Research on Engineering Structures & Materials
www.jresm.org
Research Group

Research Article

Functional analysis of high-dosage crumb rubber modified bitumen

Gajendra Kumar [*,1,2,a], R K Tomar [3,b], Farhan Ahmad Kidwai [4,c]

[1]*Civil Engineering Department, Amity University Uttar Pradesh, Noida, India*
[2]*CSIR-Central Road Research Institute, New Delhi, India*
[3]*Civil Engineering Department, Amity University Uttar Pradesh, Noida, India*
[4]*Department of Civil Engineering, Jamia Millia Islamia, New Delhi, India*

Article Info

Article History:

Received 12 July 2025
Accepted 03 Mar 2026

Keywords:

Crumb rubber modified bitumen;
Elastic recovery;
Rheological properties;
Zero shear viscosity;
Aging index

Abstract

This study evaluates the performance and aging resistance of high-dosage crumb rubber modified bitumen (CRMB) by analyzing physical and rheological properties of viscosity grade-30 (VG-30) binder modified with 0%, 10%, 15%, 20%, and 24% crumb rubber (CR) before and after short-term aging. Conventional tests (Penetration, softening point, storage stability) and rheological tests (complex modulus, phase angle, rutting factor, elastic recovery using dynamic shear rheometer (ER-DSR), multiple stress creep recovery (MSCR), frequency sweep and zero shear viscosity (ZSV)) were carried out. Elastic recovery improved with increasing CR content and showed strong correlation (R^2 = 0.79) and (R^2 = 0.96) with percent recovery obtained from MSCR test for unaged and short-term aged CRMB respectively. Aging index (AI) based on complex modulus decreased 1.85 (VG-30) to 1.03 (24% CR) at 60°C, while ZSV-based AI showed substantial reduction, from 3.22 (VG-30) to 1.44 (24% CR), indicating improved durability and resistance to oxidative aging. The ZSV increased with CR content, indicating improved resistance to permanent deformation due to stronger internal network formation. The relaxation time (λ) reached a maximum at 20% CR with balanced viscoelastic behavior. Accordingly, 20% CR was identified as the optimum rubber content based on ZSV, λ, n, and elastic recovery, since beyond this level further rubber addition does not result in significant improvements in elastic recovery and ZSV. It is concluded from the study that addition of 20% CR in VG-30 binder reduces oxidative aging and improves binder rutting performances, resulting in sustainable and environmentally friendly binder for flexible pavements.

1. Introduction

The blending of bitumen has provided valuable insight in its utilization in the road construction. A range of waste materials, including waste plastic bags, rubber from used tyres, and pyrolysis char have been added to bitumen or directly into bituminous mixes, depending on the case. Successful application of these materials requires a detailed analysis of sources and the characteristics. In India, approximately 2.5 million metric tons of tyres are produced annually, with 2.0 million metric tons of waste tyres generated each year. Disposal of scrap tyres has become a major environmental concerns. To address the large volume of tyres disposal, recycling efforts focuses on improving product properties and expanding the scope of applications. While scrap tyres are used as fuel in energy facilities and paper mills, this contributes to carbon footprint and raises additional environmental concerns [1].

---

[*]Corresponding author: gk.crri@nic.in, gk.crri@csir.res.in
[a]orcid.org/0009-0009-6752-665X; [b]orcid.org/0000-0001-8759-4099; [c]orcid.org/0000-0002-9910-3151
DOI: http://dx.doi.org/10.17515/resm2026-1022ma0712rs

Safe approach for disposing of waste tires involves grinding them into crumb rubber (CR). CR is produced through scrap tyres using cryogenic or ambient mechanical grinding. In ambient grinding, tyres are shredded and ground with metal and fiber separated. Cryogenic grinding uses liquid nitrogen at around -80°C, involving four stages: size reduction, chilling, separation, and grinding, to produce high-quality CR. The process includes hammer mills, magnetic screens, and sifters to remove contaminants and ensure the purity of the final product [2, 3].

The 30 mesh CR outperformed the 60 mesh CR while preparing the CRMB with 22.5% CR by weight. The addition of CR improved physical, rheological, and elastic recovery properties of binder. The smaller CR particles tend to swell more than the large particles due to the more surface area. There is also a possibility that the finer particles may undergo de-polymerization and dissolve in the bitumen [4]. Researchers have used varying gradation and dosage of CR based on their specific research criteria, grade of base binder and desired performance outcomes, indicating a flexible approach to modify bituminous mixtures [2, 4–6] . The Binder’s physical properties are improved (reduction in penetration and an increment in softening point and elastic recovery) after CR addition. This change can significantly enhance the performance characteristics of the CRMB, making it more durable and resistant to cracking [7–9]. Dynamic Shear Rheometer (DSR) is utilized to evaluate elastic recovery, this value is also termed as ER-DSR. Authors have been established correlation between the ER-DSR and the percent recovery values obtained from the Multiple Stress Creep Recovery (MSCR) test for polymer modified bitumen (PMB)[10–12]. Bitumen aging affects all essential properties specifically performance and durability. Aging that occurs during transport, mixing, and laying is termed as short-term aging, whereas the aging that takes place during the pavement’s service life is termed as long-term aging. These two aging influences overall quality and stability of bituminous pavements [13]. The evaporation of lighter components during production and laying at high temperatures leads to binder’s short-term aging. Long-term aging results from exposure to heat, air, moisture and sunlight. The durability of the mix decreases due to binder hardening, which is influenced by its composition and additives [14]. The particle structure of the CR is complete, preventing the lighter components from volatilizing through the internal network structure, which also explains why CRMB shows distinct aging behaviour. Researcher has found that the CRMB are less affected by the aging at higher temperatures, showing improved durability under such conditions. On the other hand CRMB exhibits high viscosity and do fully coat the bottle flow at 163 °C, which necessitates the use of special aging protocols [5, 15]. The study shows that RTFO aging temperature of 16°C in the case of CRMB binders is not adequate due to limited film formation in the RTFO bottle caused by the higher viscosity of CRMB. CRMB containing 10–20% crumb rubber requires a higher aging temperature, typically between 173 °C to 193 °C, to achieve oxidation levels comparable to actual short-term aging[16]. Storage stability using the CIGAR tube at high temperatures is key for assessing phase separation and modifier compatibility in modified binder. Higher CR concentrations reduce particle movement, preventing phase separation and ensuring a stable blend[4, 11, 17].

The complex modulus indicates overall stiffness of binder, whereas balance between binder’s elastic and viscous characteristics are indicated by phase angle. The incorporation of CR improves the complex modulus and decreases the viscous component, as evidenced by decrease in the phase angle [4, 8]. The complex modulus (G^*), phase angle (δ), and rutting factor ($G^*/\sin\,\delta$) are commonly used to assess the effectiveness of modifier matrix as an antioxidant and to evaluate aging parameters in terms of the aging index (AI). The increasing content of CR also enhances the elasticity of CRMB and percent recovery, while lowering non-recoverable creep compliance. The aging effect can be evaluated by assessing non-recoverable creep compliance at 3.2 kPa for both unaged and short-term aged binders. A lower AI value indicates minimal changes in the rheological properties, helping to prevent the breakdown of lighter components [5,15,18–20] . The non-Newtonian behavior in fluids results from changes in particles and their alignment along the flow direction. When the binder is subjected to a very low shear rate over an extended period, corresponding to steady-state flow, its viscosity at this stage is called Zero Shear Viscosity (ZSV). ZSV serves as an indicator of the binder's stiffness properties and its resistance to permanent deformation under prolonged or extended loading [21–23]. The ZSV-based AI is determined by the ratio of ZSV after and before aging, where a lower value signifies less change in ZSV as a result of aging [20].

Short-term aging may lead to oxidative and thermal degradation of CRMB, along with the hardening of the binder due to crosslinking and polymerization of CR particles at high temperatures. These changes significantly impact the long-term performance and durability of bituminous pavements. This study explored the aging resistivity potential of CRMB by analyzing its physical properties like penetration, softening point before and after aging. The aging behavior has been studied in detail in terms of AI using complex modulus, phase angle, rutting factor, non-recoverable creep compliance. The ER-DSR is an indicator of the binder's resistance to thermal and load-related cracking, which is also addressed in this study [10–12]. The aging resistivity potential also depends on the broad range of frequencies that pavements typically encounter in real-world conditions, and it can be determined by the ratio of the rutting factor before and after aging. Lower frequencies correspond to slow-moving loads and higher frequencies correspond to fast-moving loads. This aspect has been studied by various researchers for multiwall carbon nanotubes and organo-modified nanoclay, but it has not yet been addressed for CRMB [18, 24]. The addition of CR also affects the ZSV, as changes in the molecular structure and an increase in molecular weight occur during short-term aging. Therefore, it was felt that there is need for further research of CRMB to assess the impact of short-term aging on ZSV for obtaining a durable CRMB for sustainable pavements.

The novel aspects of this study is to assess the aging resistivity potential of CRMB using ER-DSR, which has not been reported in the existing literature. A correlation between ER-DSR and percent recovery obtained from MSCR test has also been established for better understanding of elastic behavior of CRMB at varying CR content, which contributes the knowledge to the existing literature. Furthermore, this study assesses the aging resistivity potential across a broad range of frequencies, and author has not come across any such study in case of CRMB. Additionally, the impact of short-term aging on ZSV, which determines the long term pavement performance, has also been investigated in case of CRMB. All these aspect has not been comprehensively addressed in the previous research on CRMB, therefore evaluating these aspects in this study provides the significant contribution to the existing literature database with regard to CRMB at varying CR content levels.

The main objective of this study is to evaluate the changes in the physical and rheological properties of high-content CRMB and their relationship before and after aging in detail. The storage stability properties are assessed using the CIGAR tube test. Additionally, the study also investigates in detail the short-term aging effects by evaluating the AI based on rheological properties such as complex modulus, phase angle, rutting factor, varying frequencies, ZSV and non-recoverable creep compliance.

2. Materials and Methodology

2.1. Materials and Binder Preparation

VG-30 grade bitumen, procured from the Panipat refinery of Indian Oil Corporation Limited, is used to prepare CRMB blends. Base binder viscosity was found 2816 Poise at 60°C. The CRMB was prepared by adding varying CR dosages (10%, 15%, 20%, 24%) by weight of the blend. The blending process was carried out using mechanical stirrer at 200-300 rpm for one hour at temperatures ranging from 175-185°C, to ensure a uniform mixture [2, 25]. Crumb rubber was made from waste tyres through mechanical shredding and was processed at ambient temperature, with particle dimension varying 0 to 0.425 mm (40 mesh). The material was carefully processed to be free from steel, fibers, and other foreign contaminants commonly found in rubber tyres. The particle size gradation of CR is presented in Fig.1.

2.2. Aging Procedure

The rolling thin film oven (RTFO) test, performed in accordance with ASTM D2872 [26], is a widely adopted laboratory method to simulate binder's short-term aging, which occurs during processes such as plant production, transportation, laying and compaction. The glass bottle is filled with thirty-five grams of binder and positioned in circular carriage inside a controlled oven. The temperature of the oven was maintained at 175 °C for 85 minutes instead of 163 °C, as the blending temperature of VG-30 bitumen with CR is maintained between 175–185 °C. The conventional RTFO aging at 163 °C is not sufficient for CRMB due to its higher viscosity and limited film formation. Hence, the RTFO aging was carried out at 175 °C to better simulate the short-term aging conditions [5, 15-16]. Whereas the bottle is rotated to form a uniform film of 1.25 mm thickness. To accelerate the aging process, hot air is injected into the bottle at a rate of 4000 ml/min.

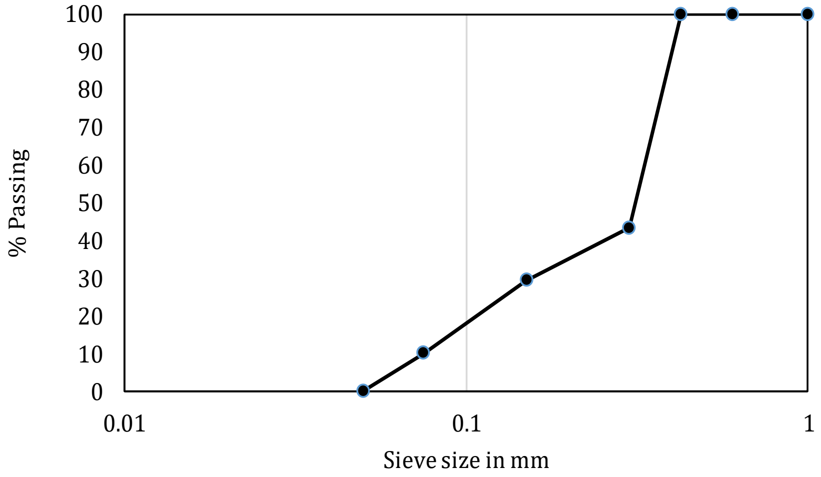

Fig. 1. Particle size gradation of crumb rubber

2.3. Conventional Tests

The penetration value of bitumen, determined through an empirical test, indicates its consistency. This test measures the depth to which a standard needle, loaded with 100 grams, penetrates into a bitumen sample for 5 seconds at a temperature of 25°C. Each 0.1 mm of penetration in the bitumen is considered one unit of penetration [27]. The softening point is the temperature at which bitumen achieves a specific level of softening. The temperature increase is maintained at 5°C per minute during the test. A higher value of the softening point indicates better resistance of bitumen at higher temperatures [28]. The penetration and softening point values were determined for VG-30 and all CRMB samples under both unaged and short-term aged conditions. To evaluate the effect of short-term aging, the difference in softening point values between unaged and short- term aged is assessed.

2.4. Storage Stability Potential

Storage stability of all the blends was analyzed using softening point approach. The CIGAR tube test is for evaluation of storage stability property. The CIGAR tube setup consists of an aluminum tube having 25.4mm dia and a height of 136.7 mm. These tubes are filled with bitumen and kept at 163 ± 5°C for 48 hours. Afterward, tubes were conditioned in a freezer for 4 hours. Samples are then collected from the top third and bottom third portions of CIGAR tube to perform the softening point test [29].

2.5. Rheological Test

ER-DSR was conducted in accordance with AASHTO TP 123 at 25°C on unaged and short-term aged blends, using 8-mm diameter parallel plate and a 2-mm gap test geometry. The sample was tested at 25°C for ER-DSR at a constant strain rate of 2.315% s^{-1} until a strain of 277.8% is achieved. Subsequently, a shear stress of 0.0 kPa was sustained for 30 minutes to facilitate the recovery phase. Stress (τ, Pa) and strain (γ, %) are recorded for one data point every two seconds throughout the entire test [30]. The ER-DSR is calculated using Eq. (1):

$$ER\text{-}DSR = \frac{(Recovered\ strain\ at\ the\ end\ of\ relaxation\ time)}{Strain\ at\ the\ end\ of\ loading\ time} \tag{1}$$

Where, ER-DSR is elastic recovery value using dynamic shear Rheometer.

DSR was utilized to access rheological parameters including complex modulus (G^*), phase angle (δ), and rutting factor ($G^*/\sin\delta$) for both unaged and short-term aged binders. The temperature sweep test was performed at frequencies of 1.59 Hz and 1% strain level at 50°C, 60°C, and 70°C. The test was conducted using 25mm dia DSR plates, maintaining 1 mm gap between the two plates. Additionally, a frequency sweep test was performed over broad range of frequency 0.1 to 100 rad/s at 60°C to evaluate behavior of binders across a wide frequency spectrum. The AI, based on the rheological parameters such as G*, δ, G*/sin δ and J_{nr} was calculated using Eq. (2,3,4 & 5) respectively.

$$AI\ Value\ based\ on\ G^*value = \frac{G^*_{short\ term\ aged}}{G^*_{unaged}} \tag{2}$$

$$AI\ Value\ based\ on\ \delta\ value = \frac{\delta_{short\ term\ aged}}{\delta_{unaged}} \tag{3}$$

$$AI\ Value\ based\ on\ G^*/\sin\delta\ value = \frac{G^*/\sin\delta_{short\ term\ aged}}{G^*/\sin\delta_{unaged}} \tag{4}$$

$$AI\ Value\ based\ on\ J_{nr}\ value = \frac{J_{nr\ at\ 3.2kPa\ unaged}}{J_{nr\ at\ 3.2\ kPa\ short\ term\ aged}} \tag{5}$$

Where, G^* is the complex modulus (kPa); δ is the phase angle (degree); G^*/sin δ is rutting factor (kPa); and J_{nr} is non recoverable creep compliance (kPa^{-1}).

ZSV was determined by conducting a steady shear test with shear 0.01 s^{-1} to 10 s^{-1} at a constant temperature of 60°C. This viscosity represents limiting value observed in Newtonian region at very low shear rates. Carreau model is commonly applied to characterize steady shear rheological behavior of binders and their flow properties [31, 32]. The AI using ZSV is expressed as a ratio of ZSV of short-term aged binder to that of the unaged binder [20]. Carreau model, represented by Eq. (6) is used for computation of ZSV.

$$\eta = \eta_o + (\eta_o + \eta_\infty)(1 + (\lambda\gamma)^2)^{[(n-1)/2]} \tag{6}$$

Where η is the steady state viscosity (Pa.s); η_0 is the Zero shear viscosity (Pa.s); $\eta_\infty$is the infinite shear viscosity (Pa.s); γ is the shear rate (s^{-1}); λ and n are the fitting parameter (relaxation time, power law index).

3. Results and Discussion

3.1. Penetration and Softening Point

Three tests were carried out for penetration, softening point, and storage stability for each sample. The reported values correspond to the arithmetic mean of the three replicates, and variability is expressed as standard error. The penetration of the VG-30 blend decreased from 58 to 20 with 24% CR in the unaged condition, as shown in Fig.2. Similarly, the penetration decreased from 46 to 20 in the short-term aged condition. The consistent penetration value for both unaged and short-term aged 24% CR binder implies that higher CR content improves the binder's resistance to aging.

The softening point is 47.3°C for VG-30 and increases to 62.6°C, 65.5°C, 67.8°C, and 72.6°C for unaged binders with 10%, 15%, 20%, and 24% CR content, respectively. Fig.3 shows, the softening point is 51.7°C for VG-30 and increases to 66.5°C, 69.2°C, 71.2°C, and 74.9°C for short-term aged binders. This increase in softening point can be attributed to the increased stiffness and improvement in high-temperature flowing properties of the blends, making it more stable under load and enhancing rutting resistance and overall performance durability. The decrease in the softening point for both unaged and short-term aged binders was 4.4°C for the VG-30 binder, which reduced to 3.9°C, 3.7°C, 3.4°C, and 2.3°C for the modified binders with 10%, 15%, 20%, and 24% CR content, respectively. The CR particles absorbs the lighter fraction of bitumen and swell multiple times to their original size. Some part of CR dissolves into the bitumen, increasing the aromatic and resin and generating smaller molecular components. The absorption of maltenes and swelling of rubber particles contributes to stiffening of binder[33, 34].

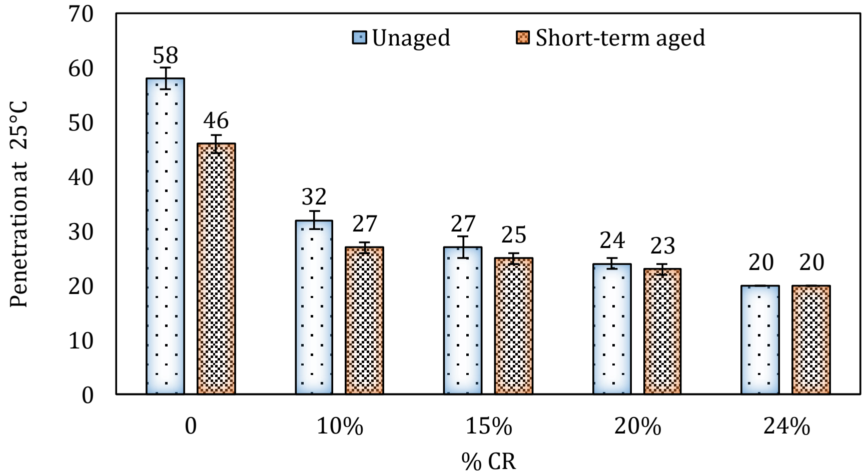

Fig. 2. Penetration of unaged and short-term aged VG-30 and CRMB

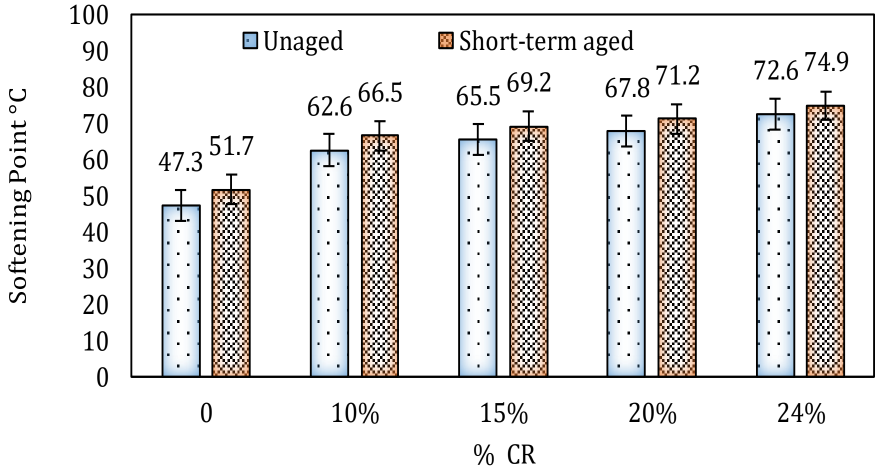

Fig. 3. Softening point of unaged and short-term aged VG-30 and CRMB

3.2. Storage Stability of CRMB

The softening points of VG-30 and various CRMB blends from the top and bottom portions of the CIGAR tube are shown in Fig.4. The bottom portion of the CIGAR tube exhibited a higher softening point in various CRMB blends, indicating the settlement of CR particles at the bottom. The difference in softening point between bottom and top portions was observed to be 3.7°C, 3.5°C, 2.4°C, and 1°C for 10%, 15%, 20%, and 24% CR content, respectively. The difference in softening point of less than 4 °C indicates uniform dispersion of CR particles in the VG-30 bitumen. This could be due to the limited space for CR particles, with higher specific gravity, to shift and settle at the bottom of the tube during storage in the oven. Similar trends were also observed in studies with higher CR content [4, 18, 35].

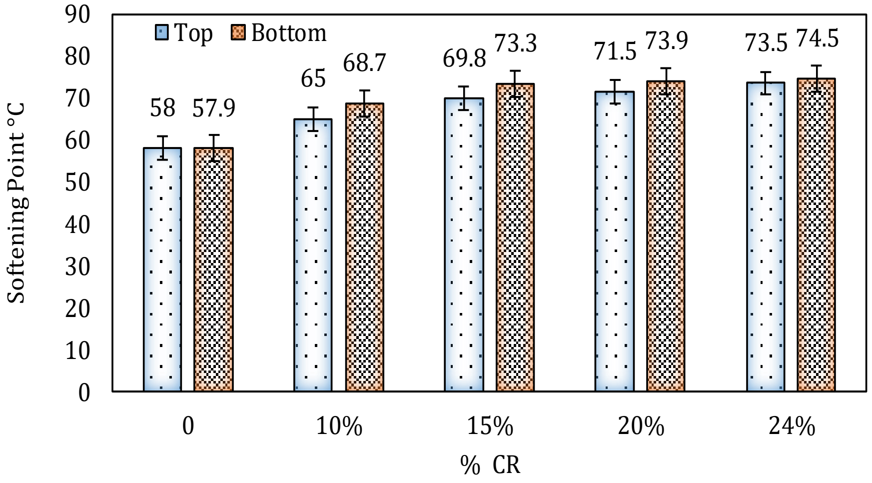

Fig. 4. Variation in softening point between top and bottom samples of the CIGAR tube

3.3. Unaged and Short-Term Aged Rheological Properties

3.3.1Elastic Recovery Analysis

The ER-DSR was calculated using Equation (1). The test results of ER-DSR for unaged and short-term aged VG-30, along with various CRMB are presented in Fig.5. It can be seen that elastic recovery is 14.2% for VG-30 and 57.8%, 65.6%, 73.2%, and 71.3% for 10%, 15%, 20%, and 24% CR content, respectively for unaged binders. Similarly, elastic recovery is 8.6% for VG-30 and 44.2%, 55.2%, 63.1%, and 70.2% for 10%, 15%, 20%, and 24% CR content, respectively for short-term aged binders. There is significant increase in elastic recovery with the addition of CR for both aged and short-term aged binders.

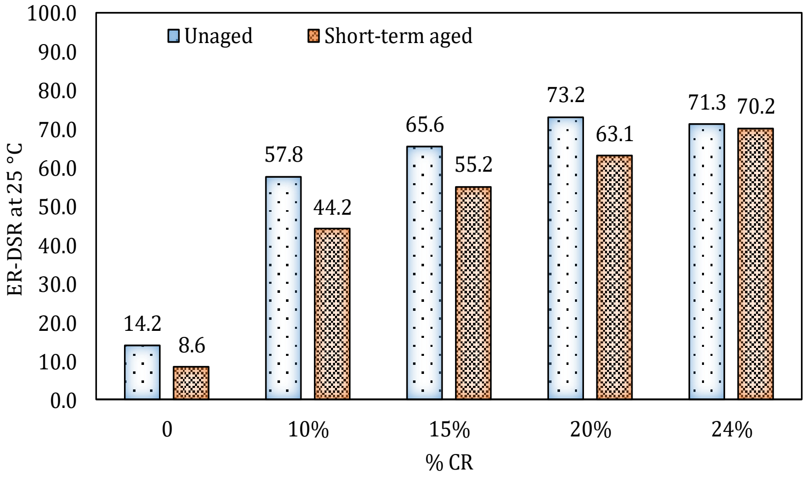

Fig. 5. ER-DSR of unaged and short-term aged VG-30 and CRMB

The ER-DSR value for the 20% CR bitumen is higher than that of the 24% CR bitumen, indicating that increasing the crumb rubber content beyond 20% does not result in further improvement in the elastic recovery properties of CRMB. It is evident that the elastic recovery shows lower values for short-term aged binders compared to unaged binders; this may be due to the aging of the binder. As the CR content increases, the difference between unaged and short-term aged binder's ER-DSR decreases, indicating that an increasing CR content is reducing the aging effect. Similar trends have also been observed by other researchers [5]. Correlation has been established between MSCR percent recovery at 3.2 kPa and ER-DSR for both unaged and short-term aged CRMB, as presented in Fig.6. It can be observed from Fig.6 that the MSCR percent recovery at 3.2 kPa and ER-DSR exhibit good correlation with correlation coefficient is 0.79 and 0.96 for unaged and short-term aged CRMB respectively. This may be due to the initial interaction between bitumen and CR particles in the unaged state, where the absorption of lighter fractions and the swelling of rubber are still in progress. CRMB undergoes stiffening, stabilizing the rubber–binder interaction and leading to a stronger correlation between the two parameters after short-term aging.

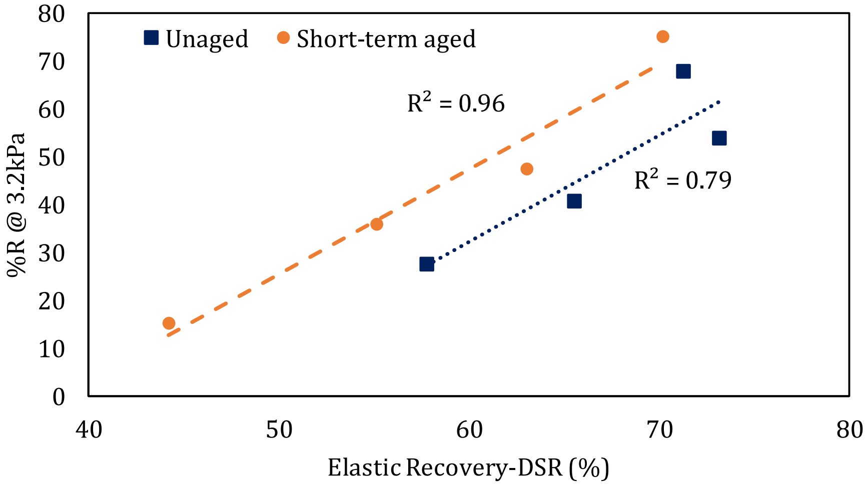

Fig. 6. Relationship between percent Recovery and ER-DSR of unaged and short-term aged VG-30 and CRMB

3.3.2 Complex Modulus Analysis

The test results for the complex modulus of VG-30 and various CRMB blends at temperatures ranging from 50°C, 60°C, and 70°C for unaged and short-term aged are presented in table 1. The complex modulus of bitumen measures its resistance to deformation, reflecting stiffness through elastic and viscous components. It is crucial for assessing binder performance under varying temperatures and loads. The complex modulus increases with higher CR content at all temperatures, indicating that addition of CR enhances the stiffness of binder as can be seen from table 1. Similar trends in complex modulus have also been reported by other researchers for CRMB, Styrene Butadiene Styrene (SBS) modified binders, and other combinations of binders with CR [5, 36]. The complex modulus values for short-term aged binders show an upward shift (increase) due to binder's aging, as can be seen from table 1. AI based on complex modulus was calculated using Equation (2). AI values at 50°C, 60°C, and 70°C are presented in Fig. 7. It is observed that the AI value decreases as the CR content increases. Similarly, the AI of VG-30 bitumen is 1.85, which reduces to 1.23, 1.19, 1.11, and 1.03 for 10%, 15%, 20%, and 24% CR content respectively at 60°C. This indicates that the presence and higher concentration of CR particles retard the upward shift of the complex modulus due to short-term aging and contribute to delay in overall oxidation process. However, minor deviations from the decreasing trend are observed at 50°C and 70°C for some binders as can be seen from Fig. 7, this may be due to temperature-dependent viscoelastic behavior of the binder–rubber system.

Table 1. Complex modulus of unaged and short-term aged VG-30 and CRMB

Binder/	Complex Modulus in kPa, unaged			Complex Modulus in kPa, aged		
Temperature	50°C	60°C	70°C	50°C	60°C	70°C
VG-30	28.20	7.58	2.27	52.80	14.00	4.00
10% CR	50.50	20.00	8.33	62.70	24.50	10.20
15% CR	67.50	23.70	9.53	72.10	28.30	11.60
20% CR	68.50	27.00	10.90	73.20	30.00	13.00
24% CR	75.70	33.10	14.10	79.50	34.20	16.10

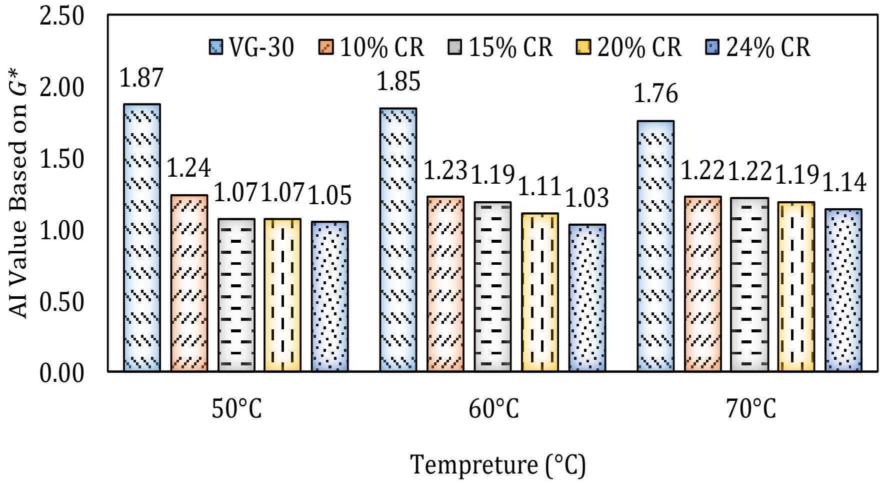

Fig. 7. Aging index based on complex modulus at different temperatures for VG-30 and CRMB

3.3.3 Phase Angle Analysis

The phase angle of unaged and short-term aged bitumen provides insight into its resistance to deformation and ability to recover after stress. A lower phase angle indicates more elastic behavior and higher energy storage. Additionally, a lower phase angle reflects increased resistance to rutting and improved durability. The phase angle for unaged and short-term aged binders at 50°C, 60°C, and 70°C is presented in table 2. AI index based on phase angle was calculated using Equation (3). AI values at 50°C, 60°C, and 70°C are presented in Fig.8. As the CR content increases, binder's phase angle decreases, indicating more elastic behavior, which can be seen from Table 2. The phase angle also decreases after short-term aging of binder, as presented in Table 2.

Table 2. Phase angle of unaged and short-term aged VG-30 and CRMB

Binder/ Temperature	Phase angle, unaged			Phase angle, aged		
	50°C	60°C	70°C	50°C	60°C	70°C
VG-30	81.9	85.1	87.3	77	81.5	85
10% CR	63.5	64.3	65.2	59.5	60.2	61.3
15% CR	63.1	63.7	64.6	58.9	59.5	60.5
20% CR	58.8	59.3	59.7	54.8	55.2	55.7
24% CR	54.2	54.7	54.8	49.8	50	50.3

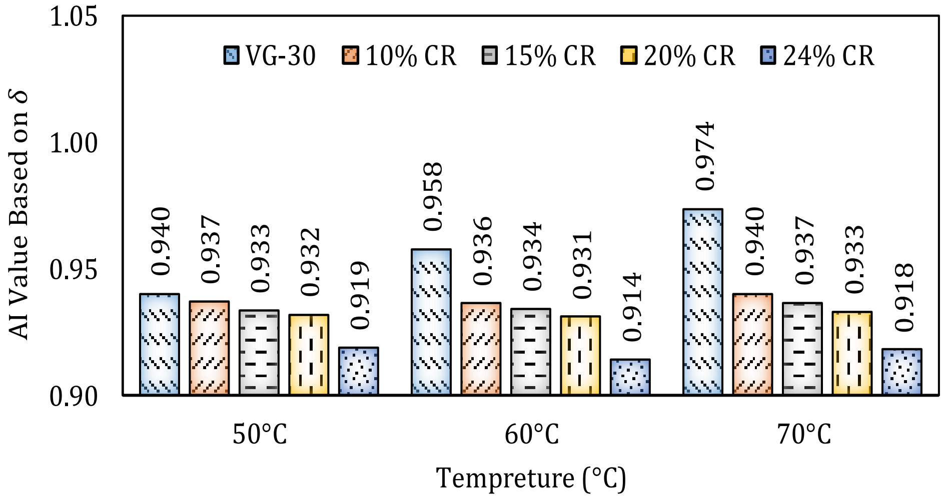

Fig. 8. Aging index based on phase angle at different temperatures for VG-30 and CRMB

The AI based on phase angle at 50°C, 60°C, and 70°C is presented in Fig.8. It is observed that as the CR content increases the AI value decreases. Specifically, the AI of VG-30 is 0.958, which decreases to 0.936, 0.934, 0.931, and 0.914 for 10%, 15%, 20%, and 24% CR content respectively at 60°C. This indicates that the presence and higher concentration of CR particles retard the downward shift of the phase angle due to short-term aging and retard aging of binder. Similar trends in the AI have also been reported by other researchers for SBS-modified binders for different aging protocols [19, 37].

3.3.4 Rutting Factor Analysis

The rutting factor is utilized to evaluate the bitumen's resilience to permanent deformation at elevated temperatures. The rutting factor values for unaged and short-term aged VG-30 and various CRMB blends at 50°C, 60°C, and 70°C are presented in table 3. The rutting factor is lower for the VG-30 and increases progressively as the CR content increases from 10 to 24%. This trend is consistent for both unaged and short-term aged binders as reported in available literature [6]. It is also observed that as the test temperature increases, rutting factor values for VG-30 and various CRMB blends (for unaged and short-term aged) decrease for all test temperatures. This reduction is attributed to the increasing dominance of the viscous component at higher temperatures. The decline in the rutting factor gradually slows down, indicating that the performance of VG-30 and CRMB deteriorates with rising temperature. AI index based on rutting factor was calculated using Equation (4). AI values at 50°C, 60°C, and 70°C are presented in Fig.9. The AI based on rutting factor at 50°C, 60°C, and 70°C is presented in Fig.9. It is observed that the AI value reduces as the CR content increases. The AI of VG-30 bitumen is 1.86, which reduces to 1.27, 1.24, 1.16, and 1.10 for 10%, 15%, 20%, and 24% CR content respectively at 60°C. The AI decreases as the CR content increases, which indicates a reduction in temperature susceptibility and an improvement in aging properties. The resistance to oxidative aging and thermal degradation is also represented by a lower AI [36].

Table 3. Rutting factor ($G^*/\sin\delta$) of unaged and short-term aged VG-30 and CRMB

Binder/ Temperature	Rutting factor in kPa, unaged			Rutting factor in kPa, aged		
	50°C	60°C	70°C	50°C	60°C	70°C
VG-30	28.5	7.6	2.3	54.2	14.2	4.0
10% CR	56.4	22.2	9.2	72.8	28.2	11.6
15% CR	75.7	26.4	10.5	84.2	32.8	13.3
20% CR	80.1	31.4	12.6	89.6	36.5	15.7
24% CR	93.3	40.6	17.3	104.1	44.6	20.9

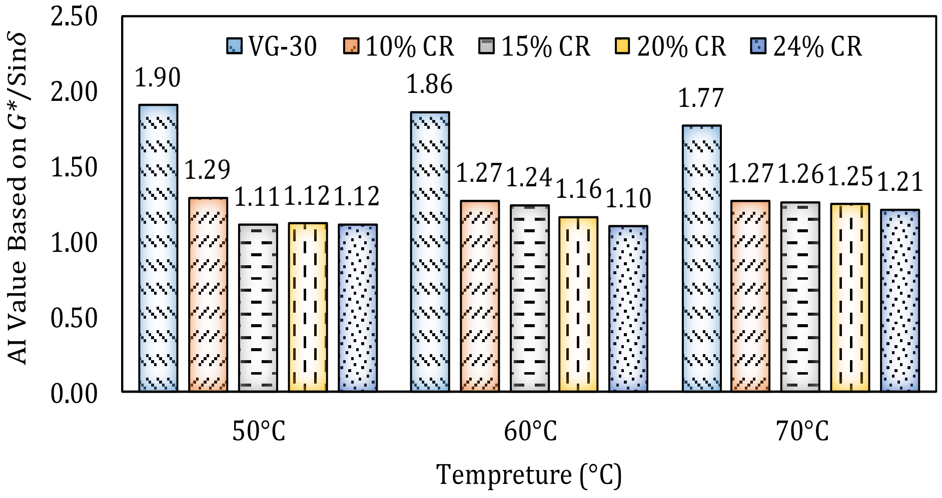

Fig. 9. Aging index based on rutting factor ($G^*/\sin\delta$) at different temperatures for VG-30 and CRMB

3.3.5 AI Based on Non-Recoverable Creep Compliance

The AI based on J_{nr} 3.2 kPa was calculated using Equation (5). This stress level more accurately simulates real-world loading conditions, especially under heavy traffic. It provides the reliable and comparable percent recovery results for PMB and CRMB, ensuring a better assessment of their elastic behavior and rutting resistance. The test results of aging index based on J_{nr} value at 3.2 kPa is presented in Fig.10. The AI of VG-30 bitumen is 2.35, which reduces to 2.02, 1.82, 1.52, and 1.01 for 10%, 15%, 20%, and 24% CR content respectively at 70°C. The AI decreases as the CR content increases, indicating that higher CR content in CRMB makes it less susceptible to aging. Similar trends have also been observed by other researchers. [15] .

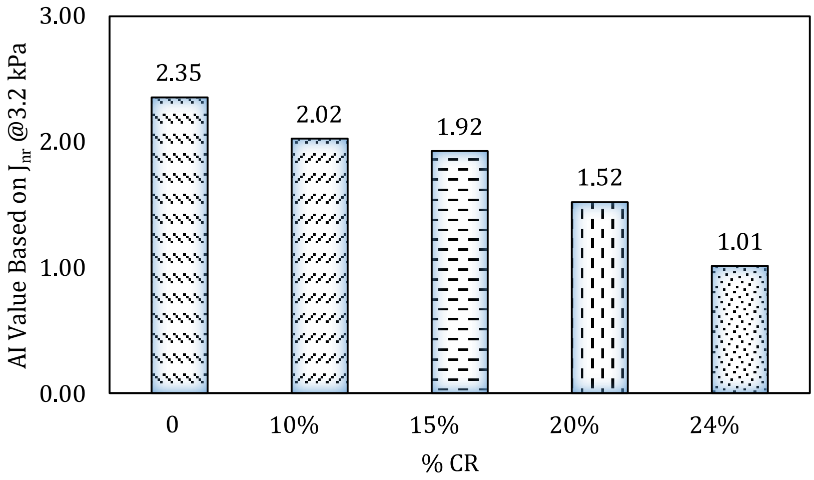

Fig. 10. AI based on J_{nr} at 3.2 kPa for VG-30 and CRMB

3.3.6 Analysis of AI Using Broad Range of Frequencies

The variation across a broad range of frequencies (0.1 to 100 rad/s) at 60°C is presented in Fig.11 for VG-30 and various CRMB blends. The lower frequencies correspond to slow-moving loads, where the viscous component of the binder plays a significant role. On the other hand, higher frequencies correspond to fast-moving loads, where the elastic component of the binder dominates. The AI of VG-30 is observed 2.08 at 0.1 rad/s and 1.46 at 100 rad/s, while the binder with 20% CR content showed an AI of 1.50 at 0.1 rad/s and 1.04 at 100 rad/s, respectively. A similar pattern of AI is observed in other CRMB. The decrease in the AI value at low frequencies indicates an improvement in the binder's resistance to cracking due to the addition of CR. This trend is rational, as lower frequencies represent higher temperatures, while higher frequencies correspond to lower temperatures. Other researchers have also reported similar trends with different types of modifiers [20, 24].

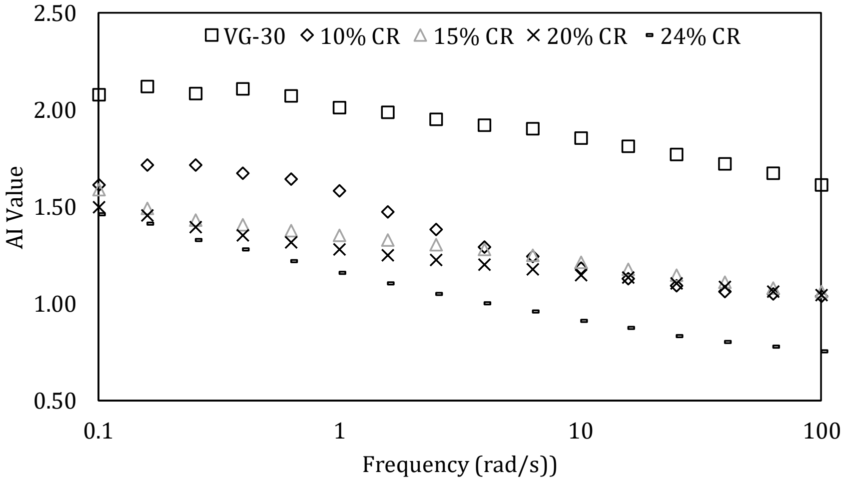

Fig. 11. Variation of aging index at 60°C over a broad range of frequencies for VG-30 and CRMB

3.3.7 ZSV Analysis

The test results of ZSV is also considered an important parameter for assessing binder's ability to resist permanent deformation caused by high temperatures and heavy axle loads under prolonged loading condition. The test results of ZSV at 60 °C for unaged and short-term aged VG-30 and CRMB binders are presented in Table 4. For unaged binders, the ZSV of VG-30 bitumen is 7.68×10^2, which increases to 6.26×10^4 at 24% CR content. Similarly, for short term aged binders, the ZSV of VG-30 increases from 2.48×10^3 to 8.99×10^4 at 24% CR content. The ZSV increases with increasing CR content, indicating enhanced resistance to permanent deformation due to the development of a stronger internal network structure. The value of λ increases from 0.94 to 6.26 for the unaged binder and from 0.58 to 6.34 for the short-term aged binders when comparing VG-30 and 24% CR binders. The 20% CR binder exhibits the maximum λ value i.e. 11.11 s, indicating the formation of the most effective elastic network and delayed stress relaxation. Although the 24% CR binder exhibits a higher ZSV, no corresponding improvement in λ is observed, indicating that the additional CR does not further enhance the elastic response.

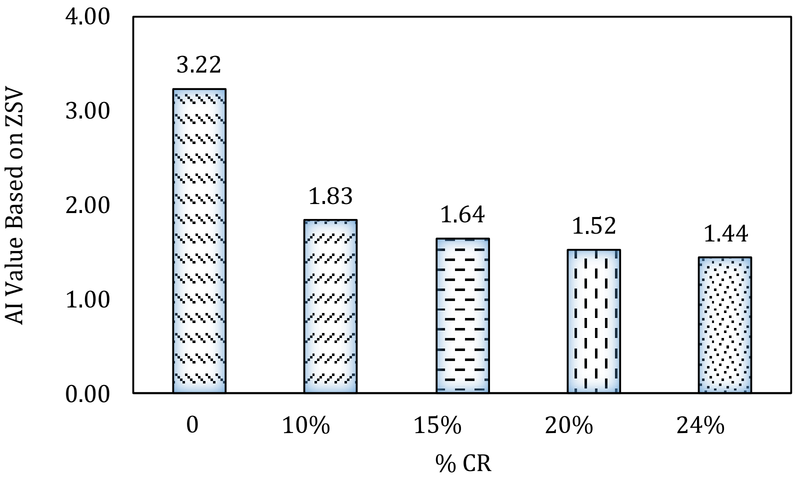

Fig. 12. Aging index based on ZSV for VG-30 and CRMB

The n value decreases from 0.93 to 0.56 for the unaged binders and from 0.75 to 0.44 for the aged binder when comparing VG-30 with 24% CR binders, confirming the increasing non-Newtonian and viscoelastic nature of CRMBs. The n values for the 20% CR binder are 0.63 for unaged condition and 0.50 for short-term aged condition, representing a balanced viscoelastic response with adequate stiffness and workability. In contrast, the 24% CR binder exhibits a much lower n value of 0.44 in the short-term aged condition, indicating excessive stiffness that may lead to compaction and constructability issues.

Table 4. Carreau model parameters of unaged and short-term aged VG-30 and CRMB

Binder/ Temperature	Unaged				Aged			
	η_0 (Pa.s)	λ (s)	N	R^2	η_0 (Pa.s)	λ (s)	N	R^2
VG-30	7.68×10^2	0.94	0.93	0.90	2.48×10^3	0.58	0.75	0.99
10% CR	4.34×10^3	5.23	0.77	0.99	7.96×10^3	7.48	0.74	0.99
15% CR	1.35×10^4	3.70	0.67	0.93	2.22×10^4	5.17	0.65	0.97
20% CR	2.43×10^4	11.11	0.63	0.99	3.69×10^4	4.54	0.50	0.94
24% CR	6.26×10^4	6.26	0.56	0.99	8.99×104	6.34	0.44	0.95

The high R^2 values (0.90–0.99) across all samples confirm excellent fit of the Carreau model to the experimental data, supporting the reliability of the predicted ZSV. Although the 24% CR binder exhibits a higher ZSV, no corresponding improvement in λ is observed, indicating that the additional CR does not further enhance the elastic response. Based on the combined evaluation of ZSV, relaxation time (λ), and flow behavior index (n), the 20% CR content is identified as the optimum dosage, providing superior resistance to permanent deformation while maintaining a balanced viscoelastic response and practical workability. The AI based on the ZSV is derived by calculating the ratio of short-term aged ZSV to unaged ZSV. The results of ZSV based AI are shown in Fig.12. The AI of VG-30 bitumen is 3.22, which reduces to 1.83, 1.64, 1.52, and 1.44 for 10%, 15%, 20%, and 24% CR content respectively at 60°C. The AI value decreases with an increase of CR content, signifying a decrease in temperature sensitivity and an enhancement in aging resistance. Similar trends of reduction in the AI have also been reported for other modifiers [20].

Table 5. Summary of Aging Index for VG-30 and CRMB based on rheological and ZSV parameters

Binder/ Temperature	AI based on G^*			AI based on δ			AI based on $G^*/\sin\delta$			AI based on J_{nr} 70°C	AI based on ZSV 60°C
	50°C	60°C	70°C	50°C	60°C	70°C	50 °C	60 °C	70 °C		
VG-30	1.87	1.85	1.76	0.940	0.958	0.974	1.9	1.86	1.77	2.35	3.22
10% CR	1.24	1.23	1.22	0.937	0.936	0.940	1.29	1.27	1.27	2.02	1.83
15% CR	1.07	1.19	1.22	0.933	0.934	0.937	1.11	1.24	1.26	1.82	1.64
20% CR	1.07	1.11	1.19	0.932	0.931	0.933	1.12	1.16	1.25	1.52	1.52
24% CR	1.05	1.03	1.14	0.919	0.914	0.918	1.12	1.1	1.21	1.01	1.44

Table 5 presents the summery of test results of AI for VG-30 and CRMB based on rheological and zero shear viscosity at different temperatures. The AI based on complex modulus (G^*), phase angle (δ), $G^*/\sin\delta$, non-recoverable creep compliance (J_{nr} at 3.2 kPa), and ZSV at 60°C presents changes in binder property due to short-term aging. VG-30 exhibited the highest aging indices among all the parameters, which shows greater susceptibility to aging. CRMB with 10 to 24 % CR content, demonstrated improved aging resistance, as AI is decreasing with the increase of CR content as evidenced by lower AI values. The AI based on ZSV is decreasing with the increase of CR content, indicating that CR enhances the long-term stability of the binder. These findings suggest that the incorporation of crumb rubber can lower the aging effects in terms of improvements in durability of bituminous binders on elevated temperatures.

4. Conclusion

Based on the detailed experimental results the following conclusions can be drawn:

The addition of CR in VG-30 reduces penetration, increases softening point and improves the binder's stiffness, thermal stability, durability and aging characteristics. Elastic recovery values increased with the increase in CR content, indicating improved recovery and flexibility. This was validated through a strong correlation between elastic recovery and percent recovery at 3.2 kPa, with correlation coefficients of 0.79 and 0.96 for unaged and short-term aged binders, respectively. The optimum rubber content is observed at a 20% CR level, as beyond this percentage, rubber does not contribute significantly to the elastic recovery. However, higher dosage of CR may provide improved aging resistance. The difference between the unaged and short-term aged elastic recovery reduced with the increase in CR content. From this it can be inferred that aging reduces with the increase in CR content.

It can be inferred that storage stability is not an issue with the use of 24% CR as the difference in softening point value between the top and bottom portion after storage stability test was less than 4°C.

The addition of CR showed lower phase angle even at higher temperatures indicating the elastic behaviour of the CR modified binders. The aging index parameter showed better resistance against oxidative aging with the increase in CR content.

The percent recovery after short-term aging indicated the elastic behaviour of the CR modified binders, especially when the CR content was higher. Therefore, it can be inferred from this study that higher CR can result in a rut resistant binder with minimal binder aging.

The ZSV increases with increasing CR content, indicating enhanced resistance to permanent deformation due to stronger internal network formation. The 20% CR binder shows the maximum relaxation time reflecting the most effective elastic network and delayed stress relaxation. Its corresponding n values indicate a balanced viscoelastic response with adequate stiffness and workability, while 24% CR exhibits excessive stiffness. Therefore, based on ZSV, λ, n, and elastic recovery, 20% CR is identified as the optimum dosage at the binder level. Although 24% CR further improves aging indices, its excessively low n-value and increased stiffness may adversely affect workability.

The present study is limited to binder-level evaluation; therefore, mixture-level investigations are required to confirm performance in future studies.

Acknowledgement

The authors are thankful to the Director, CSIR-Central Road Research Institute, New Delhi, for his kind support and granting permission to publish this research article.

References

[1] Amirkhanian SN, Corley M. Utilization of rubberized asphalt in the United States. Proceedings of the International Symposium on Pavement Recycling, Sao Paulo, Brazil; 2005.

[2] Bilema M, Yuen CW, Alharthai M, Al-Saffar ZH, Al-Sabaeei A, Yusoff NIM. A review of rubberised asphalt for flexible pavement applications: production, content, performance, motivations and future directions. Sustainability. 2023;15. https://doi.org/10.3390/su151914481

[3] Lo Presti D. Recycled tyre rubber modified bitumens for road asphalt mixtures: a literature review. Construction and Building Materials. 2013;49:863–881. https://doi.org/10.1016/j.conbuildmat.2013.09.007

[4] Jamal M, Martinez-Arguelles G, Giustozzi F. Effect of waste tyre rubber size on physical, rheological and UV resistance of high-content rubber-modified bitumen. Construction and Building Materials. 2021;304:124638. https://doi.org/10.1016/j.conbuildmat.2021.124638

[5] Zhao Z, Wang L, Wang W, Shangguan X. Experimental investigation of the high-temperature rheological and aging resistance properties of activated crumb rubber powder/SBS composite-modified asphalt. Polymers. 2022;14. https://doi.org/10.3390/polym14091905

[6] Lee SJ, Akisetty CK, Amirkhanian SN. The effect of crumb rubber modifier on performance properties of rubberized binders in HMA pavements. Construction and Building Materials. 2008;22:1368–1376. https://doi.org/10.1016/j.conbuildmat.2007.04.010

[7] Cao WD, Liu ST, Cui XZ, Yu XQ. Effect of crumb rubber particle size and content on properties of crumb rubber modified asphalt. Applied Mechanics and Materials. 2011;99–100:955–959. https://doi.org/10.4028/www.scientific.net/AMM.99-100.955

[8] Zhang B, Chen H, Zhang H, Kuang D, Wu J, Zhang X. Physical and rheological properties of rubberized bitumen modified by different methods. Materials. 2019;12. https://doi.org/10.3390/ma12213538

[9] Kumar G, Sahoo UC, Ramachandra Rao K, Bose S. Design and evaluation of stone matrix asphalt using stiffer grade crumb rubber modified bitumen. Roads and Bridges. 2019;18:151–165. https://doi.org/10.7409/rabdim.019.010

[10] Clopotel CS, Bahia HU. Importance of elastic recovery in the DSR for binders and mastics. Engineering Journal. 2012;16:3–5. https://doi.org/10.4186/ej.2012.16.4.99

[11] Kumar A, Choudhary R, Kandhal PS, Julaganti A, Behera OP, Singh A, Kumar R. Fatigue characterisation of modified asphalt binders containing warm mix additives. Road Materials and Pavement Design. 2020;21:519–541. https://doi.org/10.1080/14680629.2018.1507921

[12] Morshed MMT, Hossain Z, Chen D, Baumgardner G. Alternatives to elastic recovery and fatigue tests for modified binders. International Journal of Pavement Research and Technology. 2020;13:630–636. https://doi.org/10.1007/s42947-020-6009-2

[13] Hofko B, Hospodka M. Rolling thin film oven test and pressure aging vessel conditioning parameters. Transportation Research Record. 2016;2574(1):111–116. https://doi.org/10.3141/2574-12

[14] Petersen JC. Chemical composition of asphalt as related to asphalt durability. Transportation Research Record. 1984;13–30.

[15] Wang H, Liu X, Apostolidis P, van de Ven M, Erkens S, Skarpas A. Effect of laboratory aging on chemistry and rheology of crumb rubber modified bitumen. Materials and Structures. 2020;53:1–15. https://doi.org/10.1617/s11527-020-1451-9

[16] Jin T, Feng Y, Li M, Liu L, Yuan J, Sun L. Laboratory short-term aging of crumb rubber modified asphalt: RTFOT temperature optimization and performance investigation. Journal of Cleaner Production. 2024;434:140327. https://doi.org/10.1016/j.jclepro.2023.140327

[17] Vigneswaran S, Yun J, Lee MS, Lee SJ. Effect of nanocomposite clays on storage stability of rubberized binders under different curing and blending conditions. International Journal of Pavement Research and Technology. 2025. https://doi.org/10.1007/s42947-025-00499-3

[18] Ashish PK, Singh D. Functional characteristics of carbon nanotube modified asphalt binder. International Journal of Pavement Engineering. 2020;21:1069–1082. https://doi.org/10.1080/10298436.2018.1519190

[19] Zhang D, Zhang H, Shi C. Aging performance of SBS modified asphalt under various aging methods. Construction and Building Materials. 2017;145:445–451. https://doi.org/10.1016/j.conbuildmat.2017.04.055

[20] Kumar A, Choudhary R, Kumar A. Aging characteristics of asphalt binders modified with tire and plastic chars. PLoS One. 2021;16. https://doi.org/10.1371/journal.pone.0256030

[21] Ren S, Liu X, Xu J, Lin P. Role of swelling-degradation degree of crumb rubber on CR/SBS modified asphalt. Construction and Building Materials. 2021;300:124048. https://doi.org/10.1016/j.conbuildmat.2021.124048

[22] Wang H, Liu X, Apostolidis P, Scarpas T. Non-Newtonian behaviour of crumb rubber-modified bitumen. Applied Sciences. 2018;8. https://doi.org/10.3390/app8101760

[23] Ashish PK, Singh D. High and intermediate temperature performance of CNT modified binders. Journal of Materials in Civil Engineering. 2018;30. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002106

[24] Ashish PK, Singh D, Bohm S. Influence of nanoclay addition on rheological performance of asphalt binder. Road Materials and Pavement Design. 2017;18:1007–1026. https://doi.org/10.1080/14680629.2016.1201522

[25] Mashaan NS, Ali AH, Karim MR, Abdelaziz M. Effect of crumb rubber concentration on physical and rheological properties of rubberised bitumen. International Journal of Physical Sciences. 2011;6:684–690. https://doi.org/10.5897/IJPS11.113

[26] ASTM D2872. Standard test method for effect of heat and air on asphalt (rolling thin-film oven test). ASTM International, West Conshohocken, PA; 2022.

[27] IS 1203. Method of testing tar and bituminous material: penetration. BIS, New Delhi, India; 2022.

[28] IS 1205. Method of testing tar and bituminous material: softening point, ring-and-ball method. BIS, New Delhi, India; 2022.

[29] ASTM D7173. Standard practice for determining separation tendency of polymer in modified asphalt. ASTM International, West Conshohocken, PA; 2020.

[30] AASHTO TP-123. Method for measuring binder yield energy and elastic recovery using DSR. AASHTO, Washington DC; 2020.

[31] Biro S, Gandhi T, Amirkhanian S. Zero shear viscosity of warm mix binders. Construction and Building Materials. 2009;23:2080–2086. https://doi.org/10.1016/j.conbuildmat.2008.08.015

[32] Parvez MA, Al-Abdul Wahhab HI, Shawabkeh RA, Hussein IA. Asphalt modification using acid-treated waste oil fly ash. Construction and Building Materials. 2014;70:201–209. https://doi.org/10.1016/j.conbuildmat.2014.07.045

[33] Wang H, Liu X, Zhang H, Apostolidis P, Erkens S, Skarpas A. Micromechanical modelling of complex shear modulus of crumb rubber modified bitumen. Materials and Design. 2020;188:108467. https://doi.org/10.1016/j.matdes.2019.108467

[34] Gao Y, Cao R. Interaction theory of asphalt and rubber. Journal of Wuhan University of Technology. 2010;25:853–855. https://doi.org/10.1007/s11595-010-0107-y

[35] Ibrahim B, Wiranata A, Zahrina I, Sentosa L, Nasruddin N, Muharam Y. Phase separation study on storage of natural-rubber modified bitumen. Applied Sciences. 2024;14. https://doi.org/10.3390/app14083179

[36] Li Y, Abdelmagid AAA, Qiu Y, Yang E, Chen Y. Aging mechanism and microstructure of rice-husk-ash and crumb-rubber modified asphalt. Polymers. 2022;14. https://doi.org/10.3390/polym14101969

[37] Zhao X, Wang S, Wang Q, Yao H. Rheological and structural evolution of SBS modified asphalt under natural weathering. Fuel. 2016;184:242–247. https://doi.org/10.1016/j.fuel.2016.07.018