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Influence of Bitumen Chemistry and Crumb Rubber Pre-Treatment on the Storage Stability and Rheological Performance of Modified Binders

Naeem Aziz Memon[a*], Nur Izzi Md. Yusoff[b], Ahmed Suliman B. Ali[a], Warid Wazien[a], Aawag Mohsen Alawag[a], Zubair Ahmed Memon[c] & Shabir Hussain Khahro[c]

[a]*Faculty of Civil Engineering, Universiti Teknologi MARA, Shah Alam, 40450 Selangor, Malaysia*

[b]*Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*

[c]*Department of Engineering Management, College of Engineering, Prince Sultan University, Riyadh-11586 Saudi Arabia*

[*]*Correspondence: naeemaziz@uitm.edu.my*

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ABSTRACT

The incorporation of crumb rubber (CR) into bitumen offers significant performance and sustainability advantages, yet its widespread adoption is impeded by poor storage stability caused by thermodynamic incompatibility. To address this fundamental challenge, this study investigates the role of bitumen chemistry, specifically the balance of fractions determined via SARA analysis, and the efficacy of crumb rubber pre-treatment in creating a stable binder system. Two base bitumen with distinct chemical compositions (PG 58-28 and PG 70-22) were modified with 10% and 15% CR, comparing two distinct modification philosophies: a palliative approach using styrene-butadiene-styrene (SBS) and a fundamental approach employing devulcanized CR : a conventional stabilization approach using low dosages of styrene-butadiene-styrene (SBS) (1-3%) with untreated CR, and employing pre-treated, devulcanized CR without SBS. Binder performance was thoroughly investigated using storage stability and the Multiple Stress Creep Recovery (MSCR) test. The SARA analysis revealed that the softer bitumen, possessing a higher maltene-to-asphaltene ratio, provided a superior solvent medium for polymer swelling. Despite this, all untreated CRMB blends exhibited severe phase separation (ΔSP>7°C), and the addition of SBS at 1-3% dosages proved insufficient to achieve stability, failing to meet the standard specification criterion (ΔSP≤2.5°C). In contrast, pre-treatment of the CR via thermo-mechanical devulcanization resulted in inherently stable blends (ΔSP<2.5°C) across both bitumen grades, even without the addition of any stabilizing co-polymer. Furthermore, the devulcanized CRMB demonstrated superior rheological performance, achieving an "Extreme" traffic rating (Jnr3.2<0.5 kPa−1) with excellent elastic recovery. Statistical analysis confirmed that the modification strategy is the most significant factor influencing both stability and performance. The findings demonstrate that at the investigated dosages (1–3%), SBS is an inadequate palliative for stabilizing untreated CRMB, establishing CR pre-treatment via devulcanization as a more effective and fundamental engineering solution.

Keywords: Crumb Rubber Modified Bitumen (CRMB); storage stability; Styrene-Butadiene-Styrene (SBS); SARA Analysis; Multiple Stress Creep Recovery (MSCR); devulcanized rubber

INTRODUCTION

The integrity of global transportation infrastructure is paramount for economic vitality, yet highway pavements are deteriorating at an accelerated rate due to escalating traffic volumes, increased axle loads, and severe climatic conditions. Conventional bitumen, the primary binder in flexible pavements, possesses inherent viscoelastic properties that are highly susceptible to temperature fluctuations. This thermal sensitivity manifests as viscoplastic deformation (rutting) in hot climates and brittle cracking in cold climates, both of which significantly curtail the service life of a pavement. To mitigate these failures, the field of pavement engineering has increasingly

turned to the modification of neat bitumen to enhance its rheological and mechanical properties across a broader range of service temperatures and loading conditions (Zhou et al. 2019; Airey 2004).

Among the most effective modifiers are elastomers, such as SBS, and recycled materials like Crumb Rubber (CR) from end-of-life tires (Zhou et al. 2024). SBS is a benchmark high-performance modifier known to form a cross-linked polymer network within the bitumen matrix, which imparts superior strength and elasticity (Memon et al. 2012). The use of CR is recognized not only for its performance enhancements but also as a sustainable technology that provides a value-added application for a problematic waste stream. However, a critical gap exists in the literature between this sustainability potential and the operational reality of pavement infrastructure. While recent studies emphasize the environmental necessity of recycling tires, the widespread adoption of CRMB in critical infrastructure is severely impeded by a fundamental materials science challenge: thermodynamic incompatibility. (Airey, 2004; Dong et al. 2014; Pipintakos et al. 2025). This disconnect frequently renders 'sustainable' binders operationally unsuitable due to phase separation during storage, creating a barrier to their acceptance in high-stakes paving projects (Memon et al. 2021; Allego 2019).

The bitumen matrix, a complex colloidal system, and the largely non-polar polymer or rubber modifiers exhibit poor miscibility. This incompatibility, exacerbated by significant density differences between the CR particles and the liquid bitumen, leads to phase separation when the binder is stored at the elevated temperatures (typically above 160°C) required for production and paving operations (Wang et al. 2021). This issue of storage stability is a significant economic and logistical barrier, often necessitating specialized agitated storage tanks and complicating project logistics (Wieser et al. 2021; Ren et al. 2019; Sienkiewicz et al. 2017; Fu et al. 2007).

This challenge has given rise to two distinct modification philosophies. The first approach is palliative, aiming to manage the symptoms of incompatibility using co-modifiers like SBS, which physically restrain the CR particles and prevent settlement (Zhou et al. 2024). The second, more fundamental approach, involves engineering the CR itself through pre-treatment to improve its intrinsic compatibility with bitumen, thereby addressing the root cause of the problem. Devulcanization, a process that breaks down the rubber's cross-linked structure to make it more reactive, is a prime example of this philosophy (Vasilievici et al. 2024).

While both strategies are known, a direct, systematic comparison of their efficacy is lacking in the current literature. This study aims to fill this research gap by evaluating the performance of SBS as a stabilizing agent for untreated CRMB against an innovative approach using pre-treated, devulcanized CR without SBS. The objective is to provide clear, evidence-based guidance on whether a palliative or a fundamental approach yields a more robust, stable, and high-performing binder, thereby contributing to the development of more durable and sustainable pavement materials.

EXPERIMENTAL DESIGN

CONSTITUENT MATERIALS

The study utilized two distinct base bitumen sourced to represent a range of properties commonly found in pavement construction: a soft, high-penetration grade binder (PG 58-28) and a hard, low-penetration grade binder (PG 70-22). The modifier was a 30-mesh CR derived from scrap truck tires. For the stabilization experiments, a linear SBS triblock copolymer was used as the co-modifier. The fundamental physical properties of the base bitumen are detailed in Table 1.

TABLE 1. Properties and SARA composition of base bitumen grades

Property	Test Method	PG 58-28	PG 70-22
Penetration @ 25°C (dmm)	ASTM D5	115	65
Softening Point (°C)	ASTM D36	42.0	49.5

The data presented in Table 1 clearly distinguishes the physical and chemical nature of the two-base bitumen. The PG 58-28 is characterized as a "soft" binder due to its high penetration value (115 dmm) and low softening point (42.0°C), indicating lower viscosity and stiffness. In contrast, the PG 70-22 is a "hard" binder, with a lower penetration (65 dmm) and higher softening point (49.5°C).

THERMO-MECHANICAL DEVULCANIZATION OF CRUMB RUBBER

A portion of the crumb rubber was pre-treated using a thermo-mechanical devulcanization process to enhance its compatibility with the bitumen matrix. This technique involves subjecting the CR to a combination of high temperature and high shear forces simultaneously in a twin-screw extruder at a barrel temperature of 200°C. Following the mechanism established by Gawdzik et al. (2020), the intense mechanical energy and heat are understood to selectively break the sulfur cross-links (S-S and C-S bonds) within the rubber's vulcanized network

while essentially preserving the integrity of the leading polymer chains (Gawdzik et al. 2020). This process, presented in Figure 1, transforms the rigid, cross-linked CR particles into a more plastic and reactive material, thereby improving its potential for chemical interaction and homogeneous dispersion within the bitumen.

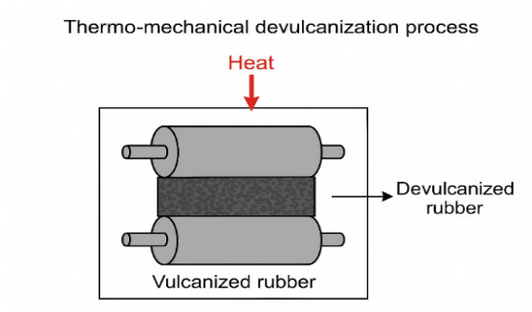

FIGURE 1. Thermo-mechanical devulcanization process

PREPARATION OF MODIFIED BINDERS AND EXPERIMENTAL MATRIX

A complete factorial experimental design was adopted based on the variables of bitumen type, CR content, and modification strategy. Modified binders were prepared using a Silverson high-shear laboratory mixer. The base bitumen was heated to 180°C, after which the specified amounts of untreated CR, Devulcanized CR (D-CR), and SBS were added. The mixture was then blended at 3000 rpm for 90 minutes to ensure thorough dispersion and interaction. This duration was selected to allow sufficient time for full polymer swelling and rubber-bitumen interaction while minimizing the potential for thermal degradation associated with prolonged high-temperature mixing (Airey 2004; Ren et al. 2019). This experimental matrix was designed to isolate the effects of each variable systematically. By testing two base bitumen, two CR contents, and multiple SBS levels, as well as the devulcanized rubber, the study allows for a comprehensive comparison between the palliative (SBS addition) and fundamental (devulcanization) modification approaches across a range of material combinations. A systematic nomenclature was assigned to each of the 22 binder blends to provide clarity, as detailed in Figure 2. A systematic nomenclature was assigned to each of the 22 binder blends to provide clarity, as detailed in Figure 2. In this system, the letter ‘A’ denotes blends using the softer PG 58-28 base bitumen, while ‘B’ denotes those using the harder PG 70-22. For example, ‘CRMB-A-10-3S’ refers to a blend using PG 58-28 bitumen, 10% untreated crumb rubber, and stabilized with 3% SBS.

This distinction allows for a direct, factorial comparison of how the modification strategies (Palliative SBS vs. Fundamental Devulcanization) perform across chemically and rheologically distinct binder systems.

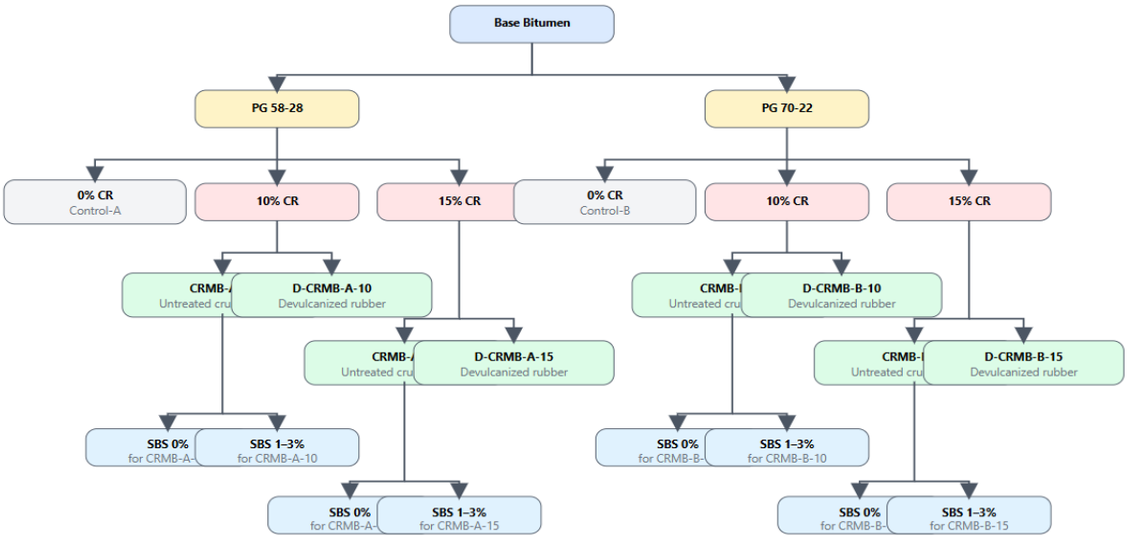

FIGURE 2. Experimental plan and sample nomenclature

BINDER CHARACTERIZATION METHODS

The prepared binders were subjected to a suite of tests to evaluate their chemical composition, storage stability, and high-temperature rheological performance.

SARA Analysis: The base bitumen was fractionated into Saturates, Aromatics, Resins, and Asphaltenes using Thin-Layer Chromatography with Flame Ionization Detection (TLC-FID) [23] according to the IP 469 standard. This analysis provides a fundamental understanding of the chemical makeup that governs binder properties.

Storage Stability: Hot storage stability was evaluated using the standard tube test as per ASTM D7173. Sealed aluminum tubes filled with the modified binder were conditioned vertically in an oven at 163°C for 48 hours. After conditioning, the tubes were cooled and sectioned into top and bottom thirds. The difference in softening point (ΔSP) between the top and bottom sections was used as the primary stability indicator. A binder is typically considered stable if ΔSP≤2.5°C (Yu et al. 2018).

High-Temperature Rheology: The high-temperature performance of short-term aged (Rolling Thin-Film Oven, RTFO) binders was characterized using the Multiple Stress Creep Recovery (MSCR) test (AASHTO T350) on a Dynamic Shear Rheometer (DSR). This test evaluates a binder's resistance to permanent deformation (rutting) and its elastic response under repeated loading. The key performance parameters, non-recoverable creep compliance (Jnr) and percent recovery (%R), were determined at a stress level of 3.2 kPa and a test temperature of 64°C. (Harman et al. 2011; Lesueur et al. 2009).

RESULTS AND DISCUSSION

BASE BITUMEN CHEMISTRY AND MODIFIER-BINDER COMPATIBILITY

The SARA analysis presented in Table 2 provides the chemical foundation for understanding the interaction between the bitumen and the modifiers. Bitumen is not a simple substance but a complex colloidal system where high-polarity asphaltene micelles are dispersed within a lower-polarity, continuous maltene phase (comprising saturates, aromatics, and resins) (Hofko et al. 2016). The stability and solvency of this system are critical for its ability to accept and interact with polymer modifiers.

To quantify the chemical characteristics of the base bitumen beyond simple percentages, two chemo-physical indices were calculated from the SARA data, as shown in Table 2. The Maltene-to-Asphaltene (M/A) ratio provides a direct measure of the balance between the solvent phase (maltenes) and the dispersed phase (asphaltenes) (Baditha et al. 2022; Read et al. 2003). A higher M/A ratio suggests a greater volume of the solvent medium is available to interact with and swell the added polymer. The Colloidal Instability Index (CII) serves as a critical indicator of the bitumen's internal sol-gel structure. It is calculated as the ratio of the dispersed, flocculating phase to the dispersing, peptizing phase , provides a measure of the internal stability of the bitumen itself (Wiehe et al. 2000).

TABLE 2. Chemo-physical indices of base bitumen

Property	PG 58-28	PG 70-22
Maltenes (%)	84.0	82.0
Asphaltenes (%)	16.0	18.0
Maltene/Asphaltene Ratio	5.25	4.56
Colloidal Instability Index (CII)	0.35	0.25

The indices in Table 2 quantify the chemical potential for polymer interaction. The higher M/A ratio of the soft bitumen (5.25) confirms it has a greater proportion of the solvating maltene phase compared to the hard bitumen (4.56). This is significant because the maltenes, particularly the aromatic fractions, are absorbed by the polymer, causing it to swell and form the desired network structure (Lo Presti et al. 2012). A higher M/A ratio, therefore, indicates a greater capacity for this crucial swelling mechanism. The lower CII of the hard bitumen (0.25) suggests it is a more stable colloidal system on its own, but this also implies a less available maltene phase for interacting with external modifiers.

STORAGE STABILITY IMPROVEMENTS

This chemical predisposition is reflected in the storage stability results for the untreated CRMB blends, presented in Figure 3. Although all untreated blends were volatile, with ΔSP values far exceeding the 2.5°C limit, a consistent trend emerged. The blends made with the softer PG 58-28 bitumen (CRMB-A-10 and CRMB-A-15) exhibited slightly lower ΔSP values than their counterparts made with the harder PG 70-22 bitumen. This suggests a more favorable initial interaction in the bitumen with higher solvency, even though this interaction is ultimately insufficient to overcome the strong thermodynamic driving forces of phase separation.

The results in Figure 3 underline the severe instability inherent in untreated CRMB systems. The ΔSP values, ranging from 7.5°C to 9.5°C, are three to four times higher than the typical specification limit of 2.5°C, indicating significant phase separation. This occurs because the dense crumb rubber particles settle out of the lighter bitumen

phase during hot storage (Memon et al. 2021). The data also shows that increasing the CR content from 10% to 15% consistently worsens stability for both bitumen types. This is an expected outcome, as a higher volume of CR particles increases the overall density difference and provides more material to settle, exacerbating the phase separation problem.

Given the inherent instability of the untreated CRMB system, the conventional approach is to introduce a stabilizing co-polymer. Figure 3 also presents the storage stability results for untreated CRMB blends stabilized with increasing dosages of SBS from 1% to 3%. The data clearly indicate that while stability improves with increasing SBS content, none of the blends achieved a stable state ($\Delta SP \leq 2.5°C$). Even at the highest dosage of 3% SBS, the best-performing blend (CRMB-A-10-3S) still exhibited a ΔSP of 3.5°C, well outside the acceptable limit. This failure is not merely a matter of degree but is rooted in the mechanism of SBS stabilization. SBS improves the storage stability of CRMB primarily by forming a continuous, three-dimensional polymer network throughout the bitumen matrix after absorbing the maltene fractions. This network physically entraps the denser CR particles, preventing them from settling due to gravity.

At dosages of 1-3% investigated in this study, the SBS concentration is insufficient to achieve this critical threshold. Instead of forming a restraining network, the SBS exists as a dispersed, swollen phase within the bitumen (Airey, 2004). While this dispersed SBS phase improves the binder's rheology, it is structurally incapable of preventing the large-scale migration and settlement of the CR particles. Therefore, attempting to stabilize CRMB with low dosages of SBS is an inefficient strategy. Achieving stability would require significantly higher, and thus more costly, concentrations of virgin SBS polymer, which would also introduce risks of polymer degradation during prolonged high-temperature storage (Wang et al. 2021).

In contrast to the palliative stabilization approach, pre-treating the CR through thermo-mechanical devulcanization addresses the root cause of instability: thermodynamic incompatibility. Figure 3 presents the storage stability results for the D-CRMB blends, which contain no SBS. This figure presents storage stability results for the binder blends modified with thermo-mechanically devulcanized crumb rubber, which contain no stabilizing co-polymer. The results are striking and unequivocally demonstrate the success of the pre-treatment strategy. All D-CRMB blends, regardless of the base bitumen type or crumb rubber content, achieved a softening point difference (ΔSP) of 2.5°C or lower. This meets the standard specification criteria for storage stability, a feat accomplished without the addition of any SBS or other chemical agents.

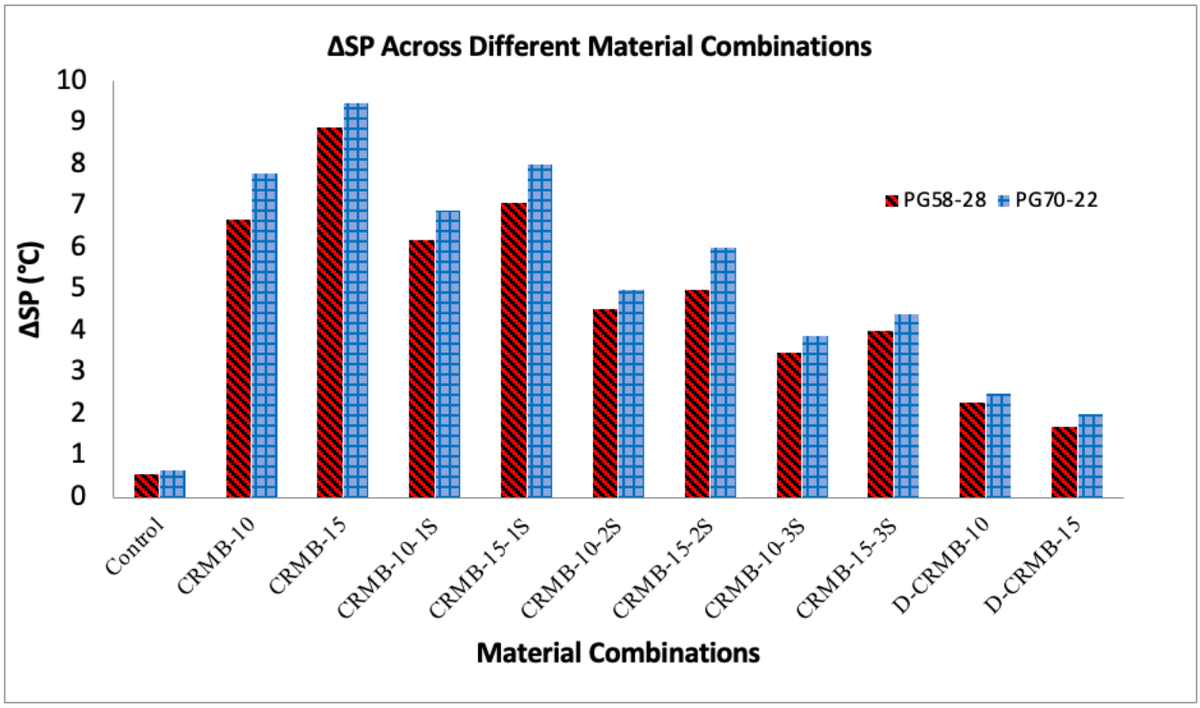

FIGURE 3. Storage stability values for untreated, SBS-stabilized, and devulcanized samples

This outcome marks a significant departure from the behavior of the untreated CRMB blends. The inherent stability of the D-CRMB system stems from addressing the root cause of phase separation: thermodynamic incompatibility. Although direct chemical characterization of the rubber was not performed in this study, the dramatic reduction in phase separation serves as strong phenomenological evidence of the structural change. By effectively transforming the rubber (likely via the scission of sulfur cross-links), the devulcanization process enhanced the surface area and chemical reactivity of the rubber particles. This fundamental change allows for a more thorough and homogeneous interaction with the bitumen's maltene phase, creating a thermodynamically favorable system that actively resists phase separation rather than merely suppressing its symptoms. This enhanced compatibility effectively eliminates the driving force for instability, establishing pre-treatment as a superior engineering solution.

The results in Figure 3 are striking and demonstrate the success of the devulcanization strategy. All D-CRMB blends, regardless of the base bitumen or CR content, achieved ΔSP values of 2.5°C or lower, meeting the standard specification for storage stability. This was accomplished without the addition of any SBS or other stabilizing agents. By breaking the sulfur cross-links in the crumb rubber, the devulcanization process increases the surface area and chemical reactivity of the rubber particles (Vasilievici et al. 2024). This allows for a much more thorough and homogeneous interaction with the bitumen's maltene phase, creating a thermodynamically favorable system that resists phase separation (Gawdzik et al. 2020). This enhanced compatibility effectively eliminates the driving force for instability.

HIGH-TEMPERATURE RHEOLOGICAL PERFORMANCES

The performance benefits of the fundamental devulcanization approach are further solidified by the high-temperature rheological data, with comprehensive MSCR test results for all blends . The devulcanized CRMB blends demonstrate a profound improvement in both rutting resistance and elasticity over their untreated and SBS-stabilized counterparts. Specifically, the D-CRMB binders exhibit exceptionally low non-recoverable creep compliance ($Jnr_{3.2}$) values and very high elastic recovery (%R). For instance, the D-CRMB-A-15 blend achieved a Jnr3.2 value of 0.18 kPa^{-1} with 85% elastic recovery. Similarly, the 10% D-CRMB blends registered. Jnr3.2 values as low as 0.20 kPa^{-1} with over 80% recovery. This level of performance qualifies them for an 'Extreme' traffic loading designation according to AASHTO M332, outperforming even the best blend stabilized with 3% SBS. This superior performance is a direct consequence of the highly integrated and robust polymer network formed by the compatible devulcanized rubber and bitumen. This network provides exceptional resistance to permanent deformation under stress and a rapid, elastic response upon load removal, properties essential for durable pavements in demanding service conditions.

To clearly illustrate the performance leap achieved through devulcanization, Figure 5 compares the key high-temperature rheological parameters, $Jnr_{3.2}$), and %R, for the most critical blends. A lower $Jnr_{3.2}$ value indicates better resistance to rutting, while a higher %R value signifies a more elastic response.

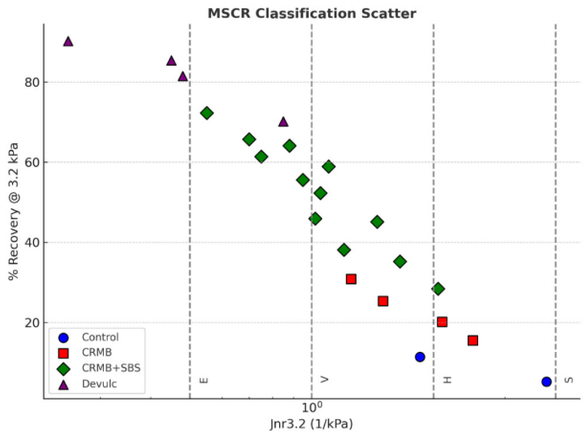

FIGURE 5. Comparison of high-temperature rheological performance at 64°C

The scatter representation in Figure 5 provides a visual justification for the relevance of the modification strategies. The data reveals a clear diagonal trend line migrating from the bottom-right quadrant to the top-left. Physically, this trajectory represents the binder's evolution from a predominantly viscous fluid (characterized by high Jnr and negligible elastic recovery) to an elastomeric solid (characterized by low compliance and high stored energy capacity). The position of a data point along this trend serves as a direct indicator of network integrity: Bottom-Right (Viscous Zone): Dominated by the base bitumen's liquid phase, prone to permanent rutting. Top-Left (Elastic Zone): Dominated by the polymer/rubber network, capable of resisting deformation and recovering shape. Therefore, the 'relevancy' of the devulcanized binders' position in the extreme top-left (e.g., Jnr < 0.2, %R > 80%) is that it confirms a fundamental change in the material's state, distinguishing it from the palliative SBS blends which linger in the transitional middle zone." As single-phase,

homogeneous materials, both control binders exhibited exceptional storage stability, with a softening point difference (ΔSP) of effectively 0°C. This result is expected, as there are no suspended modifiers to induce phase separation during hot storage. However, this physical stability stands in stark contrast to their poor rheological performance, as illustrated in the MSCR test results (Figure 5). Both control binders in the bottom-right of the plot, indicating very high $Jnr_{3.2}$ and extremely low %R. This performance classifies them with a 'Standard' (S) traffic rating, making them suitable only for low-volume traffic applications.

The main point is that although neat bitumen is very stable, it lacks the necessary elastic component to resist permanent deformation at high service temperatures. At 64°C, it acts mainly as a viscous fluid. During the MSCR test, it deforms significantly, and once the stress is removed, it cannot recover its original shape because it has no internal polymer network. This inherent rheological weakness is exactly what modification with crumb rubber and polymers aims to address. Therefore, these control binders act as the critical baseline for measuring the effectiveness of each modification strategy.

The data visualized in Figure 5 reveals a clear progression in performance. The addition of 15% untreated CR to the base bitumen (e.g., CRMB-A-15 vs. Control-A) significantly reduces Jnr3.2, improving rutting resistance. However, the %R remains low, indicating that the binder is stiffer but not substantially more elastic. The addition of 3% SBS (CRMB-A-15-3S) further improves rutting resistance and provides a notable increase in elastic recovery. However, the most profound improvement is observed in the devulcanized blends (D-CRMB-A-15 and D-CRMB-B-15). These binders exhibit exceptionally low $Jnr_{3.2}$ values (e.g., 0.18 kPa^{-1} for D-CRMB-A-15) and very high elastic recovery (e.g., 85% for D-CRMB-A-15). This level of performance qualifies them for an 'Extreme' traffic loading designation ($Jnr_{3.2} < 0.5$ kPa^{-1}) according to AASHTO M332, outperforming even the best SBS-stabilized blend.

A similar trend is observed for the binders modified with 10% CR. The addition of 10% untreated CR (CRMB-A-10 and CRMB-B-10) elevates the performance from a 'Standard' to a 'Heavy' traffic rating. The subsequent addition of SBS shows a dose-dependent improvement; however, even with 3% SBS, the soft bitumen blend (CRMB-A-10-3S) narrowly misses the 'Extreme' rating ($Jnr_{3.2}$=0.51 kPa^{-1}). While the hard bitumen blend with 3% SBS (CRMB-B-10-3S) does achieve an 'Extreme' rating, its performance is still significantly surpassed by the devulcanized blends. The D-CRMB-A-10 and D-CRMB-B-10 binders, with no SBS, exhibit exceptionally low $Jnr^{3.2}$ values (0.25 and 0.20 kPa^{-1}, respectively) and high elastic recovery (80% and 84%).

This comprehensive view across both 10% and 15% CR contents reinforces that engineering the modifier at a molecular level to ensure intrinsic compatibility is a more effective and reliable strategy than simply managing phase separation with additives. This superior performance is a direct result of the highly integrated and robust polymer network formed by the compatible devulcanized rubber and bitumen, which provides exceptional resistance to permanent deformation and a rapid elastic response.

The influence of the base bitumen chemistry, specifically the SARA fractions detailed in Table 2, is clearly discernible in these rheological outcomes. The PG 58-28 binder, characterized by a higher Maltene-to-Asphaltene (M/A) ratio (5.25), provided a superior solvent medium for the devulcanized rubber. This enhanced solvency facilitated the swelling and disentanglement of the rubber chains, promoting the formation of a more robust and integrated polymer network.

This is quantitatively supported by the magnitude of performance improvement: while the PG 58-28 base binder is inherently softer than the PG 70-22, its devulcanized blend (D-CRMB-A) achieved an 'Extreme' traffic rating with elastic recovery values exceeding 80%, effectively bridging the performance gap with the harder binder. This confirms that the thermodynamic compatibility predicted by the SARA analysis translates directly into superior mechanical efficiency, where the polymer network dictates performance rather than the stiffness of the base bitumen.

STATISTICAL VALIDATION OF MODIFICATION STRATEGIES

To provide quantitative validation for the observed differences in performance, a multi-factor Analysis of Variance (ANOVA) was conducted. This statistical test is used to determine whether there are any statistically significant differences between the means of two or more independent groups. In this study, a two-way ANOVA was employed to rigorously assess the impact of the experimental factors (Bitumen Type, CR Content, and Modification Strategy) on the key performance outcomes: storage stability (ΔSP) and high-temperature rutting resistance. The ANOVA works by comparing the variation between the different groups (e.g., different modification strategies) to the variation within each group (Glen, 2025; Minitab, 2022; JMP, 1978).

The key outputs of the ANOVA are the F-statistic and the p-value. The F-statistic, or F-value, is a ratio of the variance between groups to the variance within groups, respectively. A large F-value indicates that the variation between the groups is much larger than the random

variation within the groups, suggesting that the factor has a real effect. The p-value represents the probability of observing the experimental results, or more extreme results, if the factor had no effect (the null hypothesis). A small p-value (typically less than a significance level of 0.05) provides strong evidence against the null hypothesis, allowing us to conclude that the factor has a statistically significant effect on the outcome. The results of the ANOVA are summarized in Table 3.

To interpret these results physically, it is essential to understand the components of the ANOVA. The 'Mean Square Between Groups' represents the variance caused by the deliberate engineering changes (i.e., the signal introduced by changing the modifier). In contrast, the 'Mean Square Within Groups' represents the random experimental error or inconsistency between identical replicates. The large F-values observed in Table 3 (e.g., 128.65 and 315.44) indicate that the 'signal' from the modification strategy is orders of magnitude stronger than the experimental 'noise,' confirming the results are not due to chance. Additionally, the Degrees of Freedom (df) for the Modification Strategy (df=4) is significant as it reflects the statistical accountability for the five distinct binder conditions compared (Control, Untreated, and the distinct stabilization tiers). This ensures that the model rigorously accounts for the complexity of the experimental design rather than oversimplifying the comparison.

Similarly, for rutting resistance (Table 3), the p-values show that all factors are statistically significant. Again, the F-value for Modification Strategy (315.44) is overwhelmingly larger than those for Bitumen Type (17.33) and CR Content (10.57). This provides robust statistical evidence that the choice of modification strategy has the most profound impact on the binder's high-temperature rheological performance. The analysis offers robust, objective validation for the central conclusion of this study: devulcanization is a statistically superior modification strategy compared to the use of untreated rubber, with or without low dosages of SBS.

TABLE 3. ANOVA results for storage stability (Response: ΔSP) and rutting resistance (Response: $Jnr_{3.2}$)

Storage Stability					
Source	df	Sum Sq	Mean Sq	F value	Pr(>F)
Modification Strategy	4	240.15	60.04	128.65	**<0.001**
Bitumen Type	1	2.89	2.89	6.19	0.024
CR Content	1	5.64	5.64	12.09	0.003
Residuals	15	7	0.47		
Rutting Resistance					
Source	df	Sum Sq	Mean Sq	F value	Pr(>F)
Modification Strategy	4	29.85	7.46	315.44	**<0.001**
Bitumen Type	1	0.41	0.41	17.33	<0.001
CR Content	1	0.25	0.25	10.57	0.005
Residuals	15	0.35	0.02		

CONCLUSIONS

This study systematically investigated two distinct strategies for producing stable, high-performance crumb rubber modified bitumen, leading to a series of clear and authoritative conclusions that have significant implications for the pavement industry. First, the research reaffirms that base bitumen chemistry, particularly a higher maltene-to-asphaltene ratio, governs the intrinsic potential for modifier compatibility by providing a superior solvent medium for polymer swelling. However, this inherent potential is not sufficient on its own to guarantee a stable final product when using conventional crumb rubber.

Second, the study unequivocally demonstrates that attempting to stabilize an inherently incompatible system of untreated crumb rubber and bitumen with low dosages of SBS (1-3%) is an ineffective palliative strategy. This approach fails to create the critical, continuous polymer network required to prevent phase separation physically. Consequently, none of the binders produced under this philosophy met standard storage stability specifications. This finding is of critical importance as it challenges common practice, highlighting that such an approach at conventional low dosages does not provide a reliable engineering solution.

In contrast, the study establishes that pre-treating the crumb rubber via thermo-mechanical devulcanization provides a fundamental and superior solution. This strategy addresses the root cause of incompatibility by enhancing the rubber's reactivity at a molecular level. This results in inherently stable blends that not only meet stability requirements but also exhibit exceptional rheological performance, achieving an 'Extreme' traffic rating without

the need for costly virgin stabilizing co-polymers. The statistical analysis provides robust validation, confirming that the choice of modification strategy is the most significant factor dictating both storage stability and high-temperature performance.

RECOMMENDATIONS FOR FUTURE RESEARCH

While this study establishes the superiority of devulcanization for storage stability and high-temperature rutting resistance, further research is required to fully validate this technology for widespread adoption. Future studies should prioritize conducting FTIR and SEM analysis on the devulcanized rubber to chemically validate the mechanism of sulfur bond scission. Moreover, transitioning from laboratory evaluation to full-scale field test sections to monitor long-term durability under actual traffic loading may also be carried out.

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DECLARATION OF COMPETING INTEREST

None.

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