

Comparative Analysis of Conventional and Waste Tyre Rubber Modified Bitumen for Flexible Pavement Applications

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Abstract — Crumb rubber modified bitumen (CRMB) has gained significant attention as a sustainable and performance-enhancing binder for flexible pavements. This comprehensive review consolidates knowledge on the production methods (wet process, dry process, and terminal blending), influence of crumb rubber on physical and rheological properties of bitumen, and the consequent improvements in pavement performance including resistance to rutting, fatigue cracking, low-temperature cracking, and aging. The review also examines the Indian regulatory framework under IS 15462:2019, the environmental and economic advantages of incorporating waste tire rubber, and the challenges hindering widespread adoption. Findings from the literature consistently demonstrate that CRMB outperforms conventional bitumen in terms of high-temperature stability, elastic recovery, and long-term durability. The review identifies research gaps and provides direction for future work towards optimized mix designs and field performance evaluation in Indian climatic conditions.

Keywords: Crumb Rubber Modified Bitumen (CRMB); Flexible Pavement; Wet Process; Dry Process; Rutting; Fatigue Life; IS 15462:2019; Waste Tire Rubber

I. INTRODUCTION

Flexible pavements constitute the majority of road infrastructure across the globe, including in India where over 60 lakh kilometers of roads form the backbone of connectivity and economic activity. The performance of a flexible pavement is critically dependent on the properties of the bituminous binder. Conventional bituminous binders such as VG-30 and VG-40, while adequate for moderate traffic and climatic conditions, often fail prematurely under heavy axle loads, extreme temperatures, and increasing traffic volumes. This manifests as rutting in summer, thermal cracking in winter, and fatigue distress under repetitive loading.

Polymer modification of bitumen has been explored extensively as a solution to these challenges. Among the various modifiers investigated, crumb rubber derived from waste automobile tires has emerged as a particularly attractive option. Waste tire disposal is a significant environmental problem globally; approximately 1.5 billion tires reach their end of life annually. Converting them into crumb rubber (CR) for bitumen modification presents a dual benefit: diverting waste from landfills and incineration while simultaneously improving pavement performance.

Crumb Rubber Modified Bitumen (CRMB) is produced by blending crumb rubber particles, obtained by mechanical shredding or cryogenic processing of scrap tires, with hot bitumen. The rubber particles interact with the bitumen through swelling and partial devulcanization, altering the binder microstructure and rheological behavior significantly. CRMB exhibits higher softening point,

improved elastic recovery, greater viscosity, enhanced resistance to permanent deformation, and better low-temperature flexibility compared to unmodified bitumen.

In India, the Bureau of Indian Standards specifies CRMB through IS 15462:2019, defining three grades: CRMB-50, CRMB-55, and CRMB-60, differentiated primarily by softening point requirements. The Ministry of Road Transport and Highways (MoRTH) and the Indian Roads Congress (IRC) have incorporated CRMB in specifications for high-traffic roads. Despite these advances, widespread adoption faces challenges including higher initial cost, storage stability concerns, and inconsistency in crumb rubber characteristics.

This review aims to provide a comprehensive synthesis of the current knowledge on CRMB, covering raw material characterization, production methods, property enhancements, mix design implications, pavement performance, and economic and environmental considerations. The review also identifies gaps in knowledge and directions for future research.

II. CRUMB RUBBER: SOURCES AND CHARACTERIZATION

A. Sources of Crumb Rubber

Crumb rubber is primarily obtained from end-of-life vehicle tires (ELTs), which consist of approximately 47% rubber, 22% carbon black, 15% steel, and 16% other materials including fabric cord, plasticizers, and fillers. Automobile tires (passenger car, truck, and motorcycle) constitute the principal source, though industrial rubber products also contribute marginally. The composition of the rubber in a tire is predominantly Styrene-Butadiene Rubber (SBR) and natural rubber (NR), with sulfur-based cross-links introduced during vulcanization. These components significantly influence the interaction of crumb rubber with bitumen.

B. Production Methods of Crumb Rubber

Three main processes are used for producing crumb rubber from waste tires:

- 1) **Ambient Mechanical Grinding:** The most commonly used method, involving sequential grinding of whole tires at room temperature using a series of granulators, shredders, and cracker mills. Tire steel is separated magnetically and fiber by aspiration. This process produces irregularly shaped particles of 0.075–4.75 mm with high surface area and reactivity.
- 2) **Cryogenic Processing:** Tires are cooled to approximately -80°C to -120°C using liquid nitrogen, rendering the rubber brittle, which is then shattered by impact. Cryogenic crumb rubber has a smoother, glassy surface with less surface area, affecting its interaction with bitumen.

- 3) **Water Jet Technology:** High-pressure water jets are used to separate and size rubber particles. This produces cleaner particles with minimal contamination but at a higher operational cost.

C. Physical and Chemical Characteristics

The key parameters of crumb rubber relevant to bitumen modification include particle size (mesh size), surface morphology, specific gravity (~1.15), and chemical composition. Finer particles (20–80 mesh) generally show greater surface area and higher reactivity with bitumen. Carbon black content in crumb rubber contributes to UV resistance of the modified binder. The vulcanized network structure limits the full dissolution of rubber in bitumen, resulting in a heterogeneous two-phase system at typical blending temperatures.

III. METHODS OF INCORPORATION

A. Wet Process

In the wet process, crumb rubber is blended with bitumen before mixing with aggregates. The rubber is added to hot bitumen (typically 170–200°C) under high shear mixing for 30–60 minutes. During this period, the rubber particles absorb aromatic oils from the bitumen, swell to 2–4 times their original volume, and partially devulcanize. This process is also called the "bitumen-rubber" or "asphalt-rubber" process and is the most widely used method globally. The degree of swelling and reactivity depends on blending temperature, time, shear rate, bitumen chemistry, and crumb rubber gradation and composition.

The resultant CRMB can be stored and transported as a binder and used in conventional hot mix asphalt (HMA) plants. Rubber content in the wet process typically ranges from 15–22% by weight of bitumen. The wet process produces significant improvements in binder viscosity, elastic recovery, and high-temperature performance.

B. Dry Process

In the dry process, crumb rubber particles are added directly to the aggregate mix prior to the addition of bitumen, functioning partly as an aggregate modifier and partly as a binder modifier. Rubber content is generally 1–3% by weight of the total mixture. While the dry process is simpler and avoids specialized binder production equipment, the interaction between rubber and bitumen is less complete, and the performance improvements are generally more modest and variable compared to the wet process. The Rubberset and Plus Ride systems are notable dry-process applications.

C. Terminal Blending

Terminal blending involves processing crumb rubber with bitumen under high shear and elevated temperature (210–230°C) for extended periods (typically 2–4 hours) at a bitumen refinery or terminal, producing a more homogeneous and storage-stable binder. The product closely resembles a polymer-modified bitumen (PMB) in its uniform microstructure. Terminal-blended CRMB can be stored for weeks without significant separation, addressing one of the critical challenges of field-blended CRMB. Although the rubber particle morphology is more degraded, the binder performance is consistent and reproducible.

D. High-Shear Wet Process Variants

Advances in processing technology have led to high-shear variants of the wet process that produce binders with improved homogeneity. High-shear mill processing at 4000–6000 rpm significantly reduces rubber particle size in the blend and improves compatibility. Combined use of chemical activators (devulcanizing agents such as dibenzothiazyl disulfide, aromatic oils) alongside mechanical shearing further enhances the degree of rubber-bitumen interaction.

IV. EFFECT ON BITUMEN PROPERTIES

Property	CRMB-50	CRMB-55	CRMB-60
Penetration at 25°C (0.1 mm)	≥ 50	≥ 45	≥ 40
Softening Point (°C)	≥ 50	≥ 55	≥ 60
Elastic Recovery at 15°C (%)	≥ 50	≥ 50	≥ 50
Flash Point (°C)	≥ 220	≥ 220	≥ 220
Viscosity at 150°C (Pa·s)	≤ 3	≤ 3	≤ 3
Separation (Softening Pt. diff., °C)	≤ 4	≤ 4	≤ 4

Table I: CRMB Grades as Per Is 15462:2019

A. Penetration

Penetration, a measure of bitumen consistency, decreases significantly with increasing crumb rubber content. Incorporation of 15–20% CR typically reduces penetration by 30–50% compared to the base bitumen. This stiffening effect reflects the modification of the bitumen colloidal structure by swollen rubber particles. Lower penetration corresponds to higher stiffness at ambient temperatures, which is beneficial for rutting resistance but may adversely affect low-temperature cracking susceptibility if not optimized.

B. Softening Point

The softening point (Ring and Ball test) increases substantially with crumb rubber modification, often by 10–20°C over unmodified bitumen. CRMB-60 exhibits a softening point of at least 60°C as mandated by IS 15462:2019. Higher softening point indicates better resistance to viscous flow at elevated pavement temperatures, directly correlating with improved resistance to rutting and shoving.

C. Ductility and Elastic Recovery

Ductility, while reduced compared to unmodified bitumen, is supplemented by elastic recovery, which quantifies the resilience of the modified binder. CRMB exhibits elastic recovery values of 50–75% at 15°C, compared to near-zero for conventional bitumen. This elastic behavior is attributable to the cross-linked rubber network within the bitumen matrix, which imparts memory and spring-back characteristics to the binder. Higher elastic recovery correlates with superior fatigue resistance.

D. Viscosity and Rheological Behavior

The viscosity of CRMB is significantly higher than that of unmodified bitumen at all temperatures. At 135°C, CRMB viscosity is typically 3–6 times that of VG-30 bitumen,

necessitating elevated mixing and compaction temperatures (typically 175–185°C and 160–170°C respectively). Dynamic Shear Rheometer (DSR) testing reveals that CRMB has a higher complex modulus (G^*) and a lower phase angle (δ), indicating enhanced elastic response. The Rutting Parameter ($G^*/\sin \delta$) for CRMB at 64°C typically exceeds 1.0 kPa, meeting SUPERPAVE requirements for high-traffic conditions.

E. Storage Stability

Storage stability of CRMB, evaluated by the difference in softening point between the top and bottom of a stored sample (163°C for 48 hours), is a critical quality parameter. Blends with coarser rubber particles or prepared without high-shear mixing tend to exhibit greater separation. IS 15462:2019 limits the softening point difference to $\leq 4^\circ\text{C}$. Stabilizers such as sulfur, polyphosphoric acid, and cross-linking agents have been used to improve storage stability.

Property	Conventional Bitumen (VG-30)	CRMB-60 (15% CR)
Penetration (0.1 mm)	60–70	40–50
Softening Point (°C)	47–55	60–70
Ductility at 27°C (cm)	> 75	10–30
Elastic Recovery (%)	Nil	50–70
Viscosity at 135°C (Pa·s)	0.35–0.40	1.2–2.0
Rutting Resistance	Moderate	High

Table II Comparison of Bitumen Properties: Conventional Vs. CRMB

V. PAVEMENT PERFORMANCE WITH CRMB

A. Rutting Resistance

Rutting, or permanent deformation of the pavement surface under repeated heavy loading, is among the most common pavement distresses in hot climates such as those prevalent in India. Laboratory studies using the Hamburg Wheel Tracking Test (HWTT) and repeated creep tests consistently show that CRMB mixtures exhibit significantly lower rutting depth compared to conventional HMA. Dynamic modulus testing indicates higher stiffness at high temperatures for CRMB mixes. Field trials on high-traffic national highways and urban arterials have confirmed that CRMB sections show rutting depths 40–60% lower than conventional sections after equivalent traffic loading. The improved performance is attributed to the higher softening point and elastic recovery of CRMB.

B. Fatigue Life

Fatigue cracking, resulting from accumulated strain under repetitive traffic loading, is a critical failure mode for flexible pavements. Four-point beam fatigue tests demonstrate that CRMB mixtures exhibit fatigue lives 2–4 times longer than conventional HMA at equivalent strain levels. The elastic recovery of CRMB allows partial self-healing between load cycles, reducing strain accumulation. The improved energy

absorption capacity of the rubberized binder delays crack initiation and slows crack propagation. Studies using the Binder Bond Strength (BBS) test and Semi-Circular Bending (SCB) test further confirm enhanced fracture resistance.

C. Low-Temperature Performance and Thermal Cracking

Thermal cracking occurs in cold climates when pavement temperatures fall below the binder's glass transition temperature, inducing tensile stresses that exceed the binder's tensile strength. The incorporation of rubber imparts flexibility to the binder at low temperatures, reducing the glass transition temperature and improving resistance to thermal cracking. BBR (Bending Beam Rheometer) testing shows lower stiffness (S) and higher m -value for CRMB at low temperatures, satisfying SUPERPAVE low-temperature performance grade requirements. This benefit is particularly relevant for pavements in northern and high-altitude regions of India.

D. Moisture Damage Resistance

Moisture-induced damage (stripping) is exacerbated in regions with high rainfall. Indirect Tensile Strength Ratio (ITSR) tests show that CRMB mixtures exhibit ITSR values of 85–95%, compared to 70–80% for conventional HMA, indicating superior resistance to stripping. The rubber coating on aggregates enhances binder-aggregate adhesion, reducing susceptibility to moisture damage. Anti-stripping additives can further enhance moisture resistance when combined with CRMB.

E. Aging Resistance

Bitumen aging, caused by oxidation and volatilization of light aromatic fractions, leads to binder embrittlement and pavement cracking over time. Rolling Thin Film Oven Test (RTFOT) and Pressure Aging Vessel (PAV) simulations show that CRMB retains a higher proportion of its original properties after artificial aging compared to conventional bitumen. The carbon black in crumb rubber acts as an antioxidant, inhibiting oxidative aging. Studies report that the performance grade span of CRMB is maintained better post-aging than that of conventional PMBs.

F. Noise Reduction

A notable co-benefit of rubberized asphalt, particularly in the gap-graded or open-graded mix configurations using CRMB, is significant reduction in tire-pavement noise. Crumb rubber asphalt concrete (CRAC) can reduce traffic noise by 3–8 dB compared to conventional dense-graded HMA, contributing to urban noise mitigation. While this benefit is well-established in the USA and Europe, research in the Indian context on noise characteristics of CRMB mixes is limited and warrants further investigation.

VI. MIX DESIGN AND CONSTRUCTION ASPECTS

A. Aggregate Gradation

CRMB is compatible with most HMA gradations used in Indian practice, including DBM (Dense Bituminous Macadam), BC (Bituminous Concrete), and SMA (Stone Matrix Asphalt). SMA, which relies on a coarse aggregate skeleton with mastic filling voids, is particularly well-suited for CRMB due to its low void content and reliance on a high-

quality binder mastic. MoRTH specifications and IRC:SP:53 provide guidance on gradations compatible with CRMB.

B. Optimum Binder Content

Due to the higher viscosity of CRMB, the optimum binder content (OBC) determined by the Marshall Method or Volumetric Design is typically 0.2–0.4% higher than for conventional bitumen with the same aggregate gradation. This ensures adequate film thickness and workability. Higher OBC, combined with improved binder properties, contributes to the superior durability of CRMB mixes.

C. Mixing and Compaction Temperatures

The elevated viscosity of CRMB necessitates higher mixing (175–185°C) and compaction (165–175°C) temperatures compared to conventional bitumen. Proper temperature control is critical to ensure uniform coating, adequate compaction, and prevention of thermal degradation of the rubber. Warm Mix Asphalt (WMA) additives have been explored in combination with CRMB to reduce mixing temperatures while maintaining performance.

D. Plant and Equipment Requirements

Standard drum mix or batch mix HMA plants can produce CRMB mixes if equipped for higher viscosity binders. Binder storage tanks should be agitated to prevent rubber particle settlement. On-site blending of CRMB using mobile high-shear blending units has been practiced at large road construction sites. Field applications require modified spray bars with higher pressure and larger orifices for surface dressing and Stress Absorbing Membrane Interlayer (SAMI) applications.

VII. ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

A. Environmental Benefits

India generates over 100 million end-of-life tires annually, posing significant disposal challenges. Landfilling of tires is banned in many countries due to fire hazards, leachate contamination, and mosquito-borne disease vectors. CRMB production diverts waste tires from landfills and incineration, reducing CO₂ emissions associated with tire combustion. Life Cycle Assessment (LCA) studies consistently show a net positive environmental impact of CRMB pavements, particularly when the extended service life (which reduces frequency of resurfacing) is accounted for. Each kilometer of road constructed with CRMB utilizes approximately 2,000–3,000 waste tires.

B. Carbon Footprint

The production of crumb rubber consumes less energy than virgin polymer modifiers such as SBS (Styrene-Butadiene-Styrene), reducing the embodied carbon of the modified binder. Additionally, CRMB pavements' longer service life reduces the lifecycle frequency of maintenance and rehabilitation interventions, each of which involves significant energy consumption and greenhouse gas emissions. Overall, CRMB pavements have been estimated to reduce lifecycle carbon footprint by 15–30% compared to conventional HMA alternatives.

C. Economic Analysis

CRMB commands a price premium of 15–30% over conventional VG-30 bitumen, primarily due to crumb rubber production and processing costs. However, Life Cycle Cost Analysis (LCCA) consistently demonstrates that CRMB pavements are economically advantageous over a 20–30 year analysis period, owing to extended service life, reduced maintenance frequency, and lower user costs from smoother and more durable roads. Indian road agencies adopting CRMB for high-traffic corridors have reported extended performance periods of 5–8 years versus 3–5 years for conventional HMA, improving the benefit-cost ratio significantly.

VIII. INDIAN SCENARIO AND REGULATORY FRAMEWORK

India has made notable strides in the adoption of CRMB for road construction. The Rubber Board of India, Ministry of Road Transport and Highways (MoRTH), and the Indian Roads Congress (IRC) have collectively promoted the use of CRMB on national highways and urban expressways. IS 15462:2019, the revised standard for polymer and rubber modified bitumen, provides specifications for CRMB-50, CRMB-55, and CRMB-60, with minimum requirements for penetration, softening point, elastic recovery, viscosity, and storage stability.

MoRTH specifications (5th Revision, 2013 and subsequent amendments) prescribe CRMB for wearing courses on high-traffic roads (more than 30 million standard axles). Several National Highway projects under NHAI have been executed with CRMB, including sections on NH-44, NH-8, and the Golden Quadrilateral expansion. IRC:SP:53-2010 provides guidelines for the use of modified bitumen including CRMB. State PWDs in Kerala, Maharashtra, and Andhra Pradesh have also adopted CRMB-based pavements, leveraging the availability of natural rubber resources.

Despite regulatory support, challenges persist in India including: (a) inconsistency in crumb rubber quality from informal recyclers; (b) limited number of CRMB production facilities with quality control; (c) higher initial cost creating procurement resistance; (d) inadequate awareness among field engineers and contractors; and (e) limited long-term performance data from Indian climatic zones. Addressing these barriers through standardized crumb rubber production, capacity building, and demonstration projects is essential for scaling CRMB adoption.

IX. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite the well-established benefits of CRMB, several research gaps and practical challenges remain:

- 1) Devulcanization and Chemical Modification: Development of efficient, cost-effective devulcanization processes to produce chemically reactive crumb rubber that blends more completely with bitumen is needed. Microwave-assisted and ultrasonic devulcanization show promise.
- 2) Long-term Field Performance Data: Systematic long-term performance monitoring of CRMB pavements across diverse Indian climatic zones (hot-dry, hot-humid, cold) is lacking. Performance databases will enable better design and specification.

- 3) Warm Mix CRMB: Integration of WMA additives with CRMB can reduce production temperatures, improving workability and worker safety while maintaining performance. Further research on WMA-CRMB compatibility and performance is warranted.
- 4) Nano-modified CRMB: Incorporation of nano-fillers (nano-silica, nano-clay, carbon nanotubes) alongside crumb rubber in bitumen has shown synergistic improvements in stiffness and fatigue resistance. Optimization of multi-modifier systems requires further study.
- 5) Rejuvenated Reclaimed CRMB: Use of bio-based rejuvenators to restore the properties of aged CRMB for recycling as Reclaimed Asphalt Pavement (RAP) is a frontier area of research.
- 6) Standardization of Crumb Rubber Quality: A national standard for crumb rubber specifications (gradation, composition, metal content) is needed to ensure consistent CRMB quality across Indian producers.

X. CONCLUSION

This review has comprehensively examined the production, properties, pavement performance, and sustainability aspects of Crumb Rubber Modified Bitumen. The following key conclusions are drawn from the literature:

- 1) CRMB produced by the wet process exhibits significantly improved properties over conventional bitumen, including 10–20°C higher softening point, 50–75% elastic recovery, and substantially enhanced rutting and fatigue resistance.
- 2) The wet process provides superior CRMB properties compared to the dry process, while terminal blending offers the best storage stability and consistency.
- 3) CRMB pavements demonstrate 40–60% less rutting, 2–4 times longer fatigue life, and better resistance to thermal cracking and moisture damage compared to conventional HMA.
- 4) The use of CRMB addresses the dual challenge of waste tire disposal and pavement performance, offering a net positive environmental impact over the pavement lifecycle.
- 5) In India, IS 15462:2019 and MoRTH specifications provide a regulatory framework for CRMB adoption, though implementation challenges related to quality consistency, cost, and awareness need to be overcome.
- 6) Future research should focus on devulcanization chemistry, warm mix CRMB, nano-modified CRMB systems, and systematic long-term performance monitoring in Indian conditions.

The growing emphasis on sustainable infrastructure and the urgent need to manage waste tire accumulation make CRMB an increasingly important material in the Indian road construction sector. With appropriate quality standardization, capacity building, and policy support, CRMB has the potential to significantly enhance the performance and sustainability of India's road network.

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