

Rutting and fatigue performance of high-dosage crumb rubber modified bitumen

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This study investigates the effects of crumb rubber (CR) modification on the rheological and performance characteristics of asphalt binders, with a focus on rutting and fatigue resistance. Modified binders were prepared with CR contents 10%, 15%, 20% and 24% by weight of viscosity grade-30 (VG-30) binder. These binders are evaluated for their rheological properties, including Multiple Stress Creep Recovery (MSCR), Zero Shear Viscosity (ZSV), Shenoy parameter, and Linear Amplitude Sweep (LAS) testing the Dynamic Shear Rheometer (DSR). The addition of CR significantly increased the complex shear modulus (G^*) and storage modulus (G') by up to 3.1 and 30.3 times respectively, while reduced the phase angle (δ) by up to 34.6° , indicating improved stiffness and elasticity. Enhanced values of $G^*/\sin \delta$ and Shenoy parameter have increased by 5.34 and 10.4 times respectively for CR24 binder demonstrating improved rutting resistance. MSCR results have shown that percent recovery increased from -0.2% to 75.1%, and non-recoverable creep compliance (J_{nr}) decreased from 2.81 to 0.07 kPa^{-1} . The Rutting Resistance Index Ratio (RRIR) has been effective in evaluating crumb rubber modified bitumen (CRMB) performance with J_{nr} showing the highest sensitivity to CR content, establishing it as a robust indicator of rutting resistance. Fatigue analysis has revealed that the binder with 20% CR has offered the best balance between fatigue resistance and strain tolerance, identifying it as the optimal dosage. A strong inverse correlation with r-square value 0.91 has been found between elastic recovery (ER-DSR) and J_{nr} , and a moderate positive correlation with r-square value 0.68 has been found between ER-DSR and fatigue life (N_f), highlighting the interconnected nature of elasticity, rutting resistance, and fatigue performance.

Keywords: Crumb Rubber Modified Bitumen (CRMB), Non Recoverable Creep Compliance (J_{nr}), Rutting Factor, Rutting Resistance Improvement Ratio (RRIR), Shenoy Parameter, Zero Shear Viscosity (ZSV)

1 Introduction

The safe and effective utilization of end-of-life tyres (ELTs) always remains a key concern for researchers in an environmentally friendly manner. ELT-derived products such as reclaimed rubber, char, oil, steel, and fabric provide reusable materials that can be recovered and reused in various applications. Crumb Rubber (CR) for bitumen modification can be produced using methods like ambient, cryogenic, wet grinding, or hydrojet size reduction. Direct addition of CR to the mix is called the dry process, while blending it with bitumen to produce Crumb Rubber Modified Bitumen (CRMB) is known as the wet process^{1,2}. CR of 20–100 mesh size has been used at varying blending speeds and temperatures to modify virgin bitumen. Different CR contents and dosages have been incorporated to achieve the binder's

performance properties, showing the flexible approach for preparing the CRMB³⁻⁵.

The addition of CR or various types of polymers blended with bitumen enhances the physical and rheological properties of the binder, enabling it to perform effectively under high and low temperatures and heavy loading conditions. The elastic behavior of the binder is represented by the storage modulus, while the viscous behavior is represented by the loss modulus. CR or polymers enhances the storage modulus, thereby improving the elastic response of the binder⁶⁻¹⁰. The rutting factor ($G^*/\sin \delta$) of binder is most commonly used parameter to evaluate the rutting potential of the binder at higher temperature^{11,12}. The $G^*/\sin \delta$ represents the complex modulus in the linear viscoelastic region; however, rutting failure typically occurs in the non-linear (non-viscoelastic) deformation stage in the field. The rutting factor does not account for the binder's

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recovery response during the unloading phase. The Researchers have emphasized the need for alternative parameters to evaluate the rutting response of modified binders more effectively, with better simulation of actual field conditions^{13,14}. The Shenoy parameter more effectively evaluates the rutting potential of binders at high temperatures due to its sensitivity to the phase angle and its consideration of the damping factor ($\tan \delta$)¹⁵⁻¹⁷. The complex modulus does not represent the purely elastic response of the binder. It reflects the combined elastic and viscous behavior under loading. To address the elastic response in the temperature sweep test of rheological properties, the storage modulus (G') is taken into account, and the term Elastic Modification Index (E_m) has been introduced by researchers to quantify the enhancement in elasticity due to the addition of modifiers. E_m is defined as the ratio of the storage modulus of the modified binder to that of the virgin binder. It indicates the elastic response of the modified binder in terms of rutting potential^{18,19}. The modified binders show non-Newtonian behavior, which means their viscosity varies with loading rate, loading time, and temperature. Zero Shear Viscosity (ZSV) is another approach to evaluate the rutting performance of binders under sustained loading conditions. Different mathematical models such as the Cross model, Carreau model, Carreau–Yasuda model, and Sisko model are available to calculate ZSV²⁰⁻²³. The Multiple Stress Creep Recovery (MSCR) test is performed in ten cycles, with each cycle consisting of 1-second (s) creep loading followed by a 9 s recovery period. This test is conducted at two stress levels: 0.1 kPa and 3.2 kPa. The response is evaluated in terms of percent recovery and non-recoverable creep compliance (J_{nr}). Higher percent recovery and lower J_{nr} values are desired under heavy axle loads, as they indicate better performance of the binder against permanent deformation. The MSCR test provides a comprehensive assessment of a binder's response under real service conditions with respect to rutting potential of the binder^{17,24,25}.

The addition of CR improves the elasticity of CRMB and enhances its performance at intermediate temperatures, leading to an enhancement in fatigue life of the binder^{1,26}. CRMB and polymer modified bitumen (PMB) exhibit higher sensitivity to increasing strain levels; however, this does not adversely affect their fatigue performance under typical pavement loading condition²⁷⁻²⁹. The Elastic Recovery–Dynamic Shear Rheometer (ER-DSR)

values show a good correlation with the rutting and fatigue properties of the modified binders in the studies^{30,31}.

Bitumen modification using crumb rubber (CR) enhances the binder's physical and rheological properties both before and after aging. CR improves physical properties such as penetration, softening point, and viscosity, as well as rheological characteristics including ER-DSR, G^* , δ , G' and $G^*/\sin\delta$. It also reduces the J_{nr} and increases percent recovery under the MSCR test. The rutting resistance of the modified binder and the effectiveness of the modification method have been evaluated by various researchers using parameters such as $G^*/\sin\delta$, Shenoy parameter, Zero Shear Viscosity (ZSV), and J_{nr} ^{15,17,19}. The addition of CR also improves the fatigue life of the binder, which represents the binder's behavior at intermediate temperatures.

The evaluation using E_m of modified binders containing additives like carbon nanotubes and acid-treated fly ash has been carried out by researchers^{18,19}. The CRMB has been analyzed using the E_m property in this study. The evaluation of PMB has been carried out by developing correlations between ER-DSR and other performance parameters such as J_{nr} at 3.2 kPa, and fatigue life (N_f). These relationships assess the binder's elastic behavior, rutting resistance, and fatigue performance, and provide a detailed understanding of the effectiveness of the modifier^{30,31}.

The novelty of the present study is to investigate the properties of CRMB through the E_m and establishing correlations between ER-DSR and rutting and fatigue parameters. Specifically, relationships are developed between ER-DSR and J_{nr} at 3.2 kPa, and ER-DSR and N_f . These correlations provide deeper insight into elastic, rutting, and fatigue behavior of CRMB and also contribute to the existing literature on CRMB, with respect to varying CR contents.

1.1 Objective of the Study

The following are the objectives of the present research:

- i. To evaluate the effect of CR on the G^* , δ , G' and $G^*/\sin\delta$, percent recovery, and J_{nr} at 0.1 & 3.2 kPa, ZSV at 60 °C
- ii. To compare rutting parameters using different approaches and to assess the effect of CR on the N_f of all CRMB samples using LAS test.
- iii. To evaluate the effect of CR on ER-DSR and establish its relationship with J_{nr} , and N_f .

Table 1 — Physical Properties of VG-30 bitumen

Properties	Value Obtained
Softening Point (°C)	47.3
Penetration at 25°C in 0.1mm	58
ER-DSR at 25°C (Unaged)	14.2
ER-DSR at 25°C (RTFO aged)	8.6
PG Grading	70-XX

Table 2 — Classification of CRMB blends

Blend Code	CR Dosage %	PG Grading
VG-30	0	70-XX
CR10	10	76-XX
CR15	15	82-XX
CR20	20	82-XX
CR24	24	82-XX

2 Materials and Methodology

This section outlines the materials used in the study and the experimental methods used for evaluation of various performance parameters of CRMB binders

2.1 Materials and aging methods

The viscosity grade-30 (VG-30) bitumen, sourced from the Indian Oil Corporation, Panipat Refinery, is used as the base binder for preparing the CR blends. The bitumen has been tested for its physical properties, as presented in Table 1. The CR, sourced from a local vendor with a particle size less than 0.425mm (40 mesh), underwent thorough processing to eliminate steel, fibers, and other foreign impurities commonly found in rubber tires. The bitumen blends are prepared at different CR content by weight of total bitumen. The CR is blended into the bitumen at a temperature of 180°C and a uniform speed of 200-300 rpm. The blend details of CRMB prepared at different CR content levels are presented in Table 2.

The VG-30 bitumen and CRMB blends were placed for short-term aging using a rolling thin film oven (RTFO) at a temperature of 175°C for 85 minutes, in accordance with ASTM D2872³². The RTFO-aged samples of VG-30 and CRMB blends were again placed for long-term aging as per ASTM D6521³³ to evaluate their intermediate temperature behavior using the LAS test. Approximately 50 grams of the RTFO-aged sample were placed in a steel pan and aged in a pressure aging Vessel (Pav) at a temperature of 110°C under an air pressure of 2.2 MPa for 20 hours, simulating 5 to 10 years of field aging.

2.2 Dynamic mechanical analysis

The temperature sweep test is conducted using a Dynamic Shear Rheometer (DSR) over a temperature range of 52°C to 82°C. The test is performed with a

25 mm parallel plate geometry, maintaining a 1 mm gap, at a strain rate of 1% and a frequency of 10 rad/s. This test provides rheological parameters such as G^* , δ , G' , and $G^*/\sin \delta$ over a temperature range of 52°C to 82°C.

Shenoy introduced a parameter to refine the rutting factor. At high temperatures, $G^*/\sin \delta$ becomes less effective in predicting the rutting resistance of bitumen as $\sin \delta$ approaches 1. The Shenoy parameter accounts for the binder's non-recoverable property, making it suitable for evaluating both virgin and modified binders. This parameter incorporates the damping coefficient ($\tan \delta$) and the equation is written as³⁴.

$$\%Y_{ur} = \frac{100\tau_0}{|G^*|} \left(1 - \frac{1}{\tan \delta \sin \delta} \right) \quad \dots(1)$$

Where, $\% Y_{ur}$ = unrecovered strain, Shenoy parameter = $G^*/(1-1/\tan \delta \cdot \sin \delta)$

Several researchers have studied the E_m to evaluate the rutting performance of binders modified with carbon nanotubes and acid-treated oil fly ash^{18,35,36}. The Elastic Modification Index (E_m) is defined as the ratio of the storage modulus of the modified bitumen to the storage modulus of the VG-30 bitumen. The E_m is calculated using.

$$E_m = \frac{\text{Elastic modulus of modified bitumen}}{\text{Elastic modulus of virgin bitumen}} \quad \dots(2)$$

ZSV is a performance indicator used to assess the flow behavior of a binder at very low shear rates, approaching to zero. It is considered an indicator of long-term rutting resistance under sustained loading conditions. ZSV test was conducted using a steady shear test with shear 0.01 s⁻¹ to 10 s⁻¹ at a temperature of 60°C. Carreau model is used to characterize steady shear rheological behavior of VG-30 and CRMB binders^{13,18}. The Carreau model, as written in Eq.3, is used to determine ZSV.

$$\eta = \eta_0 + (\eta_0 + \eta_\infty)(1 + (\lambda\gamma)^2)^{[(n-1)/2]} \quad \dots(3)$$

Where, η = steady state viscosity, η_0 = Zero shear viscosity, η_∞ = infinite shear viscosity, γ = shear rate, λ and n are fitting parameter (relaxation time, power law index)

The MSCR test was conducted at 70°C for all binders, as the Performance Grade (PG) temperature of the virgin bitumen is 70°C. In many parts of India, the maximum pavement temperature during summer approaches this value. The test is performed at two

stress levels of 0.1 kPa and 3.2 kPa, using a 1-second creep period followed by a 9-second recovery period. Each binder sample is subjected to 20 cycles at 0.1 kPa as per ASTM D7405³⁷. The first 10 cycles were used for conditioning, and other 10 cycles were used for data collection. Afterward, the sample was subjected to 10 cycles at 3.2 kPa. Percent recovery and J_{nr} were calculated using.

$$R (\%) = \frac{\sum_{i=1}^{10} \left(\frac{\epsilon_1 - \epsilon_{10}}{\epsilon_1} \right)_i}{10} \dots(4)$$

$$J_{nr} (kPa^{-1}) = \frac{\sum_{i=1}^{10} \left(\frac{\epsilon_{10}}{\tau} \right)_i}{10} \dots(5)$$

Where, $R (\%)$ = percent recovery, ϵ_1 = strain at the end of 1s, ϵ_{10} = strain at the end of recovery period, and τ = applied shear stress

The LAS test was conducted on PAV aged bitumen samples using an 8 mm plate and a 2 mm gap assembly at a temperature of 25°C. The test is carried out in two stages. In the first stage, a frequency sweep test was performed at varying frequencies ranging from 0.2 to 30 Hz at a constant strain level of 1%. In the second stage, an amplitude sweep test was conducted at strain levels ranging from 0.1 to 30% at a fixed frequency of 10 Hz to assess the accumulation of damage in the material. The N_f of the bitumen was then calculated using the Visco-Elastic Continuum Damage (VECD) model, described as.

$$N_f = A(Y_{max})^{-B} \dots(6)$$

Where, N_f is the number of cycles to fail, Y_{max} is maximum shear strain, A and B are material dependent parameters.

The ER-DSR test was performed as per AASHTO TP 123 on short-term aged binder blends at a temperature of 25°C. The testing is conducted using an 8 mm diameter parallel plate geometry with a 2 mm gap. During the test, the binder was subjected to a constant strain rate of 2.315% per second until a total strain of 277.8% was reached. This was followed by a 30-minute recovery period under zero shear stress (0.0 kPa). Throughout the test, shear stress (τ , Pa) and strain (γ , %) values were recorded at two-second intervals³⁸. The ER-DSR parameter was calculated using.

$$ER-DSR = \frac{\text{(Recovered strain at the end of relaxation time)}}{\text{Strain at the end of loading time}} \dots (7)$$

3 Results and Discussion

Results of the study are discussed in following subsections.

3.1 Rheological characterization of binder

The temperature sweep test was conducted over a range of 52°C to 82°C to analyze the G^* , δ , and G' properties of VG-30 and CRMB binders. The G^* values of VG-30 and CRMB binders at different temperatures are presented in Fig. 1. The G^* decreases exponentially as the temperature increases. The addition of crumb rubber (CR) enhances the G^* by factors of 1.6, 2.0, 2.4, and 3.1 for CR10, CR15, CR20 and CR24 binders, respectively at 70°C, compared to the VG-30 binder. The increase in stiffness with higher CR content may be attributed to the absorption of lighter fractions from the VG-30 bitumen by the CR^{8,39}.

The δ represents the balance between the elastic and viscous components of bitumen at a given temperature. It tends to be low at lower temperatures and high at higher temperatures, indicating dominant elastic behavior at low temperatures and dominant viscous behavior at high temperatures. The phase angles of VG-30 and various CRMB binders at different temperatures are presented in Fig. 2. A decreasing trend in δ is

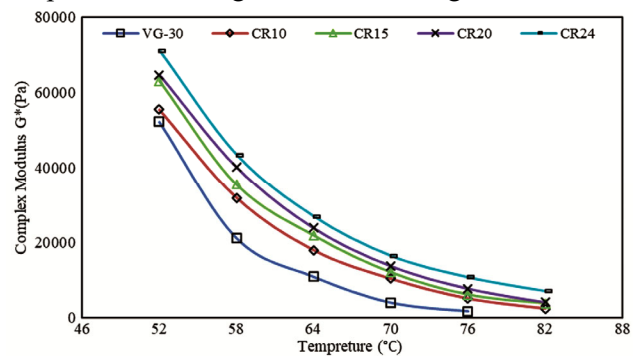


Fig. 1 — Complex modulus (G^*) of VG-30 and CRMB.

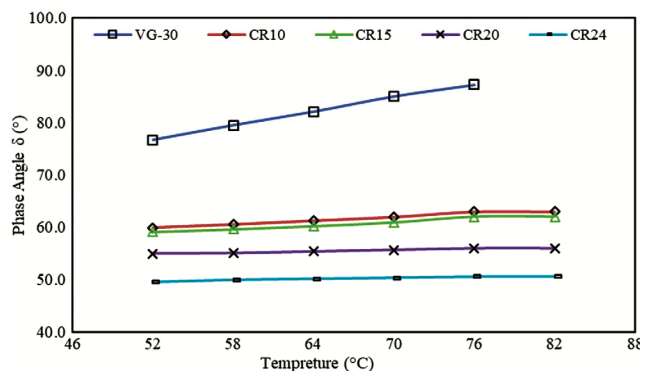


Fig. 2 — Phase angle (δ) of VG-30 and CRMB.

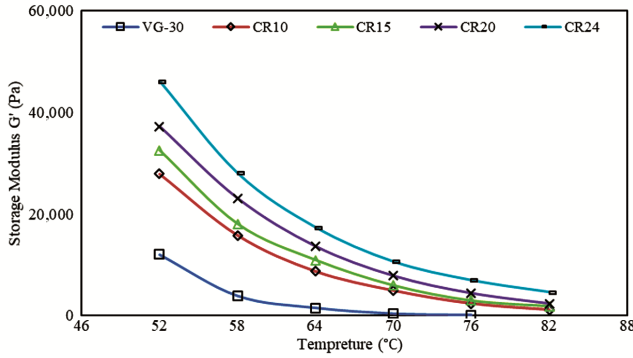


Fig. 3 — Storage modulus (G') of VG-30 and CRMB.

observed with increasing CR content. The reduction in δ values compared to the VG-30 binder at 70°C is measured as 23.2, 24.2, 29.4, and 34.6° for CR10, CR15, CR20 and CR24 binders, respectively. This decrease in δ indicates an improvement in the elastic component of the binder due to the addition of crumb rubber to VG-30 bitumen⁸.

The G' of bitumen represents the elastic (recoverable) energy stored in the material under cyclic loading. A higher G' value indicates a stiffer binder with better resistance to permanent deformation. The G' values for VG-30 and CRMB binders at various temperatures are presented in Fig. 3. For CR10, CR15, CR20 and CR24 binders, the G' values at 70°C increased by 14.2, 16.9, 22.3, and 30.3 times, respectively, compared to VG-30 binder. The G' of the binders decrease exponentially with the increases in temperature, indicating enhanced stiffness at lower temperatures. The increased G' values demonstrate that the binder becomes less susceptible to rutting, making it more suitable for high-temperature and heavy-traffic conditions³⁹.

3.2 Rutting susceptibility evaluation

The rutting susceptibility of binders can be evaluated using several parameters, including the $G^*/\sin \delta$, Shenoy parameter and J_{nr} . The concept of ZSV under sustained loading conditions is also employed to quantify the rutting susceptibility of CRMB binders. Additionally, the E_m based on the G' , is used to assess the rutting susceptibility of various binders^{18,19}.

The $G^*/\sin \delta$ is a fundamental parameter to characterize binder performance under the Superpave specifications. The $G^*/\sin \delta$ was evaluated for VG-30 and CRMB binders at different temperatures, and the results are presented in Fig. 4. The addition of CR enhances the $G^*/\sin \delta$ by factors of 2.92, 3.44, 4.14, and 5.34 for CR10, CR15, CR20 and CR24 binders,

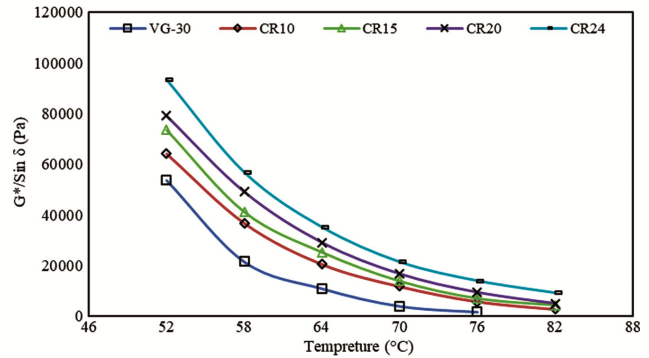


Fig. 4 — Rutting factor ($G^*/\sin \delta$) of VG-30 and CRMB.

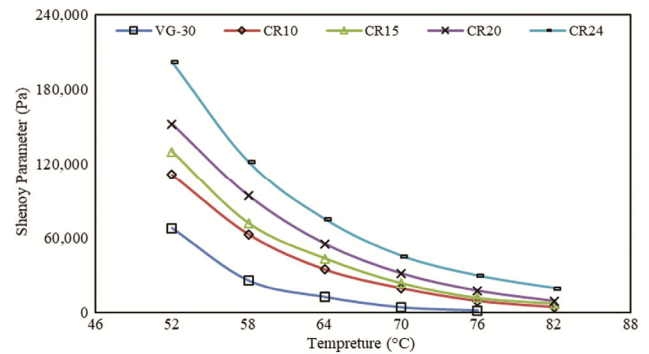


Fig. 5 — Shenoy parameter ($G^*/(1-1/\tan \delta \cdot \sin \delta)$) of VG-30 and CRMB.

respectively, at 70°C, compared to the VG-30 binder. The rubber particles swell in the bitumen and absorb the aromatic fractions, forming a gel-like network structure. This modification increases the stiffness and elasticity of the binder, leading to a significant improvement in the $G^*/\sin \delta$ of CRMB^{1,4}. The addition of 10%, 15%, 20%, and 24% CR to VG-30 increases the PG grade of VG-30 as presented in Table-2.

The Shenoy parameter was determined over a temperature range of 52°C to 82°C at a frequency of 10 rad/s for VG-30 and CRMB binders. The test results are presented in Fig. 5. As seen in Fig.5, the Shenoy parameter increases with the addition of CR, indicating improved rutting resistance against permanent deformation. At 70°C, the Shenoy parameter increased by 4.48, 5.36, 7.40, and 10.40 times for CR10, CR15, CR20 and CR24 binders, respectively, compared to VG-30 binder. The addition of CR increases the Shenoy parameter, indicating enhanced elastic and recovery properties. The effect of CR on improvement in rutting resistance is more magnifying in the Shenoy parameter compared to the conventional rutting factor¹⁶.

The G' was analyzed for all CRMB binders to evaluate the modification effect of CR on VG-30 over a broad temperature range of 52°C to 76°C. The test results for E_m are presented in Fig. 6. At 70°C, the G' values increased by 14.0, 16.8, 22.3, and 30.2 times for CR10, CR15, CR20 and CR24 binders, respectively, compared to the VG-30 binder. This indicates a significant improvement in the elastic and recovery response with the addition of CR. Past researchers have also reported a similar improvement pattern for acid-treated waste oil fly ash additives¹⁸.

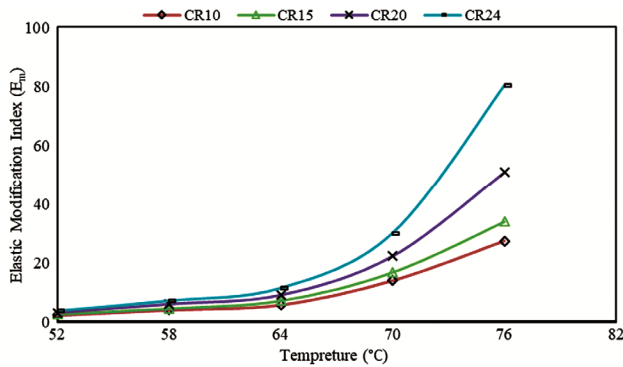


Fig. 6 — Elastic Modification Index (E_m) of VG-30 and CRMB.

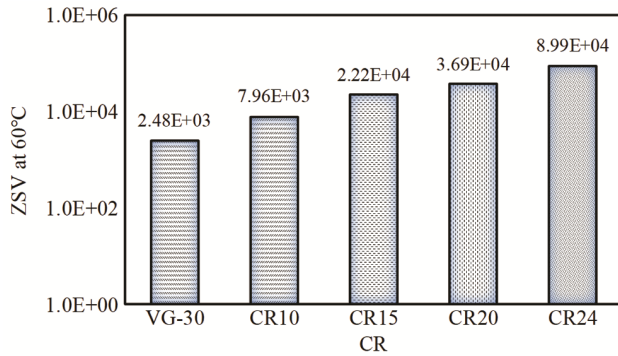


Fig. 7 — Steady shear viscosity of VG-30 and CRMB at 60°C.

ZSV represents the limiting viscosity value in the Newtonian region at very low shear rates. ZSV test was performed on VG-30 and CRMB binders at 60°C using DSR. The ZSV values are shown for the VG-30 and various CR binders in Fig. 7. At 60°C, the ZSV values increased by 3.21, 8.95, 14.90, and 36.29 times for CR10, CR15, CR20 and CR24 binders, respectively, compared to the ZSV of the VG-30 binder. As observed in Fig. 7, the shear-thinning region becomes more pronounced, while the Newtonian region decreases with increasing CR content. This behavior is consistent with findings related to ZSV reported by other researchers for different additives^{16,18}.

The PG grading temperature of VG-30 was determined to be 70°C. In most parts of India, the maximum pavement temperature also reaches up to 70°C. This temperature is therefore considered as the starting test temperature for the MSCR test. The MSCR test was carried out on VG-30 and CRMB binders at 0.1 kPa and 3.2 kPa stress level at a temperatures of 70°C, 76°C, and 82°C³⁶. The results for percent recovery and J_{nr} at 3.2 kPa are presented in Figs 8 and 9, respectively. The percent recovery was observed -0.2% for the VG-30 at 70°C. The percent recovery was 15.2%, 30.0%, 47.5%, and 75.1% for CR10, CR15, CR20 and CR24 binders, respectively at 70°C. While the percent recovery values are 2.0%, 12.7%, 21.8%, and 38.2% for CR10, CR15, CR20 and CR24 binders, respectively at 82°C. These results indicate that the addition of CR significantly enhances the percent recovery, particularly under higher stress levels and at elevated temperatures. The results for J_{nr} was observed 2.81 for the VG-30 at 70°C. The J_{nr} value was 1.47, 0.46, 0.33, and 0.07 for CR10, CR15, CR20 and CR24 binders, respectively at 70°C. The J_{nr} values were decreased 3.85, 9.72, 16.21, and 101.11

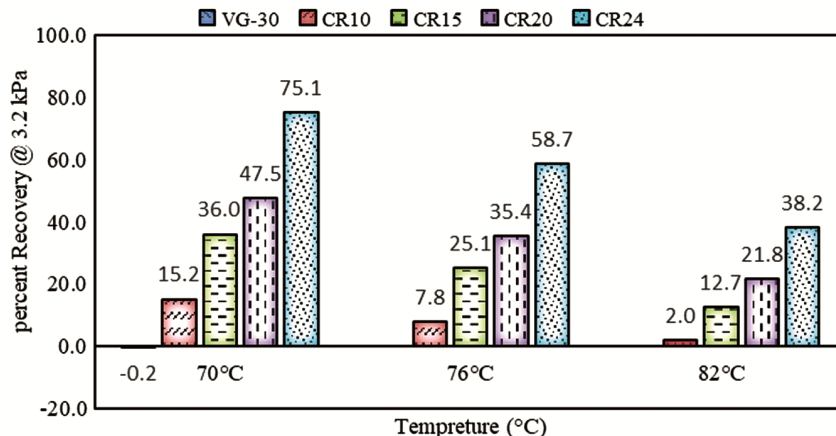


Fig. 8 — Variation of percent recovery @ 3.2 kPa for VG-30 and CRMB at various temperatures.

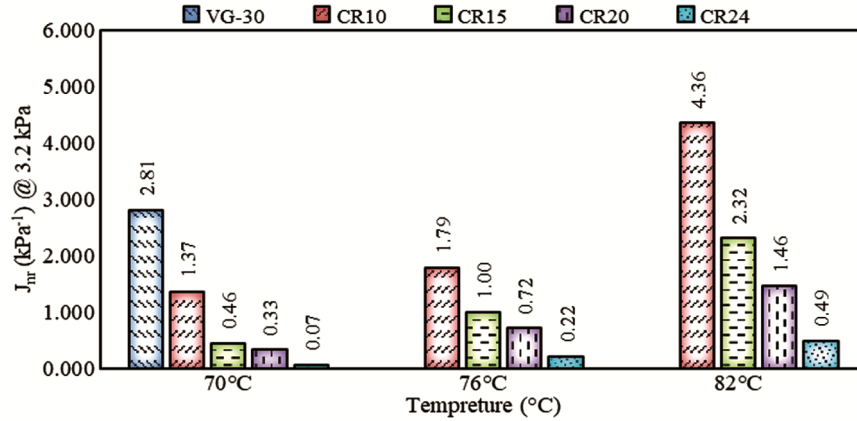


Fig. 9 — Variation of J_{nr} @ 3.2 kPa for VG-30 and CRMB at various temperatures.

times for CR10, CR15, CR20 and CR24 binders, respectively at 70°C as compared to VG-30 binder's J_{nr} . This indicates that the increase in CR content makes the binder less susceptible to permanent deformation under heavy loading conditions and it is in line with inference drawn by other researchers⁴⁰.

The relationship between CR content and percent recovery at 70°C is shown in Fig. 10. The CR content shows linear correlation with percent recovery at both 0.1 kPa and 3.2 kPa, with correlation coefficients of 0.98 and 0.93, respectively. The slope of the line at 0.1 kPa is higher than that at 3.2 kPa, indicating better elastic behavior of the binder under low loading conditions. The relationship between J_{nr} at 0.1 and 3.2 kPa at 70°C and CR content is presented in Fig. 11. A polynomial correlation is observed between CR content and J_{nr} at 0.1 and 3.2 kPa, with correlation coefficients of 1.00 and 0.99 respectively. The addition of CR significantly improves the elastic and rutting resistance properties of VG-30 binder⁴⁰.

The summary of test results for various rutting parameters is presented in Table 3. The values of various rutting parameters such as $G^*/\sin \delta$, Shenoy parameter, J_{nr} at 3.2kPa and G' at 70°C for VG-30 and CRMB binders have been considered for rutting resistance improvement ratio(RRIR). The RRIR is the normalized value of rutting parameters such as $G^*/\sin \delta$, Shenoy parameter, J_{nr} at 3.2kPa and G' with respect to the corresponding value of VG-30 binder. The RRIR based on the ZSV of the CRMB binder is calculated by normalizing it to the ZSV of the VG-30 binder at 60°C. The E_m is defined as the normalized value of the G' of the CRMB binder relative to that of the VG-30 binder. The Fig. 12 presents the RRIR based on $G^*/\sin \delta$, Shenoy parameter, and J_{nr} at 3.2kPa, G' and ZSV. The RRIR shows an increasing

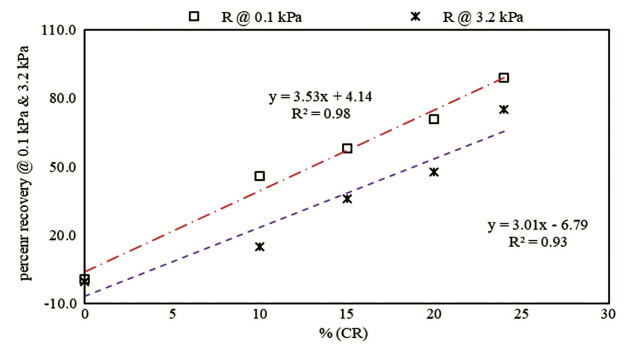


Fig. 10 — Relationship between percent recovery and CR content at 70°C.

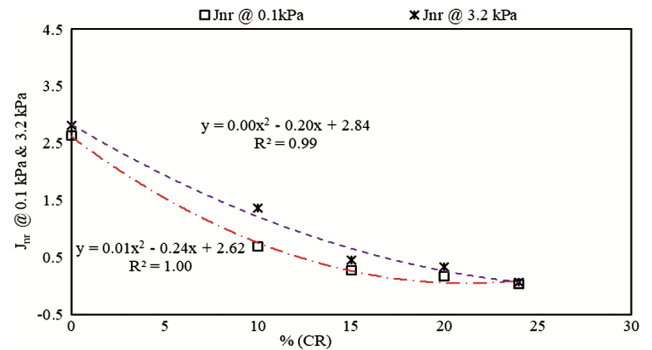


Fig. 11 — Relationship between J_{nr} and CR content at 70°C.

trend with the higher content of CR. The RRIR, based on the $G^*/\sin \delta$, Shenoy parameter, ZSV, J_{nr} at 3.2 kPa, and G' , are 4.14, 7.40, 14.90, 16.21, and 22.25 respectively for 20% CR-modified binders. As can be seen from Fig. 12, the $G^*/\sin \delta$, Shenoy parameter and G' is showing moderate improvement after addition of CR content in terms RRIR. RRIR based on J_{nr} at 3.2 shows the highest sensitivity to CR content, which makes the J_{nr} an excellent indicator for evaluating rutting resistance improvement in CRMB among all the indicators¹⁷.

3.3 Fatigue performance evaluation

The LAS test was performed on VG-30 and CRMB binders to evaluate the fatigue performance at 25°C. To study the change in N_f for different CRMB binders at various strain, the fatigue life improvement ratio (FLIR) is determined as the ratio of the fatigue life of CRMB to that of the VG-30 binder. The test results of

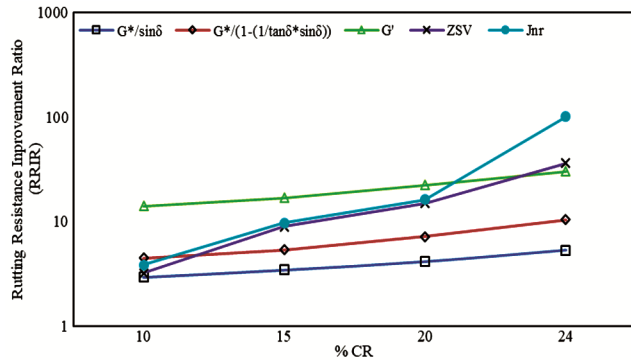


Fig. 12 — Relationship between $G^*/\sin \delta$, $G^*/(1-(1/\tan \delta \cdot \sin \delta))$, G' , J_{nr} , ZSV and RRIR.

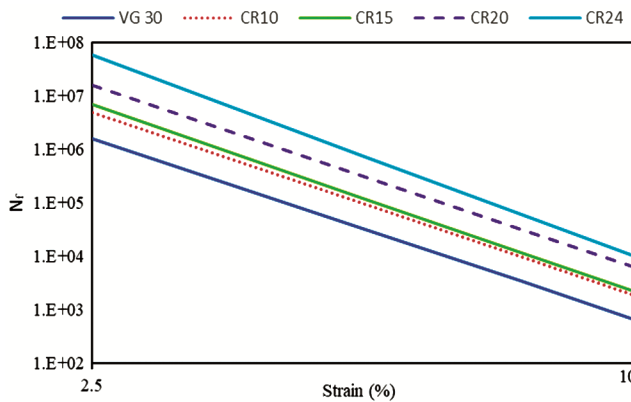


Fig. 13 — N_f prediction curve for VG-30 and CRMB.

N_f at various strain level is presented in Fig. 13. The test results of N_f , FLIR, A and B parameter are presented in Table 4 for VG-30 and CRMB binders. The variation in the integrity of the binder is represented by the A value; a higher A value indicates greater material strength. B value represents the sensitivity of the material to strain; a higher B value indicates a decrease in fatigue life under increasing loading conditions. The A value increases as the CR content increases from 0% to 24%, indicating that fatigue life improves with higher CR content. The B value also increases with increasing CR content, which indicates that the 24% CR binder is more sensitive to higher strain. The B value of the 20% CR binder is the lowest among all the CRMBs, demonstrating a better balance between fatigue life and strain sensitivity. The FLIR was found to be 3.11, 4.32, 9.93, and 36.6 times for CR10, CR15, CR20 and CR24 binders, respectively, at a 2.5% strain level. However, at a 10% strain level, the FLIR decreased to 2.78, 3.26, 9.33, and 14.8 times for CR10, CR15, CR20 and CR24 binders, respectively. The 24% CR binder shows a rapid increase in N_f at low strain (2.5%), but its improvement diminishes at higher strain (10%), as the FLIR decreases from 36.6 to 14.8 for the 2.5% and 10% strain, respectively. The FLIR decreases from 9.93 to 9.22 at 2.5% and 10% strain, respectively, for the 20% CR binder, which indicates that the 20% CR binder shows consistent performance over a broad range of strain in terms of N_f . From the test results, it can be concluded that the 20% CR binder exhibits consistent performance across the 2.5% to 10% strain in terms of N_f , FLIR, and the A and B parameters. Based on the N_f , A and B

Table 3 — Summary of the test results of various rutting parameters

Binders	Parameters				
	$G^*/\sin \delta$ (Pa)	Shenoy parameter	Storage modulus (Pa)	ZSV (Pa.s)	J_{nr} at 3.2 kPa in kPa^{-1}
VG-30	4035	4404	350	2476	2.639
CR10	11801	19718	4915	7956	0.685
CR15	13861	23626	5903	22168	0.271
CR20	16725	31722	7797	36892	0.163
CR24	21543	45781	10581	89864	0.026

Table 4 — Test results of N_f , FLIR, A and B parameter

Binder	Strain at 2.5%		Strain at 5%		Strain at 10%		A x 10 ⁸	B
	$N_f \times 10^6$	FLIR	$N_f \times 10^4$	FLIR	$N_f \times 10^2$	FLIR		
VG-30	1.60		3.31		6.84		2.70	5.596
CR10	4.99	3.11	9.74	2.94	19.02	2.78	9.07	5.678
CR15	6.92	4.32	12.42	3.75	22.33	3.26	14.04	5.799
CR20	15.89	9.93	31.85	9.62	63.81	9.33	27.95	5.641
CR24	58.59	36.6	77.04	23.28	101.29	14.81	179.70	6.249

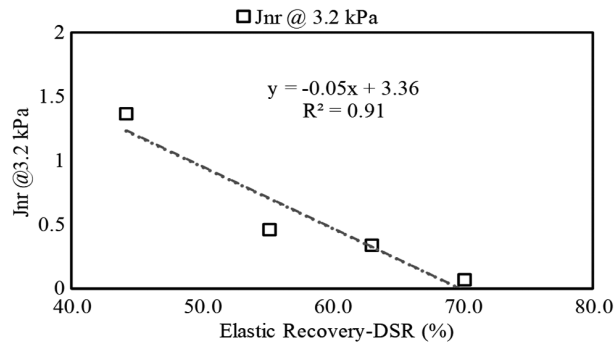


Fig. 14 — Relationship between J_{nr} @ 3.2 kPa and ER-DSR.

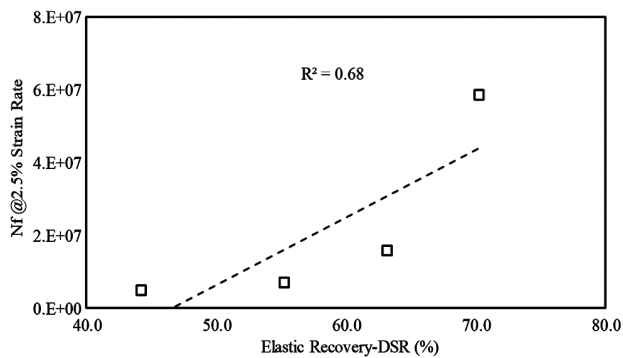


Fig. 15 — Relationship between N_f and ER-DSR.

parameter, it can be concluded that 20% CR content appears to be the optimum level for modifying VG-30 binder^{28,41}.

Elastic recovery is a property of the binder that reflects its ability to return to its original shape after deformation. J_{nr} quantifies the accumulation of permanent strain in the binder during repeated loading and unloading cycles. The relationship between ER-DSR and J_{nr} at 3.2 kPa is presented in Fig. 14. ER-DSR and J_{nr} exhibit a strong inverse relationship, with a high r-square value of 0.91. This clearly indicates that increasing CR content enhances elastic recovery while simultaneously reducing J_{nr} . Similar trends have also been reported by other researchers in the case of PMB binders^{30,31}. To ascertain the elastic behavior and durability of the binder, a graph has been plotted between ER-DSR and N_f . The relationship between ER-DSR and N_f is presented in Fig. 15. As seen in Fig. 15, the N_f of the binder increases with an increase in elastic recovery. A moderate correlation is observed between the two parameters, with an r-square value of 0.68, indicating that 68% of the variation in fatigue life can be explained by changes in the elastic recovery of CRMB binders. Similar trends have also been reported by other researchers for PMB³⁰.

4 Conclusion

Based on the detailed experimental investigation of the properties of CRMB, the following conclusions can be drawn:

- i. The addition of crumb rubber (CR) significantly enhances the complex shear modulus (G^*) and storage modulus (G'), while simultaneously reducing the phase angle (δ). This indicates an increase in binder stiffness and elasticity.
- ii. Increasing the CR content from 10% to 24% resulted in substantial improvements in $G^*/\sin \delta$, G' , Zero Shear Viscosity (ZSV), and the Shenoy parameter, thereby enhancing the binder's rutting resistance.
- iii. The Multiple Stress Creep Recovery (MSCR) test showed significant reductions in non-recoverable creep compliance (J_{nr}) and improvements in percent recovery for CR contents between 10% and 24%, confirming improved performance under repeated and sustained loading.
- iv. The Rutting Resistance Index Ratio (RRIR) proved to be effective for evaluating the performance enhancement of CR-modified binders. Among all rutting parameters, J_{nr} exhibited the highest sensitivity to CR content, confirming its robustness as a rutting performance indicator.
- v. Fatigue life analysis using the Linear Amplitude Sweep (LAS) test indicated that the binder containing 20% CR achieved an optimal balance between fatigue resistance and strain tolerance. Therefore, 20% CR is recommended as the optimal dosage.
- vi. A strong inverse correlation was observed between Elastic Recovery measured via Dynamic Shear Rheometer (ER-DSR) and J_{nr} , while a moderate positive correlation was found between ER-DSR and fatigue life (N_f). These findings indicate a clear interconnection between elastic recovery, rutting resistance, and fatigue performance.

References

- 1 Lo Presti D, *Constr Build Mater*, 49 (2013) 863–881.
- 2 Stevenson K, Stallwood B & Hart A G, *Bioremediat J*, 12(1) (2008) 1–11.
- 3 Kumar G, Sahoo U C, Ramachandra Rao K & Bose S, *Roads Bridg - Drogi Most*, 18(2) (2019) 151–165.
- 4 Bilema M, Yuen C W, Alharthai M, Al-Saffar Z H, Al-Sabaei A & Yusoff N I M, *Sustain*, 15(19)(2023)2-24.
- 5 Jamal M, Martinez-Arguelles G & Giustozzi F, *Constr Build Mater*, 304 (2021) 1-10.

- 6 Kumar G, Tomar R K & Kidwai F A, *Int Conf Commun Comput Sci Eng*, (2024) 1–4.
- 7 Rodriguez-Alloza A M, Gallego J & Giuliani F, *Mater Struct Constr*, 50(1) (2017) 1–9.
- 8 Zhang X, Han C, Yang J, Xu X & Zhang F, *Materials (Basel)*, 14(24) (2021) 1–16.
- 9 Mashaan N S, Ali A H, Karim M R & Abdelaziz M, *Int J PhysSci*, 6(4) (2011) 684–690.
- 10 Kumar P, Mehndiratta H C & Singh K L, *J SciInd Res (India)*, 68(9) (2009) 812–816.
- 11 Duan H, Zhu C, Li Y, Zhang H, Zhang S & Xiao F, *Constr Build Mater*, 277 (2021) 1–13.
- 12 Zhao Z, Wang L, Wang W & Shangguan X, *Polymers (Basel)*, 14(9) (2022) 1–16.
- 13 Biro S, Gandhi T & Amirkhanian S, *Constr Build Mater*, 23(5) (2009) 2080–2086.
- 14 Shenoy A, *J Test Eval*, 30(2) (2002) 95–102.
- 15 Goli A, Baditha A, *Int J Pavement Res Technol*, 12(6) (2019) 648–658.
- 16 Subhy A, Lo Presti D & Airey G, *Road Mater Pavement Des*, 16 (2015) 245–264.
- 17 Saboo N & Kumar P, *J Mater Civ Eng*, 28(7) (2016) 1–8.
- 18 Anwar Parvez M, Al-Abdul Wahhab H I, Shawabkeh R A & Hussein I A, *Constr Build Mater*, 70 (2014) 201–209.
- 19 Ashish P K & Singh D, *J Mater CivEng*, 30(1) (2018) 1–14.
- 20 Zoorob S E, Castro-Gomes J P, Pereira Oliveira L A & O’Connell J, *Constr Build Mater*, 30 (2012) 734–745.
- 21 Liao M C & Chen J S, *J Mater Civ Eng*, 23(12) (2011) 1672–1680.
- 22 Hajikarimi P, Rahi M & Moghadas Nejad F, *Road Mater Pavement Des*, 16(4) (2015) 751–766.
- 23 Wang H, Liu X, Apostolidis P & Scarpas T, *ApplSci*, 8(10) (2018) 1–14.
- 24 Zhang B, Chen H, Zhang H, Kuang D, Wu J & Zhang X, *Materials (Basel)*, 12(21) (2019) 1–14.
- 25 Rani S, Ghabchi R, Zaman M & Ali S A, *Airf Highw Pavements Conf*, (2019) 238–247.
- 26 Chen Z, Wang T, Pei J, Amirkhanian S, Xiao F & Ye Q, *J Clean Prod*, 234 (2019) 1262–1274.
- 27 Ye Y, Xu G, Lou L, Cai D & Y S, *Materials (Basel)*, 12 (2019) 1–17.
- 28 Wang H, Liu X, van de Ven M, Lu G, Erkens S & Skarpas A, *Constr Build Mater*, 239 (2020) 1–13.
- 29 Ameri M, Reza Seif M, Abbasi M & Khiavi A K, *Pet Sci Technol*, 35(1) (2017) 30–36.
- 30 Clopotel C S & Bahia H U, *Eng J*, 16(4) (2012) 99–106.
- 31 Morshed M M T, Hossain Z, Chen D H & Baumgardner G, *Int J Pavement Res Technol*, 13 (2020) 630–636.
- 32 ASTM D2872, Standard test method for effect of heat and air on a moving film of asphalt (RTFOT), *ASTM, West Conshohocken, PA*, (2022) 1–11.
- 33 ASTM D6521, Standard Practice for Accelerated Aging of Asphalt Binder Using a PAV, *ASTM, West Conshohocken, PA*, (2022) 1–6.
- 34 Shenoy A, *J Transp Eng*, 127(5) (2001) 357–362.
- 35 Airey G D, *Polym Modif Bitum*, (2011) 238–263.
- 36 Ashish P K & Singh D, *Constr Build Mater*, 215 (2019) 523–543.
- 37 ASTM D7405-20, Multiple Stress Creep and Recovery (MSCR) of Asphalt Binder Using a DSR, *ASTM, West Conshohocken, PA*, (2020) 1–11.
- 38 AASHTO TP-123, Measuring Asphalt Binder Yield Energy and Elastic Recovery Using DSR, *AASHTO, Washington DC*, (2022) 1–8.
- 39 Šernas O, Vaitkus A & Škuldeckė J, *Road Mater Pavement Des*, 24(S1) (2023) 107–123.
- 40 Wang H, Liu X, Apostolidis P, van de Ven M, Erkens S & Skarpas A, *Mater Struct Constr*, 53(2) (2020) 1–15.
- 41 Lagos-Varas M, Movilla-Quesada D, Raposeiras A C, Monsalve-Cárcamo P & Castro-Fresno D, of CR, Sasobit and SBS, *Case Stud Constr Mater*, 19 (2023) 1–16.