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RESEARCH ARTICLE

Multi-criteria evaluation of rheological performance of modified bitumen using Glover–Rowe index and stiffness parameters

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Abstract: Selecting modified asphalt binders requires balancing cracking resistance, temperature sensitivity and stiffness, which no single rheological indicator captures. This study proposes a multi-criteria rheological evaluation framework for a 40/50 penetration-grade bitumen modified with styrene–butadiene–styrene (SBS, 5%), animal bone ash (AB, 4–6%) and waste cooking oil (WCO, 3–5%). Frequency sweep tests were performed with a dynamic shear rheometer at intermediate temperatures of 15 °C and 25 °C. Cracking susceptibility was assessed with the Glover–Rowe (G–R) index, temperature sensitivity was quantified as the change in G–R between the two temperatures (ΔG–R), and the ratio of complex shear modulus to the sine of the phase angle (G*/sinδ) served as a relative stiffness indicator. The 5% SBS binder showed the lowest G–R values (129 kPa at 15 °C and 180 kPa at 25 °C) and the highest stiffness, but the greatest temperature sensitivity. AB-modified binders exhibited moderate G–R values, improved stiffness and a stable temperature response, whereas WCO-modified binders produced the highest G–R values (up to 298 kPa) and the lowest stiffness. The criteria were integrated using two multi-criteria decision analysis methods, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and the Weighted Sum Model (WSM). Both methods ranked 5% SBS first, AB-modified binders second and WCO-modified binders last, with only minor rank reversals between close alternatives. The framework provides a transparent basis for preliminary binder selection under laboratory, unaged conditions, identifies AB as a promising sustainable mineral modifier, and indicates that WCO requires dosage optimisation or hybrid modification.

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1. Introduction

Asphalt pavement durability is closely tied to the mechanical and rheological characteristics of its binder, particularly in resisting fatigue and intermediate-temperature cracking. With the rising demand for performance and sustainability, integrating polymer and bio-based additives such as styrene–butadiene–styrene (SBS), animal bone ash (AB), and waste cooking oil (WCO) has gained notable interest. Extensive studies have confirmed that SBS-modified binders deliver substantial improvements in fatigue and cracking resistance [1], [2]. In contrast, bio-based modifiers like WCO offer sustainability advantages but sometimes compromise performance. To evaluate such alternatives, integrative methods such as dynamic shear rheometer (DSR) testing and multi-criteria decision analysis (MCDA) are increasingly applied.

SBS has proven highly effective in enhancing binder performance, particularly in improving resistance to cracking and permanent deformation. Previous studies have shown that increasing SBS content leads to lower Glover–Rowe (G–R) index values and improved rutting resistance, as reflected by higher $G^*/\sin\delta$ values [3], [4]. These improvements are primarily attributed to the formation of a continuous elastic polymer network within the binder, which enhances stiffness while maintaining sufficient flexibility. As a result, SBS modification effectively delays crack initiation and propagation while simultaneously increasing resistance to deformation under loading.

Moreover, SBS enhances binder durability under aging conditions. Compared to base asphalt, SBS-modified binders show better resistance to long-term oxidative aging, demonstrated by lower Glover–Rowe (G–R) index values and improved relaxation recovery [5]. Similar findings have been observed in recycled asphalt mixtures, where SBS maintained superior fatigue and thermal cracking resistance after extended aging [6].

On the other hand, WCO—despite its renewability—exhibits inconsistent performance under mechanical stress. While it softens aged binders and improves low-temperature flexibility, several studies have reported increased fatigue susceptibility and higher G–R index values, signaling reduced intermediate-temperature cracking resistance. Specifically, VECD-based fatigue testing of oil-rejuvenated RAP bitumen has shown that fatigue life and failure mechanism are strongly temperature-dependent, indicating that the benefits of oil-based modification on fatigue resistance are not uniform across testing conditions [2], [7], [8].

Mineral fillers such as nanoclay—and potentially AB—also show promise. While direct research on AB is limited, studies on nanoclay-SBS composites reveal enhanced fatigue and rutting resistance. For instance, a 3% nanoclay and 2% SBS blend improved anti-deformation capacity while maintaining acceptable fatigue performance, supporting the potential of mineral additives to improve binder stiffness without sacrificing flexibility [9], [10].

Modern evaluation tools like the G–R index and LAS tests are essential in assessing cracking and fatigue behavior. The G–R index correlates strongly with fatigue cracking and adapts well to different aging conditions. Studies combining G–R and LAS data support their complementary use in assessing binder durability under mechanical and thermal stress [7], [11], [12].

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Recent studies have increasingly focused on bio-binders and hybrid modification strategies to improve the sustainability and performance of asphalt binders. Bio-binders derived from waste oils, agricultural residues, lignin, and other biomass sources have been investigated as modifiers, rejuvenators, or partial binder replacements. These studies generally show that bio-based modifiers can improve flexibility, workability, aging resistance, and environmental performance; however, their effects on stiffness, deformation resistance, and long-term durability are highly dependent on material type, dosage, and blending strategy. Table 1 summarizes representative studies related to bio-binders and hybrid modifier systems.

Table 1. Summary of previous studies on bio-binders and hybrid modifiers

Study	Modifier	Method	Key finding	Gap
[13]	WCO + steel slag	RSM, Marshall mix design	Interdependent effects on mix performance; bitumen content optimized (<0.2% error)	Mixture-level only; no binder cracking/stiffness indices
[14]	WCO + WEO	Chemical, rheological, PG, wheel tracking	Low dosage improved ductility; excess oil reduced stiffness and rutting resistance	Dosage-dependent; no MCDA ranking
[15]	Waste soybean cooking oil (microcapsules)	pH-responsive microencapsulation	Controlled release improved aging resistance and self-healing	Fabrication complexity limits practical use
[16]	WEO	Penetration, softening point, Marshall, stiffness	Optimum 0.2% WEO gave highest Marshall stability (17.71 kN); excess WEO reduced stiffness	No binder-level cracking indices or MCDA
[17]	Lignin	Review (incl. LCA, economics)	10% lignin favorable for stiffness and aging resistance	Excess lignin increases brittleness
[18]	Biomass bio-oils	Penetration, viscosity, DSR, FTIR, SEM-EDS	Restored viscoelastic balance of aged binders; reduced carbonyl/sulfoxide groups	Excess rejuvenator compromises high-temp stability
[19]	Bio-binders (waste oils, animal waste, residues)	Comprehensive review	Support circular economy; variable rheological performance	Limited field validation
[20]	Bio-binders (general)	Bibliometric analysis (1980–2025)	Trend toward integrated performance–sustainability frameworks	Standardization and durability data still lacking

Note: RSM = response surface methodology; WEO = waste engine oil; PG = performance grade; LCA = life-cycle assessment; DSR = dynamic shear rheometer; FTIR = Fourier-transform infrared spectroscopy; SEM-EDS = scanning electron microscopy with energy-dispersive X-ray spectroscopy; MCDA = multi-criteria decision analysis

As shown in Table 1, prior work on bio-based and hybrid modifiers has largely evaluated performance at the mixture level or relied on single-method testing, with limited attention to binder-level cracking indices, temperature sensitivity, and stiffness behavior in combination. Several studies also report strongly dosage-dependent outcomes, where low modifier contents improve flexibility or aging resistance while higher contents compromise stiffness or deformation resistance. Few studies, however, integrate these rheological indicators within a structured decision-making framework capable of ranking binder formulations objectively. This gap motivates the present study's use of the G–R index, $G^*/\sin\delta$, and ΔG–R together with an MCDA approach to provide a more holistic and comparative basis for binder selection.

To support sustainable and balanced binder selection, researchers have employed MCDA tools such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and the Weighted Sum Model (WSM). These approaches synthesize performance metrics like G–R, stiffness, and fatigue life to identify optimal binder formulations. One study successfully applied MCDA to compare various polymer and rejuvenator combinations, illustrating its value in handling performance trade-offs [12].

The aim of this study is to provide a comprehensive evaluation of the rheological performance and cracking susceptibility of asphalt binders modified with polymer-based styrene–butadiene–styrene (SBS) and bio-based additives, namely animal bone ash (AB) and waste cooking oil (WCO), under intermediate service temperatures. The analysis focuses on characterizing binder behavior through the Glover–Rowe (G–R) index, its temperature sensitivity (ΔG–R), and the stiffness-related parameter $G^*/\sin\delta$, derived from frequency sweep tests at 15 °C and 25 °C. In addition, the study applies two complementary MCDA methods, TOPSIS and WSM, to rank the modified binders and verify the consistency of the decision-making outcomes. By comparing the results obtained from these two approaches, the study evaluates the robustness of the proposed ranking framework and provides a more transparent basis for selecting durable and sustainable binder formulations.

Several previous studies have addressed individual components of this evaluation problem, but not in combination. For instance, prior MCDA applications to binder selection have focused on a single modifier class, such as polymer and rejuvenator combinations [12], without incorporating temperature sensitivity as an explicit ranking criterion. Other studies

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have examined SBS, AB, or WCO modification individually using G–R or stiffness indicators [3], [4], [7], but did not place synthetic and bio-based modifiers within the same comparative decision framework, nor did they verify ranking outcomes using more than one MCDA technique.

The novelty of the present study lies in integrating three rheological dimensions, cracking susceptibility (G–R at two intermediate temperatures), temperature sensitivity (ΔG–R), and stiffness-related deformation resistance ($G^*/\sin\delta$), into a single, temperature-aware MCDA framework that evaluates synthetic (SBS) and bio-based/waste-derived (AB, WCO) modifiers side by side. Rather than relying on a single indicator or a single decision-making method, this study applies both TOPSIS and WSM to the same criteria set, allowing ranking consistency to be explicitly verified rather than assumed. This combination of multi-temperature rheological characterization, cross-modifier-class comparison, and dual-method MCDA validation distinguishes the proposed framework from prior single-indicator or single-method approaches and provides a more transferable basis for binder selection across both performance and sustainability considerations.

Overall, this study offers a structured and transferable approach for binder selection that bridges rheological characterization with decision-based evaluation, contributing to the development of performance-oriented and sustainable pavement materials.

2. Materials and Methods

2.1 Binder Preparation and Modifiers

The base binder used in this study was a penetration grade 40/50 neat bitumen. The measured penetration value of 49 (0.1 mm) indicates a medium consistency binder suitable for conventional pavement applications. The ductility value exceeding 150 cm reflects a high capacity for deformation, suggesting good resistance to cracking under tensile stresses. The softening point of 50 °C indicates moderate temperature susceptibility and adequate resistance to elevated service temperatures. The flash point of 245 °C confirms safe handling and mixing conditions during binder preparation. The density of the binder was measured as 1.02 g/cm³, which is typical for conventional paving bitumen. Additionally, the rotational viscosity at 135 °C was determined as 0.488 Pa·s, indicating suitable workability during mixing and compaction processes. Thin Film Oven Test (TFOT) results showed a retained penetration of 80%, exceeding standard requirements and indicating good short-term aging resistance. The penetration index (PI) of −1.25 suggests moderate temperature susceptibility. These baseline properties characterize the inherent behavior of the neat binder and serve as a reference for evaluating the effects of subsequent modifications.

SBS was incorporated as an elastomeric modifier since it has long-established capacity to enhance elasticity, stiffness, and fatigue resistance. Radial structured SBS containing 30% styrene, which is commercially available, was used. The polymer at 5% weight of the bitumen was polymer-modified and mixed using a high-shear mixer at 180 °C for 60 minutes at 1000 rpm to achieve homogeneity.

Animal Bone Ash (AB) was produced by calcining waste animal bones at 850 °C for 3 hours in a muffle furnace to remove organic matter and obtain a white, calcium-rich ash primarily composed of hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$). The obtained ash was sieved to a particle size of ≤75 μm to ensure uniform dispersion within the binder. AB was incorporated at 4%, 5%, and 6% dosages by weight of bitumen.

Waste Cooking Oil (WCO) was retrieved from household wastes, purified to remove food particles, and heated at 110 °C to remove moisture. WCO was incorporated as a softening agent in the dosages of 3%, 4%, and 5% of the weight of the bitumen. Blending of WCO was performed at 135 °C for 20 minutes at low shear mixing to prevent degradation of the fatty acids present in WCO.

All modified binders were conditioned at room temperature for 24 hours prior to testing to ensure stabilization. Rheological characterization was conducted using a dynamic shear rheometer (DSR) in accordance with AASHTO T315. Frequency sweep tests were performed to determine the complex modulus and phase angle, from which the Glover–Rowe (G–R) index and the stiffness parameter $G^*/\sin\delta$ were evaluated.

2.2 Methodological Framework

The experimental methodology adopted in this study was designed to evaluate the rheological performance of asphalt binders modified with polymer-based and sustainable additives. As illustrated in the flowchart (Figure 1), the study began with the preparation of binders modified with styrene–butadiene–styrene (SBS), animal bone ash (AB), and waste cooking oil (WCO) at different dosages. The prepared binders were then subjected to rheological testing to characterize their viscoelastic behavior at selected temperatures. Based on the obtained data, key performance indicators, including the Glover–Rowe (G–R) index, its temperature sensitivity, and the stiffness parameter $G^*/\sin\delta$, were determined. Finally, these parameters were integrated into a MCDA framework using the TOPSIS and WSM methods to evaluate and rank binder performance.

This study focuses on the rheological characterization and MCDA-based ranking of unaged binders, establishing a baseline framework for evaluating cracking susceptibility, temperature sensitivity, and stiffness across modifier types and dosages. Aging is well established to substantially alter G–R index values and is therefore treated as a distinct research dimension rather than a secondary variable within the present scope. Evaluating rolling thin-film oven (RTFO) short-term aging and pressure aging vessel (PAV) long-term aging in combination with the eight binder formulations and two test temperatures used here would considerably expand the experimental matrix and is reserved for dedicated follow-up work, allowing aging effects to be isolated and analyzed with the depth they require rather than treated as a single additional variable within the current MCDA framework.

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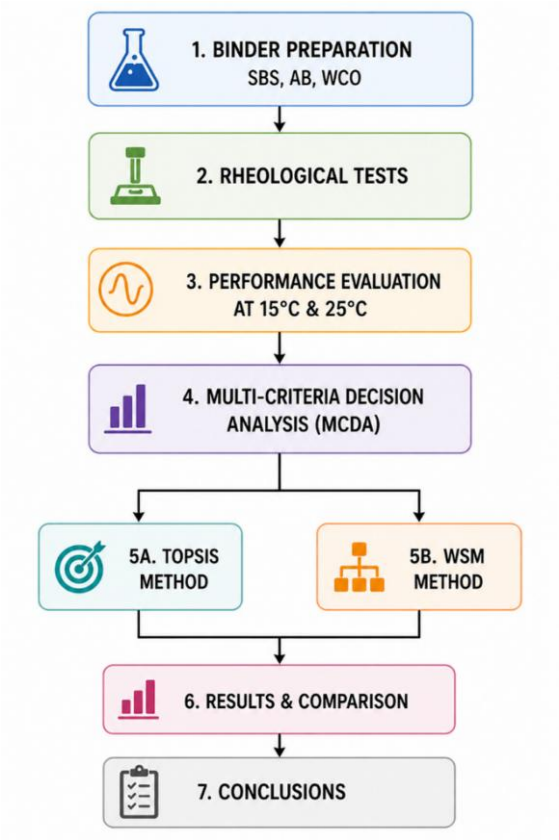


Figure 1. Flowchart of the methodological framework for binder preparation, rheological testing, and MCDA evaluation

2.3 Rheological Testing

2.3.1 Frequency sweep test

The rheological behavior of all binder samples was evaluated using a DSR equipped with parallel plate geometry (25 mm diameter and 1 mm gap) (Figure 2). The DSR equipment setup and plate geometry followed AASHTO T315; however, the frequency sweep tests conducted at intermediate temperatures (15 °C and 25 °C) for determination of the Glover–Rowe index were performed under strain-controlled conditions following established research protocols, ensuring that all measurements remained within the linear viscoelastic (LVE) range.



Figure 2. DSR testing setup and representative frequency sweep output data used for rheological characterization

Experiments were performed at two intermediate service temperatures, 15 °C and 25 °C, which are representative of conditions where cracking susceptibility becomes critical. The angular frequency was varied logarithmically from 0.1 to 100 rad/s to simulate a wide range of traffic loading conditions, from slow-moving heavy loads to high-speed traffic.

The primary rheological parameters obtained from the frequency sweep tests include the complex shear modulus $G^*$and the phase angle δ. The parameter G^*(Pa) represents the total resistance of the binder to deformation under shear

loading, while the phase angle δ(in degrees) characterizes the relative contribution of elastic and viscous components, where lower values indicate a more elastic response.

Although $G^*/\sin\delta$ was originally established as a rutting criterion at high pavement temperatures (46–82 °C) under AASHTO T315, its use as a comparative stiffness indicator at intermediate temperatures is supported by precedent in the literature. Hajj et al. [21] demonstrated that stiffness-related parameters retain diagnostic value for distinguishing binder behavior at intermediate service temperatures, where deformation resistance remains relevant to performance even though rutting is not the dominant distress mechanism. Similarly, Texas Department of Transportation (TxDOT) testing protocols have incorporated DSR-based stiffness measurements outside the standard high-temperature range to supplement conventional PG grading [22].

In the present study, $G^*/\sin\delta$ is not applied as an absolute rutting-threshold criterion, since the Strategic Highway Research Program (SHRP) specification limits were developed and validated specifically for high-temperature conditions and are not transferable to 15 °C and 25 °C. Instead, $G^*/\sin\delta$ is used strictly as a relative, within-study comparative indicator: all binders were tested under identical frequency sweep conditions, temperatures, and aging states, so that differences in $G^*/\sin\delta$ among formulations reflect genuine differences in stiffness and elastic-to-viscous response rather than measurement artifacts. This relative-comparison approach is consistent with the objective of the MCDA framework, which ranks binders against one another rather than against fixed external thresholds. The parameter is therefore repurposed here as a discriminating criterion within a multi-criteria ranking exercise rather than as a rutting-performance predictor, and it is interpreted accordingly throughout the manuscript.

Glover–Rowe (G–R) index is an indicator of cracking susceptibility at intermediate temperatures, calculated using Eq. (1):

$$\mathrm{G-R} = G^* \cdot \frac{\cos^2\delta}{\sin\delta} \tag{1}$$

where δ is converted from degrees to radians prior to computation. This index reflects the balance between stiffness and flexibility and is sensitive to binder brittleness. According to the literature, G–R values below 180 kPa indicate satisfactory cracking performance, while values above 600 kPa are associated with a high risk of block cracking, particularly in aged pavements [23], [24].

It is acknowledged that each DSR frequency sweep test required approximately 4–5 hours per binder per temperature; given the number of formulations and temperatures evaluated, replicate testing was not performed within the scope of this study. The primary objective of this work is not to establish statistically validated absolute differences between individual binders, but to develop and demonstrate an integrated multi-criteria ranking framework that combines cracking susceptibility, temperature sensitivity, and stiffness indicators into a single, transparent decision-support tool. Within this context, the MCDA methods (TOPSIS and WSM) provide a degree of inherent robustness to measurement variability, since binder rankings are derived from the convergence of multiple criteria rather than from a single statistically tested parameter. Replicate testing and formal statistical validation would nonetheless strengthen confidence in the absolute rheological values reported and are recommended as a complementary direction for future work.

2.4 Multi-Criteria Decision Analysis (MCDA)

The performance of asphalt binders is governed by multiple rheological parameters that represent different aspects of mechanical behavior, including cracking resistance, temperature sensitivity, and deformation resistance. These parameters may exhibit competing trends; therefore, an MCDA approach was adopted to provide a comprehensive and balanced evaluation of binder performance.

In this study, two widely used MCDA techniques, TOPSIS and WSM, were implemented to rank the performance of the modified binders. The evaluation was based on key rheological indicators, including the Glover–Rowe index at 15 °C and 25 °C, its temperature sensitivity (ΔG–R), and the stiffness parameter $G^*/\sin\delta$.

2.4.1 Data normalization

To enable meaningful comparison among parameters with different units and scales, all criteria were normalized using the min–max normalization method. The criteria were classified based on their performance preference, as follows:

- **Cost criteria (lower is better):** G–R (15 °C), G–R (25 °C), and ΔG–R.
- **Benefit criterion (higher is better):** $G^*/\sin\delta$.

For cost criteria, normalization was performed using Eq. (2):

$$x'_i = \frac{x_{\max} - x_i}{x_{\max} - x_{\min}} \tag{2}$$

For benefit criteria, normalization was calculated using Eq. (3):

$$x'_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \tag{3}$$

where x'_i is the normalized value of alternative i, x_i is its measured value, and $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of the criterion across all binders. This transformation rescales all variables to a dimensionless range between 0 and 1, allowing for direct comparison and integration within the MCDA framework.

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2.4.2 Technique for order preference by similarity to ideal solution (TOPSIS)

TOPSIS ranks alternatives based on their Euclidean distance from an ideal (best) and anti-ideal (worst) solution in the normalized decision space [25]. The relative closeness to the ideal solution was calculated using Eq. (4):

$$C^* = \frac{D^-}{D^- + D^+} \tag{4}$$

where D^+ is the Euclidean distance of each alternative from the positive ideal solution and D^- is the Euclidean distance from the negative ideal (anti-ideal) solution. Alternatives with higher C^* values, indicating closer proximity to the ideal solution, are considered more favorable.

2.4.3 Weighted sum model (WSM)

To complement the TOPSIS analysis, a Weighted Sum Model (WSM) was implemented to evaluate the overall performance of the binders. In this approach, the final score of each alternative is calculated as a weighted sum of the normalized criteria.

The performance score for each binder, S_i, was determined using Eq. (5):

$$S_i = \sum_{j=1}^{n} w_j \cdot x'_{ij} \tag{5}$$

where w_j represents the weight assigned to the j-th criterion, x'_{ij} is the normalized value of the i-th alternative for that criterion, and n is the number of criteria.

In this study, equal weights (w_j = 0.25) were assigned to all four criteria, G–R at 15 °C, G–R at 25 °C, ΔG–R, and $G^*/\sin\delta$, to ensure an unbiased and balanced evaluation. This assumption reflects the equal importance of cracking resistance, temperature sensitivity, and deformation resistance in assessing overall binder performance.

Equal weighting was adopted as a transparent and reproducible baseline in the absence of an established, field-validated weighting scheme specifically calibrated for this combination of cracking, temperature-sensitivity, and stiffness indicators. This approach is consistent with standard MCDA practice, where equal weights are commonly used as a neutral starting point when no prior consensus exists on the relative importance of criteria, avoiding the introduction of subjective bias that more elaborate weighting schemes (e.g., AHP-derived or expert-elicited weights) can carry without independent validation [25]. While equal weighting ensures that cracking resistance, temperature sensitivity, and deformation resistance each contribute proportionally to the overall ranking, it is acknowledged that actual field priorities may vary with climate and traffic conditions, where cracking indicators may warrant greater emphasis in cold climates and stiffness parameters in hot climates. Climate-calibrated weighting is therefore identified as a necessary refinement for field-specific implementation of the proposed framework (see Section 3.6), with the equal-weight scheme presented here serving as the baseline configuration against which such application-specific calibrations can be compared.

The resulting WSM-based scores were used to rank the binders, where higher values indicate better overall performance. The results were subsequently visualized using bar charts to facilitate comparison among alternatives.

The combined application of TOPSIS and WSM enhances the robustness of the MCDA framework by providing consistent ranking trends across different evaluation methods, thereby supporting reliable and evidence-based material selection.

3. Results and Discussion

3.1 Glover–Rowe Index at 15 °C and 25 °C

The Glover–Rowe Index (G–R), determined from low-frequency values of the complex modulus and phase angle at 0.005 rad/s, is widely used to assess binder susceptibility to fatigue and block cracking at intermediate temperatures. In this study, G–R values were evaluated at 15 °C and 25 °C, representing typical service temperatures under moderate climatic conditions.

As shown in Figure 3, the G–R values at 15 °C revealed clear differences among the binders. The 5% SBS and 6% AB binders exhibited the lowest values, 129 kPa and 145 kPa, respectively, both well below the commonly accepted fatigue cracking threshold of 180 kPa. These results indicate a significant improvement in resistance to microcrack initiation at intermediate-low temperatures. This reduction is consistent with Alani et al. [3] and Almusawi et al. [4], who similarly reported substantial G–R decreases with increasing SBS content, attributed to the formation of a continuous elastomeric network. In contrast, the unmodified binder and all WCO-modified binders showed higher G–R values exceeding 250 kPa, with the 5% WCO binder recording the highest value of 298 kPa - significantly above the fatigue cracking threshold of 180 kPa and the highest among all tested formulations - while remaining well below the block cracking threshold of 600 kPa reported in the literature [26]–[29].

To further examine temperature effects, G–R values at 25 °C are presented in Figure 4. The variation of G–R with temperature was found to be non-uniform across binder types, reflecting the combined influence of reduced stiffness and increased phase angle. While the unmodified binder showed a slight reduction in G–R (220 kPa), SBS- and AB-modified binders exhibited values near or slightly above the fatigue threshold, with 5% SBS and 6% AB recording 180 kPa and 185 kPa, respectively. WCO-modified binders maintained relatively high G–R values ranging from 260 kPa to 285 kPa, indicating limited resistance to fatigue cracking at elevated intermediate temperatures.

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The observed trends demonstrate the beneficial role of SBS and AB in enhancing binder performance. SBS improves elasticity through polymer network formation, while AB contributes to increased stiffness and structural stability. In contrast, WCO-modified binders, although more flexible, exhibit reduced fatigue resistance due to lower modulus and higher phase angle.

These results establish a clear cracking-resistance hierarchy (SBS ≈ AB > unmodified > WCO), examined further in terms of temperature sensitivity (Section 3.2) and stiffness (Section 3.3).

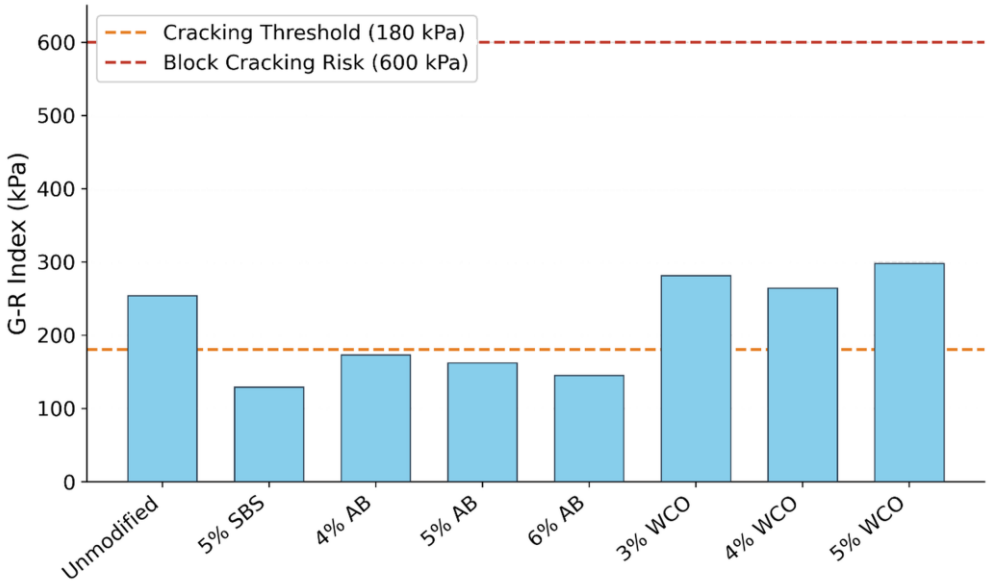


Figure 3. Glover–Rowe index of all binders at 15 °C

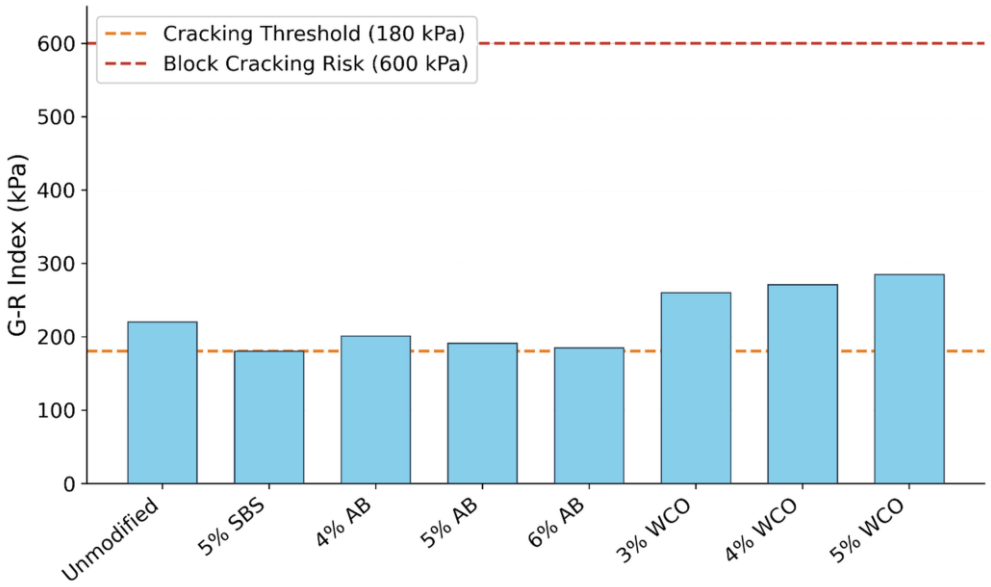


Figure 4. Glover–Rowe index of all binders at 25 °C

3.2 Temperature Sensitivity of Glover–Rowe Index

To further assess the stability of binder performance across temperatures, the temperature sensitivity of the Glover–Rowe (G–R) index was evaluated using both the difference and normalized ratio between values at 25 °C and 15 °C, as defined in Eqs. (6) and (7):

$$\Delta G - R = G - R_{25\,^{\circ}C} - G - R_{15\,^{\circ}C} \tag{6}$$

$$G - R \text{ ratio} = \frac{G - R_{25\,^{\circ}C}}{G - R_{15\,^{\circ}C}} \tag{7}$$

As shown in Figure 5, the binders exhibit non-uniform temperature sensitivity, with both positive and negative ΔG–R values observed. The 5% SBS binder recorded the highest positive ΔG–R, indicating a noticeable increase in G–R with temperature. This suggests that although SBS significantly enhances cracking resistance at lower temperatures, its

rheological response becomes more temperature-dependent at higher service conditions. This behavior can be attributed to the temperature-sensitive nature of the polymer network, where elasticity reduces with increasing temperature. This pattern is consistent with Shi et al. [5], who reported that SBS-modified binders show measurable shifts in rheological response with temperature and aging state, reflecting the inherent thermal sensitivity of the polymer network rather than a deficiency specific to this formulation.

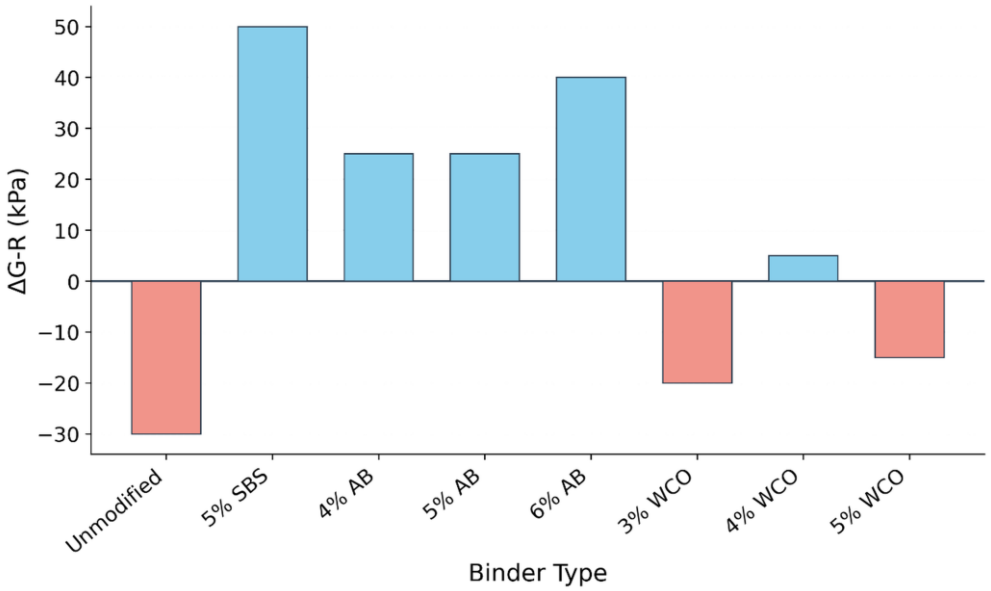


Figure 5. Temperature sensitivity of Glover–Rowe index (ΔG–R) for all binders

The AB-modified binders displayed moderate positive ΔG–R values, indicating a controlled sensitivity to temperature changes. Among them, the 6% AB binder showed a slightly higher increase compared to lower dosages, reflecting the influence of increased stiffness and structural reinforcement. These results suggest that AB provides a relatively stable performance across temperatures while still benefiting cracking resistance.

The unmodified binder and several WCO-modified binders exhibited negative or near-zero ΔG–R values, indicating that their G–R decreases slightly or remains unchanged with increasing temperature. This behavior reflects thermal softening at 25 °C, which reduces binder stiffness and lowers the G–R value marginally. However, this should not be interpreted as favorable performance — these binders already exhibit high absolute G–R values at 15 °C, indicating significant crack susceptibility at lower intermediate temperatures. The slight reduction at 25 °C does not bring their G–R values within acceptable limits; rather, it reflects a binder that is crack-susceptible across the entire intermediate temperature range. Therefore, a negative ΔG–R in this context indicates thermal softening of an already poorly performing binder, not improved cracking resistance.

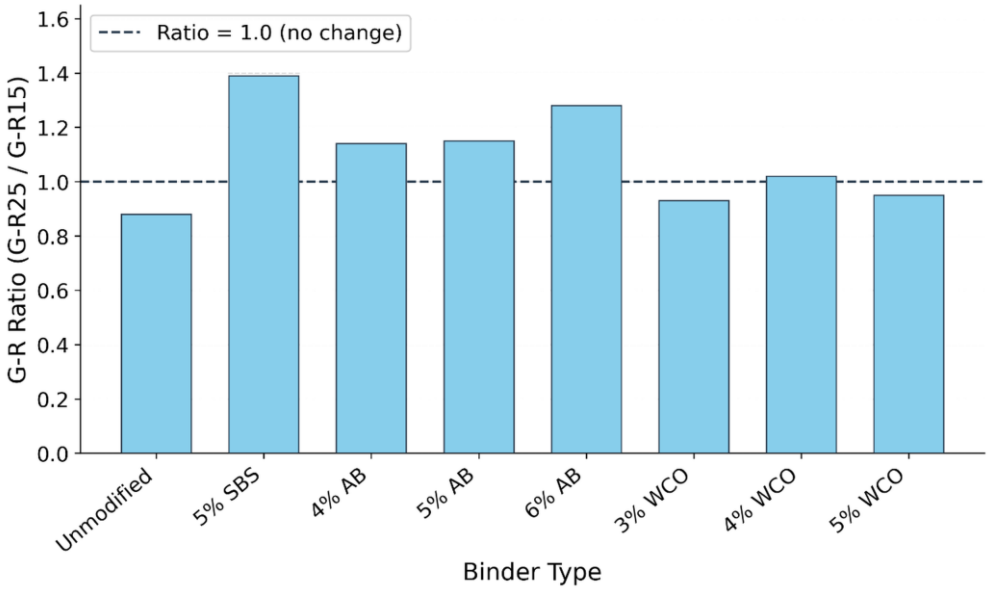


Figure 6. Normalized G–R ratio ($G–R_{25}/G–R_{15}$) for all binders

The normalized trends presented in Figure 6 further support these observations. The G–R ratio for SBS-modified binders exceeds unity, confirming their higher sensitivity to temperature variation. The AB-modified binders show ratios

moderately above 1, indicating balanced performance. In contrast, the WCO-modified binders and the unmodified binder exhibit ratios close to or below 1, reflecting lower temperature sensitivity but not necessarily improved performance.

These results indicate that temperature sensitivity and absolute cracking resistance must be interpreted jointly rather than independently, a distinction that becomes particularly relevant when these indicators are combined with stiffness measurements in Section 3.3 and the MCDA framework in Section 3.5.

3.3 Stiffness and Deformation Resistance Evaluation Using $G^*/\sin\delta$

The parameter $G^*/\sin\delta$, obtained from frequency sweep tests, is widely recognized as an indicator of binder stiffness and resistance to deformation under loading. As discussed in Section 2.3.1, $G^*/\sin\delta$ is interpreted here as a relative comparative indicator rather than an absolute rutting criterion, and the same caveat regarding SHRP threshold non-transferability applies to the results below.

In this study, the variation of $G^*/\sin\delta$ with angular frequency for all binders at 15 °C and 25 °C is presented in Figures 7 and 8, respectively. For comparison, values at a representative angular frequency of 10 rad/s were selected to evaluate the relative performance of the binders.

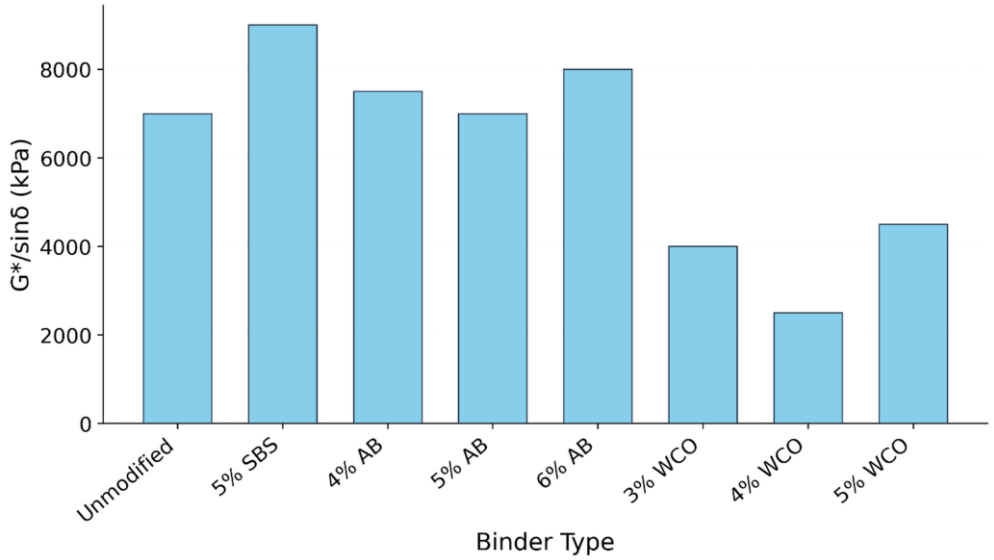


Figure 7. Variation of stiffness parameter $G^*/\sin\delta$ with angular frequency at 15 °C

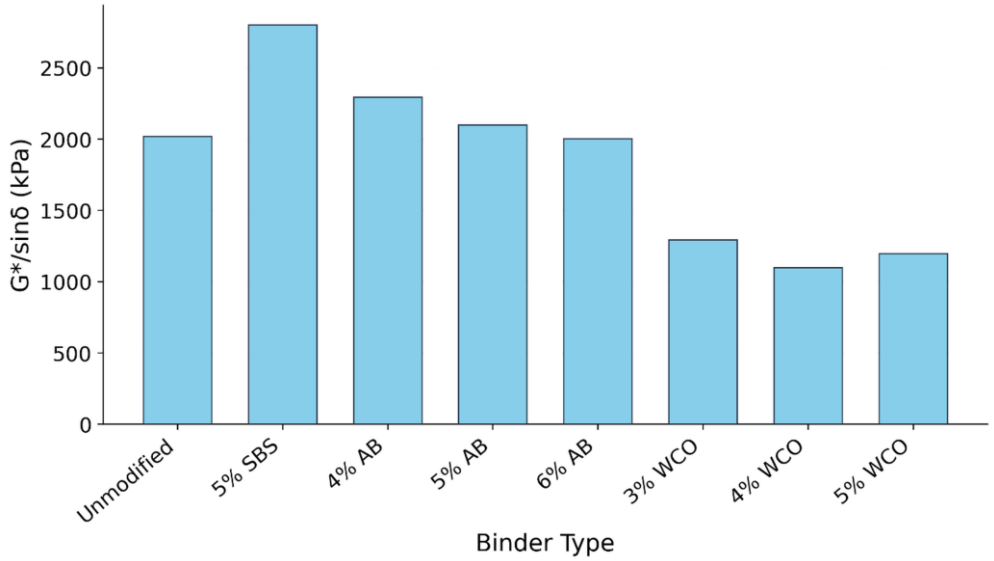


Figure 8. Variation of stiffness parameter $G^*/\sin\delta$ with angular frequency at 25 °C

At 15 °C (Figure 7), the overall magnitude of $G^*/\sin\delta$ increased substantially for all binders due to reduced temperature and increased stiffness. The ranking trend remained consistent, with SBS-modified binders maintaining the highest values, followed by AB-modified binders, while WCO-modified binders showed the lowest performance. Notably, the increase in stiffness at lower temperatures was more pronounced for SBS and AB binders, indicating their ability to retain structural integrity under varying thermal conditions. The AB-modified binders provide a balanced response, contributing to both stiffness and stability, consistent with the authors' related prior work on AB-modified binders [10], where moderate

filler dosages similarly produced stable stiffness gains without excessive embrittlement. WCO-modified binders, despite improving workability and low-temperature flexibility, exhibited reduced deformation resistance.

At 25 °C, as shown in Figure 8, all binders exhibited an increasing trend of $G^*/\sin\delta$ with frequency, reflecting the typical viscoelastic behavior of asphalt binders. Among the tested formulations, the 5% SBS-modified binder demonstrated the highest $G^*/\sin\delta$ values, indicating superior stiffness and elastic recovery capacity. This improvement is attributed to the formation of a continuous polymer network within the binder matrix, which enhances load-bearing capacity and reduces viscous flow. The AB-modified binders (4–6%) showed moderate values, suggesting a balanced improvement in stiffness without excessive rigidity. In contrast, the WCO-modified binders exhibited significantly lower values, confirming the softening effect of waste cooking oil and its tendency to reduce deformation resistance.

These stiffness trends parallel the cracking-resistance hierarchy established in Section 3.1, reinforcing the rationale for combining both indicators within the MCDA framework that follows.

3.4 Mechanistic Interpretation of Rheological Behavior

The rheological trends described above can be further interpreted in terms of the underlying viscoelastic structure and modifier-binder matrix interactions.

SBS modification improves both cracking resistance and stiffness primarily through the formation of a continuous, physically crosslinked polymer network within the binder matrix [3], [4]. The styrene end-blocks of the SBS copolymer aggregate into discrete domains that act as physical crosslink points, while the polybutadiene mid-blocks form flexible, elastically deformable chains connecting these domains. At 5% dosage, this network becomes sufficiently continuous to shift the binder's response toward more elastic behavior, consistent with the lower phase angle and higher $G^*/\sin\delta$ observed for the SBS-modified binder. The elevated ΔG–R for this binder reflects the temperature sensitivity inherent to a physical (rather than chemical) network: the styrene domains soften progressively as temperature approaches the polymer's glass transition region, partially relaxing the network and shifting the response toward more viscous behavior at 25 °C relative to 15 °C.

AB modification acts through a different mechanism, behaving as a rigid mineral filler rather than an elastomeric network former [10]. The fine hydroxyapatite particles likely interact with the binder through physical adsorption and interfacial bonding with the polar asphaltene and resin fractions, restricting molecular mobility and increasing stiffness without introducing a separate elastic phase. This filler-reinforcement mechanism is comparatively less temperature-dependent than polymer network behavior, since it does not rely on a glass transition or chain-mobility threshold, which explains the lower ΔG–R and more stable performance of AB-modified binders relative to SBS.

WCO modification follows a plasticizing rather than reinforcing pathway [2], [7], [14]. The fatty acid chains in WCO are compatible with the maltene fraction of the binder, increasing the proportion of low-molecular-weight, mobile components and weakening the network of polar interactions among asphaltenes and resins that normally contributes to stiffness. This plasticization lowers both the complex modulus and the elastic component of the binder response, manifesting as reduced $G^*/\sin\delta$ and elevated phase angle, and explains the consistently higher G–R values observed for WCO-modified binders despite their improved low-temperature flexibility.

Taken together, these interpretations indicate that the three modifiers act through distinct structural pathways, polymer network formation (SBS), particulate reinforcement (AB), and matrix plasticization (WCO), and that these pathways, rather than dosage alone, govern the observed differences in viscoelastic behavior, temperature sensitivity, and overall rheological performance.

3.5 Multi-Criteria Decision Analysis Results

The MCDA results obtained from both TOPSIS and WSM methods demonstrate a high level of consistency, supporting the consistency of the multi-criteria evaluation framework under the adopted criteria and weighting scheme (Figures 9 and 10). Both methods identified the 5% SBS binder as the clear top performer, with a margin over all other formulations that held regardless of the ranking technique used. The AB-modified binders (4–6%) consistently occupied the second performance tier under both methods, while the WCO-modified binders consistently ranked lowest, reflecting agreement at both extremes of the ranking.

Despite this overall agreement, two minor rank reversals were observed among closely performing alternatives. The unmodified binder and the 6% AB binder switched relative positions between the two methods, as did the 4% WCO and 5% WCO binders within the lowest-performing group. These reversals reflect the differing mathematical structure of the two methods: TOPSIS ranks alternatives by geometric distance from the ideal and anti-ideal solutions, capturing non-linear trade-offs among criteria, whereas WSM aggregates normalized criteria linearly, making it more sensitive to compensatory effects between strongly and weakly performing indicators. Because both reversals occur between alternatives with closely spaced overall scores, they do not affect the broader ranking pattern. The agreement at the extremes, the clear superiority of 5% SBS and the consistently poor performance of WCO modification, together with the minor sensitivity observed among closely performing mid-tier binders, indicates that the proposed MCDA framework is robust overall while still benefiting from the use of two complementary methods when distinguishing binders of similar performance.

The analysis clearly identifies the 5% SBS-modified binder as the best-performing formulation. This superior ranking is attributed to its combined performance across all criteria, including low Glover–Rowe values at both temperatures and the highest $G^*/\sin\delta$, reflecting strong resistance to both cracking and permanent deformation. Although the SBS-modified

binder exhibited relatively higher temperature sensitivity in terms of ΔG–R, its overall rheological performance remained dominant due to its significantly improved stiffness and elastic behavior.

The AB-modified binders (4–6%) consistently ranked in the second tier, with 5% AB and 4% AB showing particularly balanced performance. These binders demonstrated moderate G–R values and acceptable stiffness levels, resulting in stable performance across temperature conditions. Unlike SBS, AB modification provided a more uniform response, with lower sensitivity to temperature variations, which contributed positively to their overall MCDA scores.

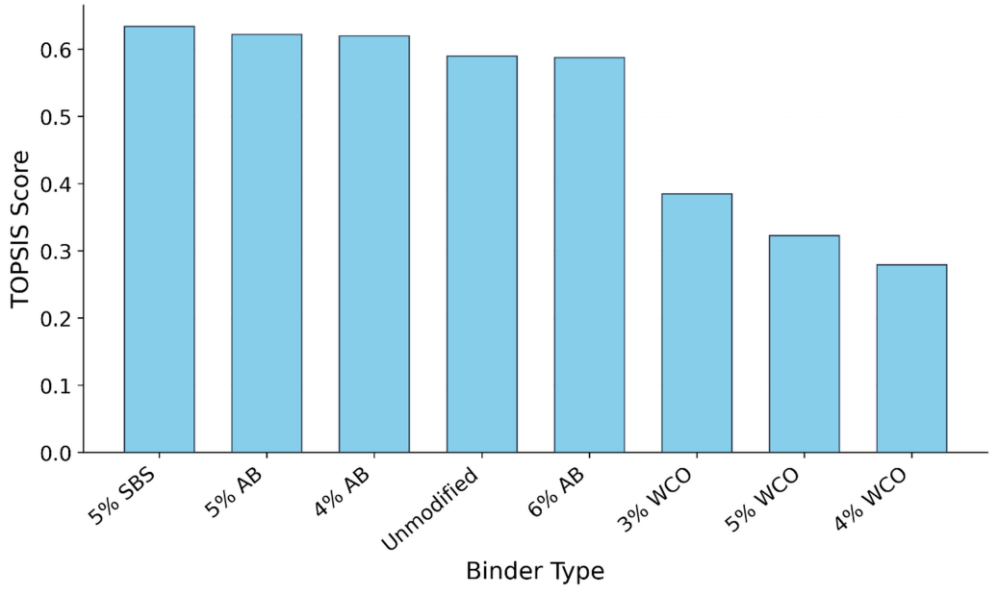


Figure 9. TOPSIS ranking results for modified binders based on rheological criteria

The unmodified binder showed intermediate performance, indicating that while it does not benefit from modification, its behavior remains relatively stable compared to some modified formulations. However, its relatively higher G–R values and lower stiffness compared to SBS and AB binders limit its overall ranking.

In contrast, the WCO-modified binders consistently ranked lowest in both MCDA methods. This outcome is primarily due to their low $G^*/\sin\delta$ values, which reflect reduced stiffness and poor resistance to deformation. Although WCO modification may improve flexibility and workability, its adverse effect on mechanical strength outweighs these benefits within the context of multi-criteria evaluation. Furthermore, the relatively high G–R values of WCO-modified binders indicate limited effectiveness in improving cracking resistance.

An important outcome of this analysis is that binder performance cannot be adequately captured by a single parameter: G–R values represent cracking susceptibility, while $G^*/\sin\delta$ introduces the complementary dimension of stiffness and deformation resistance, and their integration, validated here by the consistency between TOPSIS and WSM, provides a more comprehensive and reliable basis for binder selection than either indicator alone.

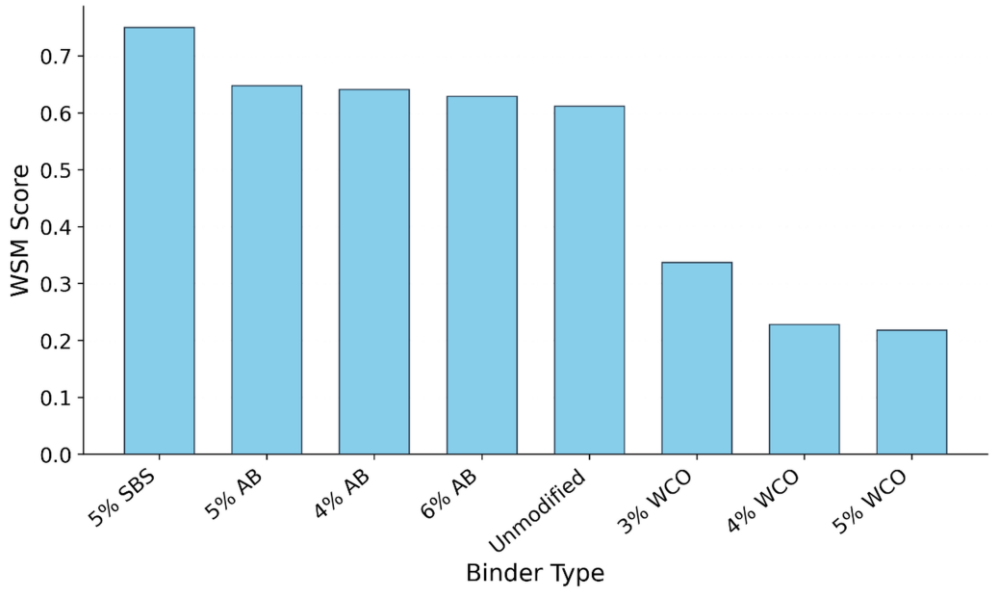


Figure 10. Weighted sum model (WSM) ranking of modified binders

3.6 Limitations and Future Work

This study has several limitations that should be acknowledged, which also help define clear directions for future work. The rheological characterization presented here reflects single-measurement testing per binder and temperature; incorporating replicate testing and statistical analysis, such as standard deviations, error bars, and significance testing, would further strengthen confidence in the reported values. The evaluation was conducted on unaged binders, and given the known sensitivity of the Glover–Rowe index to aging, extending the framework to short- and long-term aged conditions is a priority for follow-up work. The MCDA framework adopted an equal-weighting scheme as a transparent baseline; developing climate-calibrated weighting schemes that reflect regional priorities, such as greater emphasis on cracking indicators in cold climates and stiffness in hot climates, represents a valuable refinement. Finally, the present analysis is limited to binder-level characterization; mixture-level testing and field monitoring under real traffic and climatic conditions would help confirm whether the rankings established here translate to long-term pavement performance. Collectively, addressing these directions through replicate testing, aging evaluation, climate-calibrated weighting, and mixture- or field-scale validation offers a clear path for extending the proposed framework toward practical implementation.

4. Conclusions

This study evaluated the rheological performance of asphalt binders modified with SBS, AB, and WCO using the Glover–Rowe (G–R) index, temperature sensitivity (ΔG–R), and $G^*/\sin\delta$ as a comparative stiffness indicator at intermediate temperatures, integrated within an MCDA framework. The results showed that 5% SBS provides the best overall performance, exhibiting the lowest G–R values and highest $G^*/\sin\delta$, indicating superior resistance to cracking and deformation. AB-modified binders demonstrated balanced and stable behavior across the investigated temperatures, offering a viable sustainable alternative with moderate stiffness and acceptable cracking resistance. In contrast, WCO-modified binders showed reduced stiffness and consistently higher G–R values, reflecting limited effectiveness in improving either cracking or deformation resistance despite their flexibility benefits.

It should be noted that $G^*/\sin\delta$ was applied at intermediate temperatures (15 °C and 25 °C) as a relative stiffness and deformation resistance indicator, rather than as a conventional rutting predictor, which is its established role at high pavement temperatures. Within this context, the parameter effectively distinguished binder performance across the tested formulations.

The MCDA results from TOPSIS and WSM were consistent, confirming the reliability of the proposed framework. Overall, the study highlights that combining cracking indices, temperature sensitivity, and stiffness parameters within a unified MCDA approach offers a robust and practical tool for binder selection, supporting the use of SBS for high-performance applications and AB as a balanced and sustainable alternative. Therefore, the lower ranking of WCO-modified binders in this study should be interpreted within the tested dosage range and standalone modification conditions, rather than as a general rejection of WCO as a modifier. The findings also suggest that WCO requires dosage optimization or hybrid modification to better balance flexibility, stiffness, and cracking resistance.

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Declaration of Competing Interests
The author declares no conflicts of interest.

CRediT Author Contribution Statement
A. Almusawi: Conceptualisation; Methodology; Investigation; Writing – original draft; Writing – review & editing; Supervision.

Availability of Data and Materials
The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Statement
This study did not involve human participants or animal subjects. The animal bones used to produce the bone ash were waste by-products, and no animals were used for the purposes of this research. Ethical approval was therefore not required.

Generative Artificial Intelligence Disclosure
The AI-based tool Claude was used solely for language editing and grammar refinement. No AI content generation or data interpretation was performed. All intellectual contributions are original and solely attributable to the author.

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