to the formation of long-chain amide structures. Additionally, a green aminolysis process was used to synthesize PET derivatives from waste PET, which effectively anchored crumb rubber in bitumen. When combined with a bifunctional compound, PET derivatives provided further improvements in storage stability, rutting resistance, low-temperature cracking resistance, and fatigue behavior, making the modified binders suitable for heavy-traffic applications.

5.1 Future Scope

Given their dual hydrophobic–hydrophilic nature, the synthesized amide-based additives show potential for use as emulsifiers in bitumen emulsion and PMB emulsion technologies, suggesting an important direction for future research.

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