From Waste to Pavement: Used Motor Oil Rejuvenation of Guayule Resin–Crumb Rubber Sustainable Asphalt Binders

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ABSTRACT

This study evaluated waste-derived used motor oil (UMO) as a rejuvenator in sustainable asphalt binders incorporating guayule resin and crumb rubber modifier (CRM). Guayule resin is a bio-based by-product of natural rubber extraction exhibiting asphalt-like characteristics. While it offers environmental benefits and resists oxidative aging due to natural antioxidants, its intrinsic stiffness limits performance at intermediate and low temperatures. CRM enhances elasticity and rutting resistance but further amplifies stiffness when combined with guayule. A hybrid binder system, designated ARG75(20):25, was formulated with 75% asphalt rubber and 25% guayule resin (12.5% CRM by total binder weight), with a continuous performance grade (PG) 73-16. To restore viscoelastic balance across service temperatures, UMO was incorporated at 1%, 3%, and 5%, targeting base asphalt grade PG 64-22. Rheological properties were assessed under original, RTFO-, and PAV-aged conditions using dynamic shear rheometer (DSR), bending beam rheometer (BBR), and black phase analysis. PG and viscoelastic metrics were used to evaluate aging response, rutting and fatigue potential, as well as low-temperature stiffness and relaxation. Results showed that UMO reduced binder stiffness and improved relaxation behavior, significantly enhanced fatigue and thermal cracking resistance without compromising rutting tolerance. The 3% UMO dosage yielded the most balanced formulation, restoring the PG grade to 66-22 and meeting Superpave criteria. Black phase analysis confirmed enhanced compliance, and BBR at -12℃ validated low-temperature cracking resistance. Compared to the PG 64-22 benchmark, UMO-ARG binders delivered comparable or superior performance while displacing ~40% of petroleum asphalt with recycled and bio-based materials, supporting circular economy goals.

Keywords: Asphalt Rejuvenation, Guayule Resin, Used Motor Oil, Crumb Rubber, Binder Rheology, Sustainability

INTRODUCTION

The pursuit of sustainable and high-performing materials in the asphalt industry has driven researchers to explore bio-based binders and recycled modifiers that reduce reliance on petroleum resources while maintaining or improving pavement performance [1-5]. Among these innovations, guayule resin, a co-product derived from the guayule shrub during natural rubber extraction, has emerged as a viable bio-binder candidate due to its inherent viscoelastic properties, asphalt-like chemical structure, and domestic availability [6-10]. Guayule resin represents approximately 10% of the guayule plant's dry biomass [9-11] and has demonstrated promising physical compatibility with asphalt binder, particularly in flexible pavement applications [6, 8]. However, due to its inherently polar and oxygen-rich composition, guayule resin exhibited high baseline stiffness (at intermediate and low temperatures) and thermal susceptibility, despite its resistance to further oxidative aging [12]. These pre-existing oxygenated functional groups can mimic the characteristics of aged binders, limiting relaxation and ductility when used as a primary phase binder [8].

To address these challenges, previous studies have proposed hybrid binder systems that integrate guayule resin with crumb rubber modifier (CRM), sourced from recycled tires [6-8, 13-20]. CRM not only enhanced elastic recovery and rutting resistance but also contributed to circular economy goals by mitigating tire waste [21]. Hemida and Abdelrahman evaluated asphalt–rubber–guayule (ARG) systems, revealing that the CRM–guayule composite system exhibited potential performance benefits in the binder and mixture scales [7, 20, 22]. Notably, the ARG75(20)25 binder, comprising 25% guayule resin and 12.5% CRM by total binder weight, demonstrated reasonably high-temperature stiffness and elastic behavior compared to conventional asphalt binder [6]. This blend effectively replaced 37.5% of virgin asphalt binder with sustainable by-product, establishing it as a strong candidate for environmentally responsible pavement design [8].

Furthermore, component analyses using FTIR and TGA revealed key microstructural and chemical interactions in ARG systems [8]. FTIR confirmed oxygen-rich functional groups (carbonyl and sulfoxide) in guayule resin; while these polar groups can enhance compatibility and cohesion, they also indicate oxidative pre-aging that leads to hardening and reduced flexibility, compromising fatigue resistance at low temperatures [7, 8, 17]. These limitations highlight the need for a rejuvenation strategy to restore the balance between strength and flexibility. Although guayule resin shares several functional groups with asphalt (e.g., carbonyl and aromatic), it forms a physical blend with asphalt and rubber with no new chemical bonds [8]. CRM showed signs of devulcanization and partial migration of polymeric chains into the binder phase [8], interactions that improved high-temperature performance [6]. Nevertheless, guayule-based binders were more susceptible to intermediate- and low-temperature distress due to the resin's oxidative unsaturated bonds [8].

[6, 8]Incorporating rejuvenators is increasingly used to address aging-related limitations and improve binder workability, a need that is critical in guayule–CRM systems where both constituents increase stiffness and reduce ductility, motivating a maltene-rich, flow-promoting additive [23]. Used motor oil (UMO) is attractive because its light fractions and aromatics can replenish maltenes lost to oxidative aging or absorption by crumb rubber [24-28]. Although UMO has been widely studied for RAP, its use in bio-rubber binders containing guayule resin remains unexamined. Introducing UMO may mitigate the effect of oxidative unsaturated bonds in guayule resin, rebalance light components, enhance intermediate-temperature performance and low-temperature relaxation, and counteract system stiffness [24-26, 29].

OBJECTIVE AND SCOPE

The ARG binder blend, specifically the ARG75(20):25, effectively replacing 37.5% of conventional petroleum-derived asphalt, has shown pronounced high-temperature stiffness and elasticity, making it a promising sustainable alternative to the conventional binder [6-8]. However, guayule-rich systems exhibited emerging limitations at intermediate and low temperatures, including increased stiffness and limited relaxation, which restrict broader implementation. It is unknown whether adding a rejuvenator such as UMO can rebalance the thermal grade and aging response of ARG75(20):25 (hereafter referred to as the reference binder) while preserving its high-temperature performance. A systematic evaluation is needed to determine if UMO-modified ARG binders can meet at least the performance grade of the PG 64-22 base asphalt (hereafter referred to as the control binder) of the base asphalt used in this study. This study evaluated UMO as a rejuvenator for ARG75(20):25 at 0%, 1%, 3%, and 5% by binder weight. Performance is assessed with DSR (original, RTFO-aged, and PAV-aged) and BBR (PAV-aged); viscoelastic behavior is interpreted via black-phase diagrams, and oxidative aging via rheological indices. All formulations are benchmarked against PG 64-22 to identify the minimum UMO dosage that restores the low-temperature grade to ≤ -22°C without compromising high-temperature grade or aging indices. The scope is limited to binder-level laboratory characterization.

MATERIALS AND METHODS

Materials

This study utilized a multi-component binder system comprising conventional, recycled, and bio-based materials to investigate the rejuvenating effect of UMO on the viscoelastic behavior of ARG systems. The base binder was a performance-graded asphalt cement (PG 64-22), commonly used in pavement applications across moderate to high temperature zones and conforming to AASHTO M 320 specifications [30]. This neat asphalt (A) served as the control binder for the performance evaluation of the UMO-ARG modified binders.

CRM was introduced at a dosage of 20% by weight of the asphalt portion, following established specifications for asphalt–rubber binder production. The CRM conformed to ASTM D6114 [31]. A mesh #30–40 gradation was selected in alignment with common practice for wet-process asphalt–rubber binders, offering a favorable balance between interaction efficiency and binder stability [32-36].

Guayule resin (G) was used in raw, solid form as a partial bio-based alternative to the conventional asphalt binder. Prior to blending (**Figure 1**), guayule resin was conditioned at 160°C under continuous stirring (600 rpm) to remove residual moisture until bubbling ceased, ensuring binder homogeneity and batch-to-batch consistency. **Table 1** summarizes the key physical properties of the base asphalt and guayule resin used.

Figure 1. Sequential Stages of Guayule Resin Conditioning: (1) transfer from storage container, (2) resin in raw form, (3) initiation of thermal mixing at 160°C with moisture bubbling, and (4) post-conditioning homogeneous molten resin.

Table 1. Properties of Base Asphalt vs. Heat-Treated Guayule Resin

Property	A	G	Method
Flash Point [°C]	320	242	ASTM D92 [37]
Fire Point [°C]	330	261	ASTM D92 [37]
Density at 25°C [g/dm^3]	1028	1038	ASTM D70 [38]
Penetration at 25°C	50/60	40/50	ASTM D5 [39]
Viscosity at 135°C [Pa.s]	0.403	0.203	ASTM D4402 [40]
Softening Point [°C]	47	48	ASTM D36 [41]

The primary binder system investigated was an asphalt–guayule–rubber composite binder designated as ARG75(20):25. This blend consisted of 75% asphalt rubber (AR), which itself was made by combining 20% CRM with base asphalt (A), and 25% guayule resin (G), by total binder weight. The ARG binder was further modified with UMO at three dosage levels: 1%, 3%, and 5% by total binder weight. The UMO was collected from a local automotive repair shop, filtered to remove impurities, and stored in sealed containers to prevent premature aging and preserve its properties prior to blending [24-26]. The neat binders (A and G) were included in the study to establish baseline performance and material variability (**Table 2**).

Table 2. Designation and Proportions of Binder Blends with Varying UMO Dosages

Binder Label	Binder Proportions				
	A%	G%	CRM%	AR%	UMO%
	by wt. of blend				
A	100	--	--	--	--
G	--	100	--	--	--
ARG75(20):25	62.5	25	12.5	75	--
ARG75(20):25(1%UMO)	61.9	24.8	12.4	74.3	1
ARG75(20):25(3%UMO)	60.7	24.3	12.1	72.9	3
ARG75(20):25(5%UMO)	59.4	23.8	11.8	71.3	5

A: base asphalt (PG 64-22); G: heat-treated guayule resin; AR: asphalt-rubber portion; ARG: asphalt-rubber-guayule binder blend; UMO: used motor oil

Sample Preparation

All binder blends were prepared using a multi-stage, controlled mixing process to ensure complete dispersion of crumb rubber and uniform integration of guayule resin and UMO within the asphalt matrix. The preparation protocol was designed to maintain consistency across all formulations. First, the asphalt–rubber (AR) blend was prepared by gradually incorporating oven-dried CRM into preheated PG 64-22 base asphalt at 190°C, using a high-shear mixer operating at 3000 rpm [6]. Continuous high-shear mixing was maintained for 40 minutes to ensure adequate swelling and diffusion of CRM particles into the asphalt binder matrix [8].

Subsequently, the ARG75(20):25 blend was produced by combining the AR product and heat-treated guayule resin in a 75:25 ratio by total binder weight. The mixing was performed at 160°C for 30 minutes at 600 rpm, ensuring uniform dispersion of the guayule in the blend.

For UMO-modified formulations, UMO was added after the ARG blend had been homogenized. The UMO was added with the specified dosage gradually while maintaining the temperature at 160°C and the mixing speed at 600 rpm. Blending continued until the binder became thoroughly homogeneous.

All prepared binders were poured into silicone molds, cooled to room temperature, and ready for further rheological testing at high temperatures as original binders (unaged).

Methods

In order to assess the rheological behavior of the prepared binder systems across temperature ranges relevant to pavement performance, a comprehensive testing framework was implemented per AASHTO and ASTM specifications to ensure repeatability and reliability. Binder samples were evaluated at three aging states: original (unaged), short-term aged, and long-term aged, to simulate different stages of binder service life.

Short-term aging was carried out using the Rolling Thin Film Oven (RTFO) procedure, following AASHTO T 240 [42], to simulate the oxidative and thermal aging conditions that binders undergo during hot-mix asphalt production and laydown. Long-term aging was subsequently conducted in a Pressure Aging Vessel (PAV) in accordance with AASHTO R 28 [43]. The RTFO-aged binders were placed in standard metal pans and subjected to a pressure of 2.1 MPa at 100°C for 20 hours in the PAV, simulating long-term oxidative aging equivalent to approximately 5 to 10 years of field exposure [44, 45]. After each aging stage, binders were allowed to cool to room temperature and gently homogenized with a spatula to ensure uniformity prior to rheological testing.

Dynamic Shear Rheometer (DSR) testing was conducted to evaluate the high- and intermediate-temperature rheological properties of the binders per AASHTO T 315 [46]. For original and RTFO-aged binders, tests were performed using 25 mm parallel plates with a 1 mm gap over the temperature range of 58°C to 70°C in 6°C increments, at an angular frequency of 10 rad/s and a shear strain of 12% for OB and 10% for RTFO-aged binders. For PAV-aged binders, 8 mm plates with a 2 mm gap were used, and testing was carried out at intermediate temperatures between 19°C and 25°C, with an angular frequency of 10 rad/s and a shear strain of 1%. The DSR measured the complex shear modulus ($|G^*|$) and phase angle (δ), from which rutting and fatigue parameters, $|G^*|/\sin(\delta)$ and $|G^*|\cdot\sin(\delta)$, respectively, were determined. In addition, black phase diagrams ($|G^*|$ vs. δ) were developed to qualitatively capture the evolution of binder viscoelastic behavior across different formulations and aging stages.

Low-temperature performance was characterized using the BBR per AASHTO T 313 [47]. PAV-aged binders were poured into standardized rectangular molds and trimmed after conditioning. Testing was performed at -12°C with a constant load of 980 mN applied for 240 seconds. Two key parameters were extracted: creep stiffness (S) at 60 seconds, with a Superpave compliance threshold of $\leq$ 300 MPa, and the m-value, defined as the slope of the log stiffness vs. log time curve, with an acceptable minimum of 0.300. Each binder was tested to assess its low-temperature (thermal) cracking resistance.

Testing was performed following the number of replicates specified by the relevant standards, ensuring acceptable variability and reproducible average values.

RESULTS AND DISCUSSION

High-Temperature Performance: Rutting Evaluation and Aging Response

The potential of UMO to rejuvenate and rebalance the mechanical performance of the ARG75(20):25 binder system was first examined under high-temperature conditions using the DSR. As shown in **Figure 2a&b**, the reference ARG binder exhibited the highest $|G^*|$ values and the lowest δ values under both unaged and RTFO conditions, indicating high stiffness and limited viscoelastic response. These characteristics are typical of ARG systems [6], likely due to the oxidative sensitivity of guayule resin and the reinforcing effect of CRM particles [7].

With increasing UMO content (1%, 3%, 5% by total binder weight), $|G^*|$ decreased, and δ increased under both unaged and RTFO conditions, indicating a consistent softening and flow enhancement trend. The 5% UMO-modified binder showed the lowest $|G^*|$ and highest δ across the evaluated temperature range (58–

70°C), supporting its effectiveness in counteracting over-stiffening. The high-temperature Superpave rutting parameter |G*|/sin(δ) (**Figure 2c**) remained above the 1.0 kPa threshold at 64°C for all unaged binders. It also exceeded the 2.1 kPa threshold for all RTFO-aged binders, indicating that rutting resistance was not compromised despite the softening effect of UMO compared to the base asphalt (PG 64-22) used in this study.

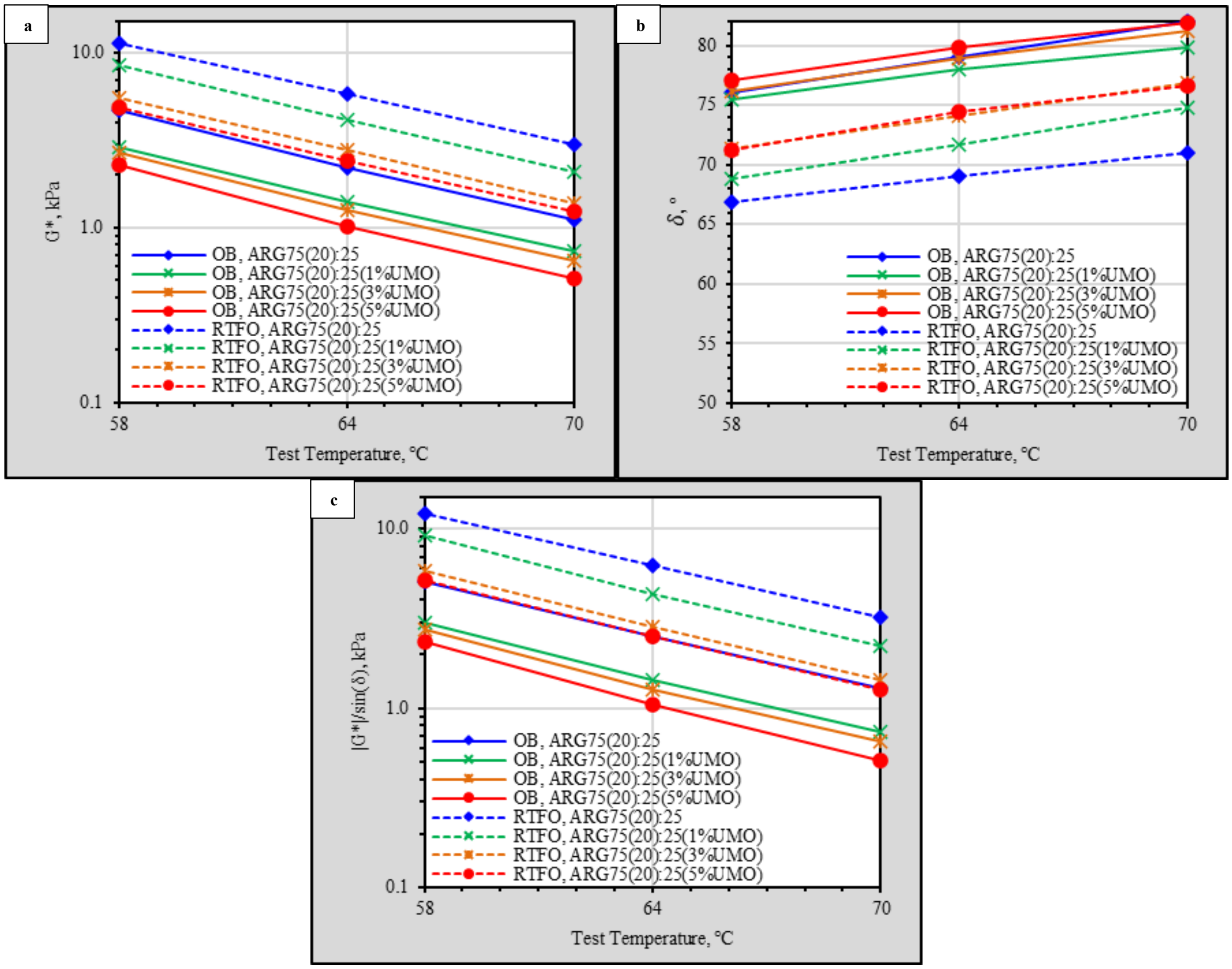

Figure 2. High-Temperature DSR Sweep: (a) Complex Shear Modulus (|G*|); (b) Phase Angle (δ); (c) |G*|/sin(δ)

Notably, the RTFO aging index, also shown in **Figure 3** as a dashed line, provides critical insight into aging susceptibility. Among all blends, the neat guayule resin binder exhibited the lowest aging index of 1.6, reflecting a minimal increase in |G*|/sin(δ) upon RTFO aging. This low susceptibility may be attributed to the presence of intrinsic antioxidant compounds in guayule resin, such as polyphenols and terpenoids, which can delay oxidative chain reactions during thermal exposure [12]. These compounds may contribute to the oxidative stability observed under short-term aging conditions. Conversely, the reference ARG75(20):25 binder and its UMO-modified counterparts demonstrated aging indices ranging from 2.2 to 3.0, values that remained within a reasonable range and comparable to the base asphalt, which recorded an index of 2.6. This trend indicated that while ARG systems exhibited higher aging than pure guayule resin, the addition of UMO did not introduce abnormal or excessive aging behavior.

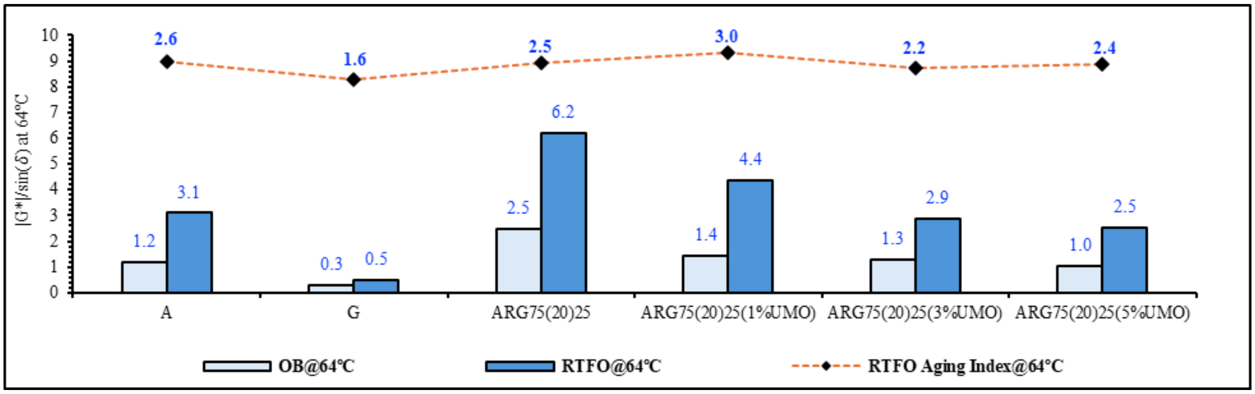

Figure 3. Rutting Resistance, |G*|/sin(δ) at 64°C, and RTFO Aging Index

Notably, the study aimed to, at least, gain a sustainable binder that can achieve the conventional binder PG. The RTFO-aged ARG binder achieved PG 70 (with pass/fail (P/F) temperature of 73°C), whereas UMO-modified binders exhibited reduced PGs, approximately 70°C, 66°C, and 65°C for 1%, 3%, and 5% UMO, respectively (**Figure 4**). While this softening was expected due to UMO's diluting and plasticizing effects [24-26], the binders still met performance requirements for moderate to high climate zones (PG 64 target).

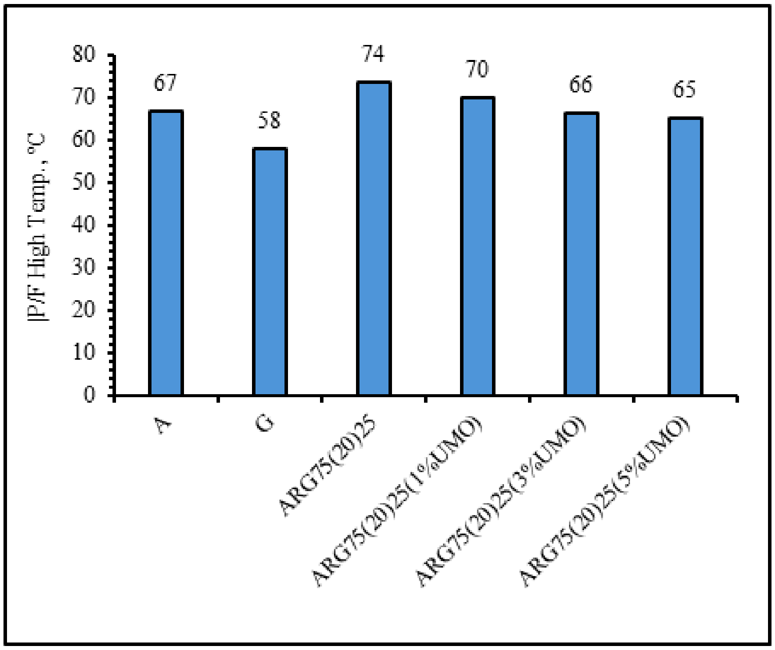

Figure 4. Pass/Fail PG High-Temperature

The high-temperature black phase diagram (**Figure 5**) reinforced the softening trends introduced by UMO modification compared to the reference (ARG75(20):25) binder. The control binder (PG 64-22) displayed relatively moderate |G*| values with high phase angles, reflecting a balanced viscoelastic response suitable for rutting resistance in conventional formulations. In contrast, guayule resin showed significantly lower |G*| values and much higher δ values, consistent with its softer, more flow-prone nature and limited elastic recovery at elevated temperatures. The reference ARG75(20):25 binder exhibited the stiffest response, with high |G*| and low δ, reflecting an elastic-dominated behavior resulting from CRM reinforcement and the viscoelastic contribution of guayule resin. UMO-modified binders progressively shifted toward lower stiffness and higher phase angles, with 5% UMO showing the most compliant response. These shifts suggest that UMO effectively offset the stiffening effects and shifted the binder response toward more viscous behavior, thereby promoting greater stress dissipation. The inclusion of binders A and G in the diagram provides a clearer context for the compositional influence on rheological behavior, highlighting the transition from rubber-rich matrices toward a more compliant and rejuvenated viscoelastic domain with increasing UMO dosage.

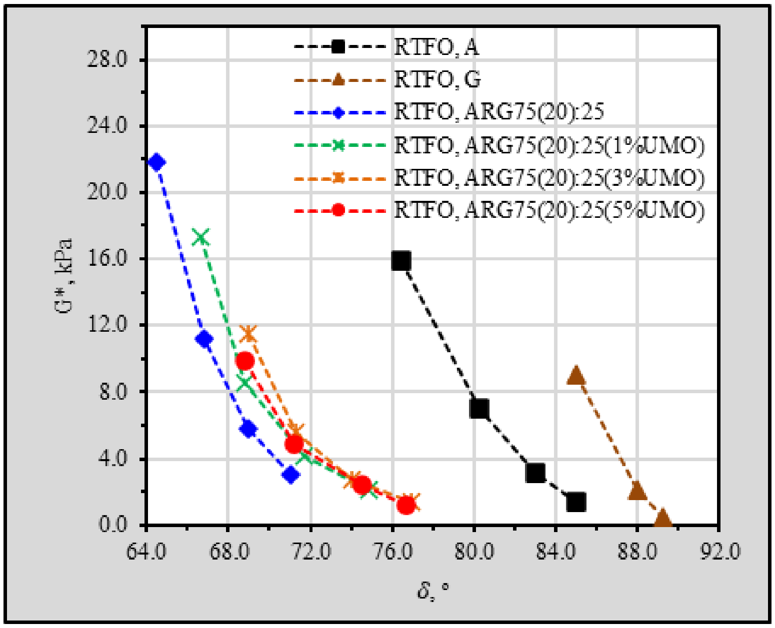

Figure 5. High-Temperature Black Phase Diagrams

Intermediate-Temperature Performance: Fatigue Resistance and Viscoelastic Recovery

To further characterize the aging and rejuvenation behavior of ARG75(20):25 binders, intermediate-temperature rheological properties were assessed using DSR testing under PAV-aged conditions. As shown in **Figure 6a–c**, three key parameters were evaluated at 19°C to 25°C: |G*|, δ, and the Superpave fatigue parameter |G*|·sin(δ). These parameters collectively represent the binder's stiffness, elastic-viscous balance, and its resistance to fatigue-induced damage under service temperatures.

As illustrated in **Figure 6a**, the reference ARG75(20):25 binder exhibited the highest |G*| values across the tested temperature range, a result consistent with the expected behavior of aged binders containing rubber and guayule resin [6]. The inclusion of UMO led to a consistent reduction in |G*|, with the 5% UMO-modified binder showing the lowest stiffness. This reduction signifies increased binder compliance and suggests improved ability to dissipate intermediate-temperature stresses, which may be beneficial in reducing fatigue cracking potential. The corresponding phase angle values presented in **Figure 6b** confirmed the softening trend. All UMO-modified binders showed higher δ values than the reference ARG75(20):25 binder, indicating a shift toward more viscous behavior. The progressive increase in δ from 1% to 5% UMO suggested that the rejuvenator enhanced the binder's relaxation capacity and reduced its elastic dominance, supporting stress dispersion under cyclic loading conditions typical of intermediate service temperatures. As shown in **Figure 6c**, the fatigue parameter |G*|·sin(δ) decreased with increasing UMO dosage, consistent with the observed trends in |G*| and δ.

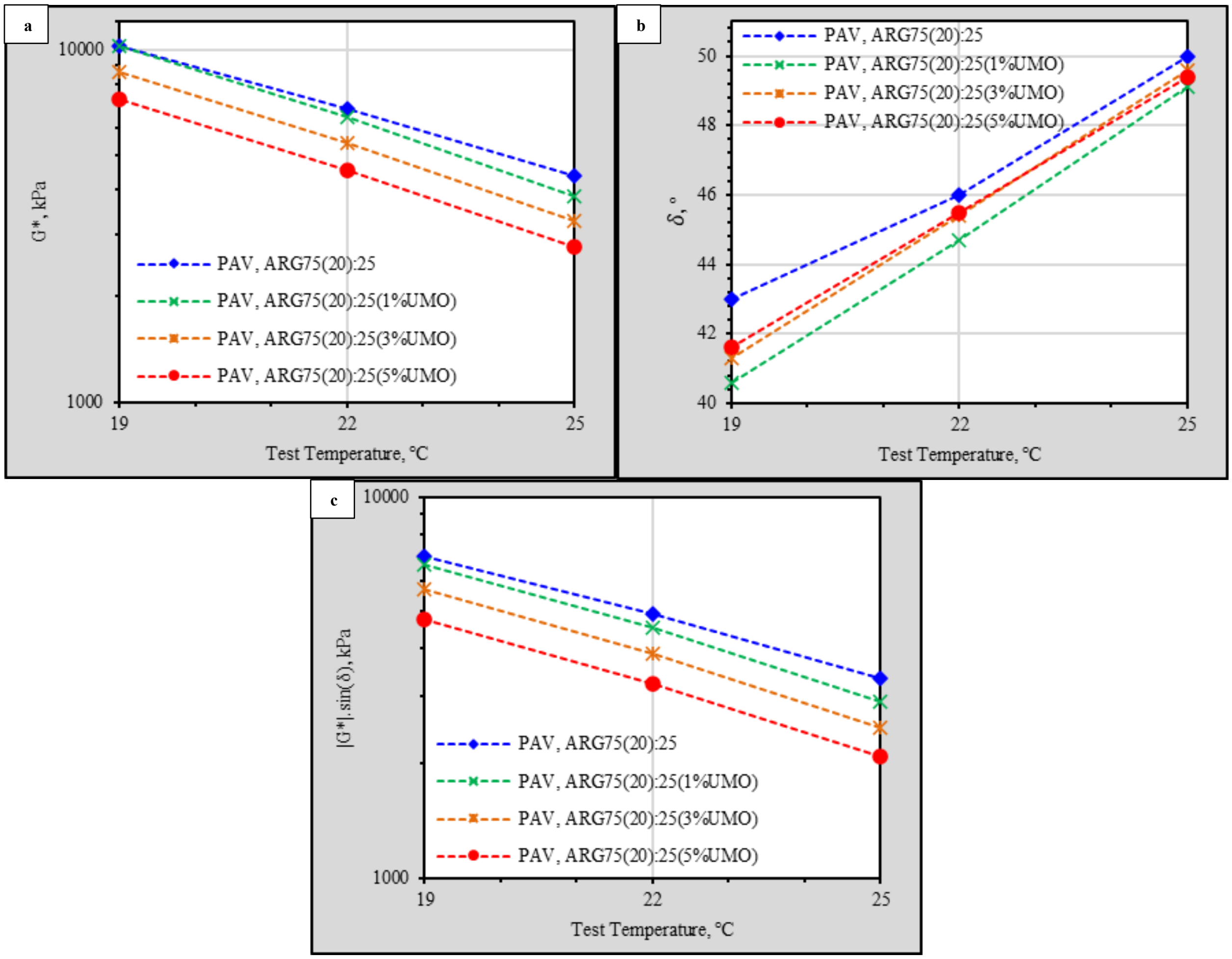

Figure 6. Intermediate-Temperature Sweep: (a) Complex Shear Modulus (|G*|); (b) Phase Angle (δ); (c) |G*|·sin(δ)

To further illustrate the effects of UMO on intermediate-temperature fatigue performance, **Figure 7** presents the |G*|·sin(δ) values at 25°C for all studied binders. The reference ARG75(20):25 binder exhibited a considerably higher value (3352 kPa) compared to the conventional base asphalt (2905 kPa), reinforcing its relatively stiffer and more elastic nature after long-term aging. However, a consistent reduction in |G*|·sin(δ) was observed with increasing UMO dosage, reaching 2900, 2490, and 2090 kPa at 1%, 3%, and 5% UMO, respectively. These results confirmed the rejuvenating effect of UMO in reducing stiffness and enhancing flexibility, key factors in improving resistance to fatigue cracking at intermediate service temperatures.

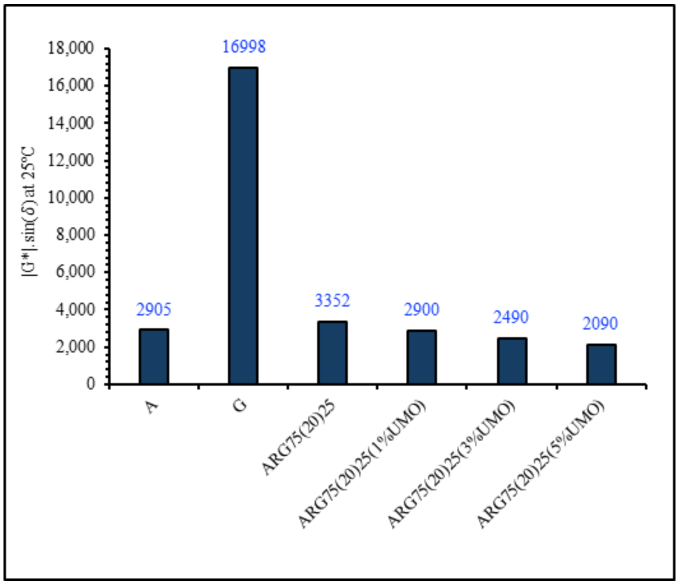

Figure 7. Superpave Fatigue Cracking Parameter |G*|·sin(δ) at 25°C

The corresponding P/F PG intermediate temperatures (**Figure 8**) further supported this trend. The reference ARG binder registered a P/F temperature of 22°C, slightly above the base asphalt (20°C), indicating a higher fatigue susceptibility. In contrast, UMO-modified binders exhibited progressively lower P/F temperatures of 21°C, 20°C, and 19°C with increasing UMO content. These reductions are indicative of improved stress-relaxation capability and delayed onset of fatigue cracking, suggesting that UMO effectively restored the balance between stiffness and ductility in aged ARG systems.

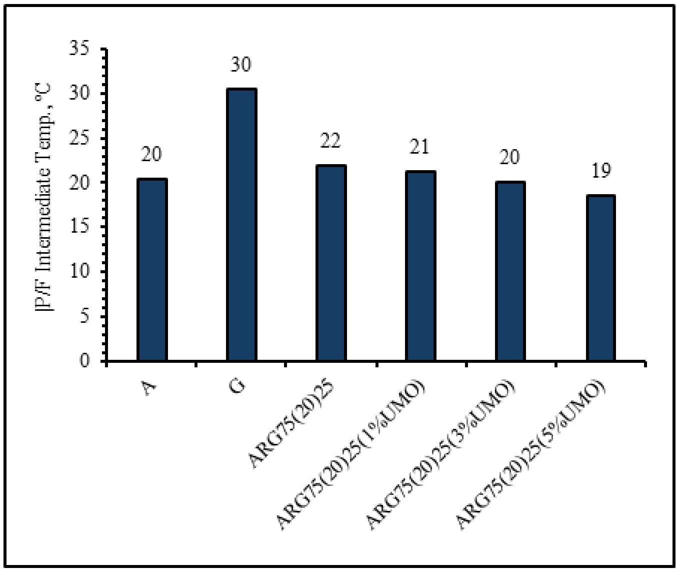

Figure 8. Pass/Fail PG Intermediate-Temperature

The intermediate-temperature black phase diagram (**Figure 9**) reinforced the previous trends. UMO-modified binders shifted downward and rightward from the reference binder, reflecting reduced stiffness and increased phase angles. The 3% and 5% UMO blends notably exhibited greater viscoelastic compliance, supporting enhanced fatigue resistance.

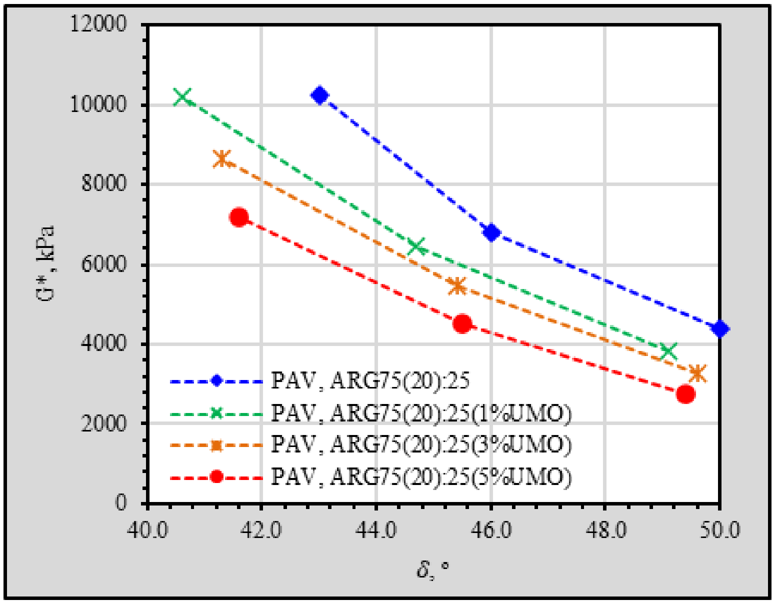

Figure 9. Intermediate-Temperature Black Phase Diagrams

Low-Temperature Performance: Thermal Cracking Resistance

Low-temperature behavior was evaluated using BBR at −12°C, with results shown in **Figure 10a** for stiffness and **Figure 10b** for m-value. The reference ARG75(20):25 binder exhibited inadequate thermal cracking resistance compared to the target asphalt binder (PG 64-22), with a stiffness of 411 MPa (exceeding the 300 MPa Superpave limit) and an m-value of 0.228 (below the 0.300 threshold), indicating excessive brittleness and poor relaxation properties based on Superpave criteria [47]. In contrast, UMO modification led to marked improvements. At 1% UMO, stiffness decreased to 135 MPa and the m-value increased to 0.285, approaching acceptable limits. At higher dosages (3% and 5% UMO), stiffness values dropped further to 113 MPa and 89 MPa, while m-values rose to 0.296 and 0.306, respectively. Notably, the 5% UMO binder met both Superpave criteria, confirming UMO's efficacy in restoring viscoelastic flexibility and relaxation potential, likely due to enrichment in maltenic and aromatic fractions that counteract oxidative embrittlement [48].

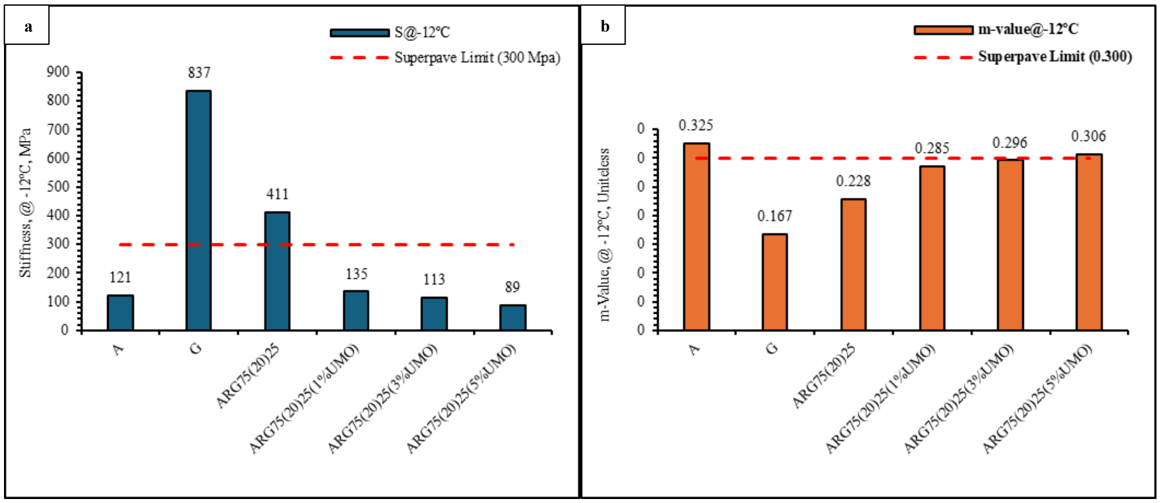

Figure 10. Low-Temperature BBR Performance at −12 °C: (a) Stiffness; (b) m-Value

Viscoelastic Evolution Across Temperature Domains

Interestingly, the 1% UMO binder showed mild short-term stiffening under RTFO aging (**Figure 2a**), possibly due to structural enhancement within the ARG matrix. However, this effect diminished at higher δ values and did not persist at intermediate temperatures (**Figure 6b**), where all UMO binders demonstrated softened, more viscous-like behavior.

To provide deeper insight into the intrinsic temperature sensitivity of the two main binder components, **Figure 11** presents a comparative analysis of RTFO-aged and PAV-aged rheological parameters for base asphalt and guayule resin. As illustrated in **Figure 11a**, guayule resin exhibited a steeper decline in |G*|/sin(δ) with increasing temperature, suggesting higher thermal sensitivity in the high-temperature range. Conversely, base asphalt maintained a more stable response, indicating less temperature susceptibility. This distinction becomes more pronounced under intermediate-temperature conditions (**Figure 11b**), where PAV-aged guayule resin exposed higher |G*|·sin(δ) values compared to base asphalt, further reflecting its inherently stiffer and less compliant nature at intermediate temperatures. These trends corroborate the study's hypothesis that guayule resin, despite its aging resistance at high temperatures, contributes to increased rigidity and reduced relaxation potential at intermediate temperatures. Therefore, understanding this material behavior is critical when designing hybrid binder systems aimed at balancing stiffness, relaxation, and sustainability.

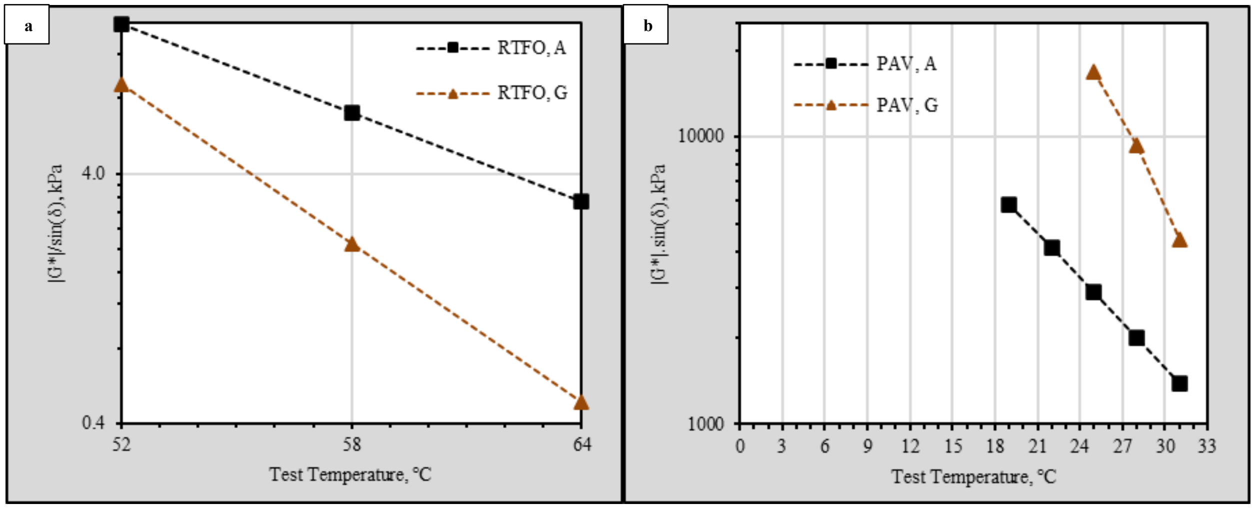

Figure 11. Temperature susceptibility of base asphalt (PG 64-22) and guayule resin: (a) |G*|/sin(δ) for RTFO-aged binders (high-temperature domain) and (b) |G*|·sin(δ) for PAV-aged binders (intermediate-temperature domain)

This rheological shift aligns with the expected rejuvenation pathways: UMO promoted flow at high temperatures while preserving flexibility at intermediate and low temperatures. Overall, these results suggest that UMO acts as a functional rejuvenator. While CRM primarily enhances elasticity and stiffness [49], UMO counteracts these effects by restoring maltenic content and promoting stress relaxation, especially under oxidative aging, tuning the ARG system's viscoelastic properties across the service temperature spectrum.

Summary and Practical Implications for Transportation Infrastructure

This study confirmed the viability of incorporating waste-derived UMO as a rejuvenator in ARG systems to address performance imbalances across service temperature ranges typical of flexible pavements. UMO inclusion improved the viscoelastic characteristics of the binder, mitigating oxidative stiffening and enhancing compliance and relaxation without compromising Superpave rutting or cracking criteria.

As shown in **Figure 12**, PG grading trends support the observed rheological shifts. The base asphalt binder achieved a continuous grade of PG 67-25, while neat guayule resin exhibited PG 58-11, indicating limited low-temperature performance. The reference ARG75(20):25 binder attained PG 73-16, confirming relatively superior rutting resistance but insufficient relaxation at low temperatures. UMO addition progressively softened the binder, yielding grades of PG 70-19, PG 66-22, and PG 65-24 for 1%, 3%, and 5% UMO, respectively. Notably, both the 3% and 5% UMO blends restored the low-temperature grade to the target threshold of -22°C, meeting or exceeding the performance grade of the base PG 64-22 asphalt used in this study.

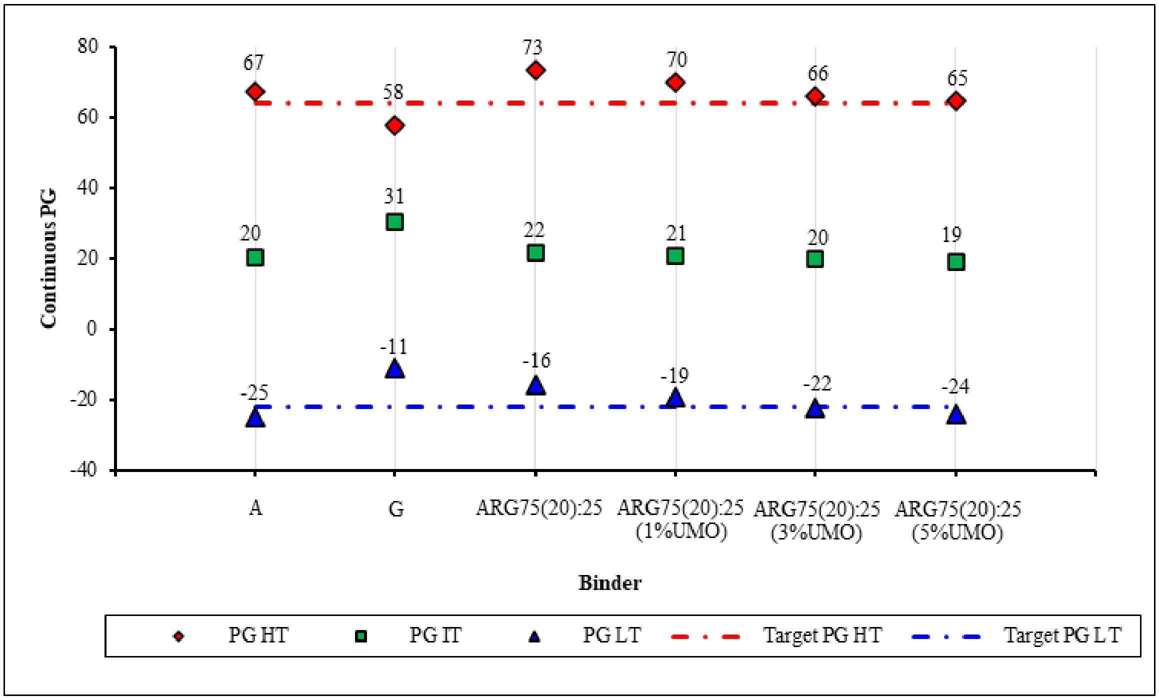

Figure 12. Continuous PGs for All Designated Binders: PG High Temperature (PG HT), PG Intermediate Temperature (PG IT), and PG Low Temperature (PG LT) Grades vs. Target PG 64-22

These improvements were further corroborated by DSR and BBR testing: at high temperatures, UMO-modified binders reduced |G*| and increased δ while maintaining |G*|/sin(δ) above rutting thresholds in all modification levels; at intermediate temperatures, lower |G*|·sin(δ) values and P/F temperatures signaled better fatigue resistance; and at low temperatures, improved stiffness and m-values confirmed enhanced thremal cracking tolerance.

Among all dosages, 3% UMO emerged as the most balanced and effective formulation, restoring the PG low temperature threshold without over-softening and maintaining high-temperature strength. This dosage aligns with specifications for moderate to high climate zones, confirming its practicality in pavement applications.

Beyond technical performance, this formulation offers significant environmental value. The combination of guayule resin, recycled CRM, and waste-derived UMO displaces ~40% petroleum asphalt, advances circular economy practices, and reduces landfill-bound waste, reinforcing the sustainability of this innovative binder system.

CONCLUSIONS

This study demonstrated the technical feasibility and sustainability potential of integrating waste-derived used motor oil (UMO) as a rejuvenator into guayule–crumb rubber modified asphalt binder (ARG) systems. Through binder-level evaluation across unaged, short-term, and long-term aging conditions, UMO was shown to enhance flexibility, stress relaxation, and fatigue resistance without compromising rutting performance, enabling a balanced rheological profile across service temperatures.

Key findings include:

- Guayule resin, despite exhibiting antioxidant-driven aging resistance, demonstrated inherent viscoelastic limitations at intermediate and low temperatures, necessitating rejuvenation to ensure adequate relaxation and cracking resistance. With appropriate modification, it remains suitable for broader binder applications.
- UMO effectively softened the ARG binder matrix, reduced stiffness, and improved low-temperature stiffness and relaxation in addition to enhanced fatigue cracking resistance, particularly at 3% and 5% dosages.
- The 3% UMO formulation offered the most balanced performance, restoring the binder's low-temperature grade to -22°C while maintaining compliance with rutting thresholds at high temperatures.
- Compared to the base asphalt PG 64-22, UMO-ARG binders provided comparable or improved performance while displacing approximately 40% of virgin petroleum binder with sustainable, recycled constituents.

This work supports the transportation community's transition toward greener infrastructure by advancing a binder system that integrates recycled motor oil, tire-derived rubber, and bio-based guayule resin, collectively reducing environmental impact, promoting circular economy principles, and enhancing resource efficiency in pavement materials.

Future efforts should focus on mixture-level validation, long-term field performance, and life-cycle assessments to quantify environmental gains, emissions offsets, and economic feasibility of UMO-ARG systems under real-world traffic and climate conditions.

AUTHOR CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: study conception and design: A. Hemida, M. Abdelrahman; data collection: A. Hemida; analysis and interpretation of results: A. Hemida; draft manuscript preparation: A. Hemida, M. Abdelrahman, A. El-Ashwah. All authors reviewed the results and approved the final version of the manuscript.

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