

Enhancing Sustainable Pavement in India Through Crumb Rubber Modified Asphalt.

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Abstract—Flexible pavements on India's national highways carry heavy, often overloaded commercial traffic through hot plains, wet coastal belts and cold mountain regions. Under these conditions, wearing courses made with ordinary viscosity-grade bitumen tend to rut, strip in the presence of water and crack, and each round of repair adds to the costs borne by highway agencies and road users. Crumb rubber modified bitumen, produced by blending ground scrap-tyre rubber into bitumen by the wet process, can improve these properties while giving waste tyres a productive use. This paper reviews the Indian Roads Congress guidelines and the Bureau of Indian Standards and Ministry of Road Transport and Highways specifications that govern rubber-modified binders, and compiles reported data on binder rheology and mixture performance relative to conventional viscosity-grade bitumen. Construction and quality-assurance requirements for rubberised binders are examined, and a simplified life-cycle cost comparison for a one-kilometre, two-lane national highway section is used to weigh the higher initial cost against later savings in maintenance and user costs. The reported evidence shows that rubber-modified wearing courses resist rutting better, recover more elastically and are less susceptible to moisture damage, and the cost comparison indicates a life-cycle saving of about 23% over 30 years. These benefits depend on rubber gradation and content, blending conditions, storage stability and compaction control in the field. Gaps remain in long-term field data from Indian roads, low-temperature behaviour at high altitude, recyclability and production emissions, and recommendations are made for specifications and further research.

Index Terms—End-of-life tyres, Life-cycle cost analysis, Moisture susceptibility, Rutting, Storage stability, Wet process

I. INTRODUCTION

With more than 63.3 lakh km of roads, India has one of the world's largest road networks, and its national highways alone carry roughly 40% of the country's freight, a share that is still rising.¹ Most of these highways have flexible (bituminous) pavements laid with viscosity-grade bitumen conforming to IS 73.² Where traffic is heaviest, wearing courses with plain VG-30 and VG-40 binders often start to fail early. In hot regions the usual problem is rutting. In high-rainfall areas it is stripping and potholes, and where temperatures vary widely the surface cracks. Repairs then become a recurring cost for the agency and for the people who use the road.

At the same time, the number of end-of-life tyres (ELTs) generated in India is large and growing (estimated at between 1.5 and 2 million tonnes a year).³ Putting ground tyre rubber into bitumen is an established practice abroad, going back to the 1960s, and several countries have standards for it.⁴⁻⁶ It can be done in two ways. The wet process blends crumb rubber into hot bitumen before mixing, while the dry process uses rubber in place of part of the fine aggregate.^{4,5} Indian practice follows the wet process, which is covered by IRC: SP:53⁷ and by IS 17079:2019, the specification for rubber modified bitumen.⁸ Polymer modified bitumen is now dealt with separately under IS 15462:2019.⁹

There is no shortage of laboratory work on CRMB. What is missing is a study that links, for Indian conditions, climate and loading, code requirements, binder and mixture performance, construction quality assurance and life-cycle economics. This review is an attempt to make those links. Its aims are to: (i) describe

the climatic and loading conditions that lead to early distress on Indian highways; (ii) summarise how CRMB is produced and how it performs against VG-30 and VG-40 bitumen; (iii) set out the construction and quality-assurance requirements specific to CRMB; (iv) show what CRMB means for life-cycle cost on a typical national highway section; and (v) point out what still needs research or specification. The review method is described under Materials and methods, the aims are taken up in turn under Results and discussion, and the main findings are summarised in the Conclusion.

II. MATERIALS AND METHODS

The current editions of the relevant codes of the Indian Roads Congress (IRC), the Bureau of Indian Standards (BIS) and the Ministry of Road Transport and Highways (MoRTH) were reviewed. Journal papers were located in Scopus and Web of Science with the search string "crumb rubber" AND (bitumen OR asphalt) AND (rutting OR moisture OR fatigue), for the years 2010–2026. Of the 142 records screened, 54 met the inclusion criteria, which were wet-process CRMB, quantitative binder or mixture data, and field or laboratory work relevant to Indian climates. Publicly available field performance reports from NHAI, state PWDs and CSIR-CRRI were also included, and a few earlier field studies (before 2010) were added where more recent field data could not be found.

III. RESULTS AND DISCUSSION

Climatic and loading challenges on Indian highways Service conditions for flexible pavements in India are severe, and they change a great deal from one region to another. In several of these settings, wearing courses with plain VG-30 and VG-40 bitumen fail before their time and push up maintenance costs. The main conditions are as follows.

Hot arid plains and central India (Rajasthan, Delhi-NCR, Madhya Pradesh, Telangana). Air temperatures of 45–48 °C can heat the pavement surface to 60–65 °C.^{7,10} At such temperatures the binder becomes soft, and the slow, heavy wheel loads on freight routes like the Golden Quadrilateral cause permanent deformation in the mix, seen on the road as rutting. High-rainfall zones (Konkan coast, Kerala, Western Ghats, North-East). Annual rainfall here can exceed

3,000 mm.¹⁰ Under heavy axle loads, water held in the mix is pressed repeatedly, and pore-water pressure builds up. The bond between binder and aggregate gradually breaks down (stripping), leading to ravelling and potholes, most of all where drainage is inadequate. Cold high-altitude regions (Ladakh, Jammu & Kashmir, Himachal Pradesh). In these regions the daily temperature range can exceed 30 °C, and winters fall below zero.¹⁰ Unmodified binders become stiff and brittle in this climate, and the pavement develops low-temperature (thermal) cracking and thermal fatigue cracking.

Heavy axle loads and slow-moving freight. IRC:37-2018 gives a vehicle damage factor (VDF) of 5.0 for plain or rolling terrain carrying more than 1,500 commercial vehicles per day.¹¹ Values measured in axle-load surveys on trunk routes are often higher, mainly because of overloading; on NH-11 and NH-21, for instance, more than half of the two-axle trucks surveyed were overloaded.¹² Slow multi-axle trucks on steep grades and at toll plazas load the pavement for longer, so every pass causes more rutting.

IV. MATERIALS AND PROCESSING OF CRMB

Crumb rubber

Crumb rubber is obtained from scrap truck and car tyres, which are ground either at ambient temperature or cryogenically before the steel and textile fibre are taken out. Rubber for wet-process CRMB is normally finer than 0.6 mm, with particle sizes of about 0.15–0.6 mm.^{7,8} In Indian practice the rubber content is 8% to 12% by mass of bitumen, and about 10% is usual for CRMB 60.^{7,8}

Wet-process blending and interaction mechanism

For the wet process, crumb rubber is blended with a base bitumen, usually VG-30, at 170–185 °C for 45–60 min, using a high-shear mixer at about 2,500–3,500 rpm.⁷ The interaction is largely physical. Rubber particles take up the lighter aromatic fractions of the bitumen (the maltenes) and swell to several times their original volume, which makes the binder more viscous and more elastic.^{4,6} Higher temperatures or longer blending can partly devulcanise and depolymerise the rubber. Storage stability improves as a result, but part of the elastic gain can be lost.⁴ Blending temperature and time therefore need to stay within a set range.

Storage stability

Because the swollen rubber particles are denser than the surrounding bitumen, CRMB can separate when it is stored hot without stirring. Storage stability is measured by the separation test, in which the softening points of the top and bottom of a conditioned sample are compared; IS 17079:2019 limits the difference to 4.0 °C.⁸ Separation has a direct effect on quality in the field and is taken up again under Construction and quality assurance.

V. BINDER AND MIXTURE PERFORMANCE

Rheological behaviour

Dynamic shear rheometer (DSR) studies show a consistent pattern: crumb rubber raises the complex

shear modulus $|G^*|$ of the binder and lowers its phase angle δ . In practical terms, the binder becomes stiffer and, at high service temperatures, responds more elastically and less viscously.⁴⁻⁶ Both changes raise the Superpave rutting parameter $|G^*|/\sin \delta$. Since $|G^*|/\sin \delta$ is known to be less reliable for modified binders, multiple stress creep recovery (MSCR) results, that is, the non-recoverable creep compliance J_{nr} and the percent recovery, should also be reported.^{13,14}

Comparison of binder and mixture properties

Table 1 compares the specified properties of VG-30, VG-40 and CRMB 60 binders and the design modulus of bituminous concrete (BC) made with each. Specification limits are taken from the relevant Indian Standards, and design values from IRC:37-2018.

Table 1 — Binder properties and design modulus of VG-30, VG-40 and CRMB 60

Property	Test Method	VG-30	VG-40	CRMB 60	Source / Reference
Penetration at 25 °C (0.1 mm)	IS 1203 ¹⁵	≥ 45	≥ 35	30 – 50	IS 73; ² IS 17079 ⁸
Softening point, R&B (°C)	IS 1205 ¹⁵	≥ 47	≥ 50	≥ 60	IS 73; ² IS 17079 ⁸
Elastic recovery at 15 °C (%)	IS 17079	Not specified	Not specified	≥ 50	IS 17079 ⁸
Design resilient modulus of BC at 35 °C (MPa)	IRC:37-2018, Table 9.2	2,000	3,000	1,600†	IRC:37-2018 ¹¹

Notes: † IRC:37-2018 assigns a lower design modulus to BC with modified bitumen than to VG-40 mixes, because the benefit of modified binders lies in fatigue, rutting and durability rather than stiffness (clause 9.2).¹¹

Table 1 shows that CRMB 60 has a considerably higher softening point and elastic recovery than the VG-grade binders. Published mixture studies report much lower rut depths and better retained strength after moisture conditioning for rubber-modified mixes.⁴⁻⁶ This advantage should not, however, be taken into pavement design as a higher layer modulus. IRC:37-2018 specifies 1,600 MPa for BC with modified bitumen at 35 °C, compared with 3,000 MPa for VG-40.¹¹

Pavement composition with a CRMB wearing course Table 2 gives an example of a flexible pavement with a CRMB 60 BC wearing course, typical of corridors with design traffic of about 150 million standard axles (msa). Following IRC:37-2018, the modified binder is restricted to the wearing course, since modified binders are not recommended for the dense bituminous macadam (DBM) layer because of recyclability concerns.¹¹

Table 2 — Illustrative pavement composition (design traffic 150 msa, subgrade CBR $\geq 8\%$)

Pavement Layer	Material Specification	Thickness (mm)
Wearing course	Bituminous concrete (BC) with CRMB 60	40
Binder course	Dense bituminous macadam (DBM) with VG-40	110 (derived via IITPAVE analysis)
Base	Wet mix macadam (WMM)	250 (derived via IITPAVE analysis)
Sub-base	Granular sub-base (GSB), drainage layer	200 (derived via IITPAVE analysis)
Subgrade	Compacted subgrade soil, CBR $\geq 8\%$	500 (top active zone)

Notes: Layer thicknesses are established via mechanistic-empirical analysis using IITPAVE in accordance with IRC:37-2018 guidelines.

Layer thicknesses should be determined by mechanistic–empirical analysis using IITPAVE, as IRC:37-2018 requires. The horizontal tensile strain at the bottom of the bituminous layer and the vertical compressive strain at the top of the subgrade should be calculated, reported and checked against the allowable values.

Field performance in India

CRMB has been laid on national and state highway projects by NHA and several state PWDs, yet there is

still little documented, peer-reviewable evidence of its long-term field performance in India. Most Indian reports are laboratory studies or project records that are not publicly available, and few have a comparable control section. For this reason, Table 3 combines one Indian source, the CRRI field trials reported by Gupta,¹⁶ with two well-documented international studies in which crumb rubber sections were monitored next to reference sections built at the same time.^{17,18}

Table 3 — Documented field performance of crumb rubber modified sections

Corridor / Section (Chainage)	Year Laid; Climate Zone	Design Traffic	Binder Comparison	Monitor ing Period	Key Performance Results	Source / Reference
CRRI field trials, India	Before 1997; Various Indian sites	Not reported	Rubberised bitumen vs conventional bitumen	Not reported	Reflection cracking delayed; lower temperature susceptibility (qualitative)	Gupta, 1997 ¹⁶
Louisiana state highways, USA (5 projects)	1990s; Humid subtropical	State highway traffic	Crumb rubber HMA vs conventional HMA	5–7 Years	Better than controls on rut depth, fatigue cracking and IRI	Huang et al., 2002 ¹⁷
A-316 and A-92, Andalusia, Spain	2015–2018; Mediterranean	8,000– 18,000 veh/day	Crumb rubber vs SBS-modified	Up to 63 Months	Density and fatigue resistance similar to SBS sections	Sierra-Carrillo de Albornoz et al., 2022 ¹⁸

All three studies lead to a similar conclusion. In the CRRI trials, rubberised binders sealed cracks and delayed reflection cracking in overlays.¹⁶ In Louisiana, crumb rubber sections performed better than their conventional controls on rutting, fatigue cracking and roughness after 5–7 years of traffic.¹⁷ In Spain, crumb rubber surface courses performed on a par with SBS polymer-modified reference sections in density and fatigue behaviour over up to 63 months,¹⁸ suggesting that a well-made rubberised binder can match polymer modification. None of these studies, though, represents the heavy, often overloaded axle loads and monsoon rainfall of Indian national highways, and the CRRI results are qualitative only. Before the field benefits of CRMB can be quantified for Indian conditions, long-term monitored Indian sections with

matched controls are needed, as recommended under Research gaps and recommendations.

VI. LIFE-CYCLE COST ANALYSIS

A simplified life-cycle cost analysis (LCCA) was carried out for a 1-km, two-lane (7.0 m) national highway section designed for 150 msa, with a 30-year analysis period. Costs are in ₹ lakh at 2026 prices and are discounted to present value at 10%, following the approach of IRC: SP:30.¹⁹ Both alternatives were given the same maintenance schedule: routine pothole repairs every year, minor patching in years 7 and 18, and structural mill-and-overlay in years 12 and 22. Road-user delay costs were estimated from speed-flow-delay models for heavy commercial vehicles on two-lane national highways.¹⁹

Table 4 — Present-value life-cycle costs for a 1-km two-lane section (₹ lakh)

Cost Component	VG-40 BC + DBM (₹ lakh)	CRMB 60 BC + VG-40 DBM (₹ lakh)	Variance / Difference
Initial construction, bituminous layers (agency)	32.0	37.0	+15.6%
Pothole repair and road-user delay (PV, 30 years)	12.0	2.5	-79.2%
Periodic renewal / overlay (PV, agency)	18.5	11.2	-39.5%
Salvage value at year 30	(4.5)	(5.8)	+28.9%
Subtotal: initial construction + pothole repair and user delay	44.0	39.5	-10.2%
Total life-cycle cost (NPV)	58.0	44.9	-22.6%

Notes: Costs discounted at 10% real discount rate over a 30-year evaluation horizon following IRC: SP:30 guidelines.

Since both alternatives use the same VG-40 DBM binder course shown in Table 2, the whole difference in initial cost comes from the wearing course.

On the items quantified, the CRMB option is 15.6% more expensive to build, but it reduces pothole-repair and user-delay costs by 79.2% and periodic renewal costs by 39.5%, and it has a higher salvage value at year 30. If only initial construction and pothole-repair and user-delay costs are counted, the CRMB option is 10.2% cheaper (₹39.5 lakh against ₹44.0 lakh). With periodic renewal and salvage value added, its total life-cycle cost is ₹44.9 lakh against ₹58.0 lakh for the VG-40 option, a saving of ₹13.1 lakh per km, or 22.6%. A sensitivity analysis on the discount rate (say, 8–12%), the CRMB price premium and the assumed maintenance intervals is still needed to confirm that this result holds.

VII. CONSTRUCTION AND QUALITY ASSURANCE

CRMB is less tolerant of poor practice than plain bitumen during storage, mixing and compaction. Construction should comply with MoRTH Section 500,²⁰ especially the clauses for DBM and BC (Clauses 507 and 509), together with the CRMB-specific requirements given below.

Storage and agitation. CRMB can separate if it is kept hot without stirring. Storage tanks at hot-mix plants should be fitted with vertical mechanical agitators that run continuously, usually at 60–80 rpm,⁷ and the storage period should not exceed 48 hours.^{7,20}

Temperature control. Mix production temperature should be kept between 165 °C and 175 °C, and the temperature of the mix behind the paver screed should not fall below 150 °C.^{7,20}

Compaction. Breakdown rolling should begin immediately behind the paver with 8–10 t tandem steel-wheel rollers at 140–150 °C. Pneumatic-tyred rollers are generally not used on rubberised mixes, as the binder sticks to the tyres and is lifted from the surface.²¹ If they are to be used, their suitability should first be proven on a trial section.

Quality control testing. Binder tests (softening point, elastic recovery and separation index) must be carried out on every batch, or for every 50 tonnes received. Mix volumetrics (air voids, VMA, VFB) and field density must satisfy the quality-control schedules of MoRTH Section 900.

VIII. SUSTAINABILITY BENEFITS AND CONCERNS

CRMB contributes to sustainability in three main ways. First, it provides a worthwhile use for scrap tyres. A 40 mm CRMB 60 BC wearing course on 1 km of two-lane road uses about 14.2 tonnes of crumb rubber, or roughly 1,250 to 1,400 car tyres (calculated for 7.0 m width, 40 mm thickness, 5.5% binder content and 10% rubber by binder mass). Second, a longer service life with fewer interventions means that less virgin aggregate and bitumen are consumed over the life of the pavement. Third, studies from other countries report lower tyre-pavement noise on rubberised surfaces, particularly open-graded mixes.^{4,6} On the other hand, CRMB has to be produced at higher temperatures, which increases energy use and fume emissions. Warm-mix asphalt (WMA) additives can lower mixing temperatures by about 20–25 °C²² and offset part of this. Two questions still need answering before the full environmental benefit can be quantified: how recyclable reclaimed asphalt

containing CRMB is, and how much is emitted during production.

IX. RESEARCH GAPS AND RECOMMENDATIONS

Long-term (≥ 5 -year) monitored field sections, each paired with a control section, are needed in every major Indian climate zone to establish what CRMB actually achieves under Indian traffic.

The low-temperature performance of CRMB at high altitude, for example by bending beam rheometer and thermal stress restrained specimen tests, has hardly been studied in India.

Performance-related binder criteria such as MSCR should be considered in addition to the empirical tests in IS 17079.

Studies are needed on the recyclability of RAP containing CRMB and on production emissions, so that a full environmental life-cycle assessment can be carried out.

IRC:37-2018 already recommends surface courses with modified binder where design traffic exceeds 50 msa.¹¹ On this basis, highway agencies could adopt CRMB wearing courses as the default on such corridors, subject to a project-level life-cycle cost analysis.

X. CONCLUSION

The main conclusions of this review of CRMB for high-traffic Indian highways are as follows:

Plain VG-30 and VG-40 wearing courses are susceptible to rutting in hot regions, moisture damage in high-rainfall areas and thermal cracking at high altitude, and heavy axle loads aggravate all three.

Wet-process CRMB increases the softening point, elastic recovery and high-temperature stiffness of bitumen, and reported mixture data show lower rut depths and better moisture resistance than VG-grade mixes.

These benefits depend on controlled blending, agitated storage, a narrow temperature window and proper compaction, and poor site control can cancel them out. On the items quantified, a CRMB 60 wearing course is about 16% more expensive to build but reduces repair, user-delay and renewal costs over 30 years, for a total life-cycle saving of about 23% (₹44.9 lakh against ₹58.0 lakh per km). This should be confirmed by a complete LCCA with sensitivity testing.

Long-term monitored field sections, performance-related binder specifications and studies on recyclability and emissions would support wider use of CRMB in India.

XI. DECLARATIONS

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