Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Effects of Ground Tire Rubber and Trans-Polyoctenamer on the Rheological Properties and Aging Response of Asphalt Binders

Azharul Islam

ai02681@georgiasouthern.edu

Georgia Southern University

Research Article

Keywords: Asphalt, Recycling, Rubber, GTR, TOR, Rheology, Durability, Sustainability, Pavement, Performance

Posted Date: November 11th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11262616/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Effects of Ground Tire Rubber and Trans-Polyoctenamer on the Rheological Properties and Aging Response of Asphalt Binders

Azharul Islam

Department of Civil Engineering and Construction,

Georgia Southern University, Statesboro, GA 30458, United States

Email: ai02681@georgiasouthern.edu

***Corresponding Author:**

Azharul Islam

Department of Civil Engineering and Construction,

Georgia Southern University, Statesboro, GA 30458, United States

Email: ai02681@georgiasouthern.edu

Abstract:

The sustainable management of end-of-life tires represents a persistent environmental challenge, with declining recycling rates leading to increased landfilling and associated ecological risks. This research aligns with the conference theme by presenting a waste-to-resource pathway that transforms ground tire rubber (GTR) into a high-value modifier for asphalt binders, simultaneously addressing waste diversion and infrastructure performance needs. With transportation agencies increasingly specifying higher performance grades such as PG 82-22 for demanding applications, this study investigates whether elevated dosages of GTR can serve as a primary, sustainable modifier to meet these specifications.

Through a comprehensive experimental program, base binders (PG 64-22 and polymer-modified PG 76-22) were modified with GTR contents ranging from 10% to 15% and 3% to 8%, respectively, both with and without the compatibility agent trans-polyoctenamer (TOR). Advanced rheological testing using DSR and BBR coupled with chemical characterization via FTIR spectroscopy, evaluated performance and aging characteristics.

Results demonstrate that a 15% GTR dosage successfully elevates the high-temperature grade of a base binder from PG 64 to PG 82, achieving the target specification while maintaining critical low-temperature performance. The incorporation of GTR significantly enhanced rutting resistance and elastic response, with the hybrid use of TOR further improving binder compatibility and long-term durability. Critically, this approach can increase the consumption of recycled tire rubber in asphalt by over 50% compared to conventional practice.

This study concludes that high-dosage GTR modification presents a technically viable and environmentally strategic method to produce superior asphalt binders. It provides a direct, scalable pathway to enhance the circular economy for scrap tires, reduce reliance on virgin polymer modifiers, and support the development of sustainable, high-performance infrastructure. The findings offer actionable insights for policymakers, material developers, and transportation agencies seeking to integrate waste recycling objectives with advanced engineering performance.

Keywords: Asphalt, Recycling, Rubber, GTR, TOR, Rheology, Durability, Sustainability, Pavement, Performance.

1. Introduction

The management of scrap tires in the United States has emerged as a critical environmental and resource recovery challenge due to the rapidly increasing volume of discarded tires and the stagnating recycling rates [1,2,3,4,5,6]. In 2021, the United States generated more than 500 million tons of scrap tires, yet only about 70% were recycled or repurposed representing a significant decline from the 96% utilization reported in 2013 [7,8,9]. This widening gap between tire generation and recycling capacity has resulted in substantial accumulation of scrap tires in landfills and stockpiles, where they pose serious environmental and public health risks [10,11]. These risks include persistent tire fires that release hazardous emissions, the creation of breeding habitats for disease-carrying vectors, and the potential contamination of soil and groundwater through leachate generation [12]. Addressing this escalating challenge requires innovative and scalable strategies that enhance the beneficial reuse of scrap tires while mitigating their environmental footprint [13].

The incorporation of ground tire rubber (GTR) into asphalt binders and mixtures has gained increasing attention as one of the most sustainable and technically promising solutions for large-scale tire recycling [14,15]. Produced by mechanically grinding scrap tires into fine particles, GTR can be incorporated into asphalt through wet- or dry-process modification to produce rubber-modified asphalt (RMA) [14,16,17]. Previous research has demonstrated that RMA provides several performance benefits, including improved elastic recovery, superior resistance to rutting under heavy traffic loads, and enhanced cracking resistance under low-temperature conditions [18]. These improvements have the potential to extend pavement service life, reduce maintenance costs, and improve the overall resilience of roadway infrastructure [19]. Given these dual environmental and engineering benefits, the use of GTR-modified asphalt presents a viable pathway for expanding scrap tire recycling markets in the United States [20,21].

In Georgia, the application of GTR in pavement systems has been investigated through both laboratory studies and field validation projects. Prior research and performance monitoring of test sections on major interstate corridors, such as I-75 near Perry, Macon, and Valdosta and I-20 near Augusta have shown that RMA can deliver performance comparable to polymer-modified asphalt (PMA), which is traditionally preferred for high-performance applications but is associated with higher material costs [20,22]. Despite these encouraging findings, the adoption of GTR in Georgia's asphalt mixtures remains limited. Over the past two years, only 16.5% of modified

asphalt concrete produced in the state incorporated GTR, indicating a substantial gap between its demonstrated engineering value and actual market utilization [20,22,23]. This underuse suggests the presence of technical, specification-related, or industry-readiness barriers that must be addressed to enable broader implementation.

A major factor currently influencing GTR adoption is the recent shift in performance grade (PG) requirements by the Georgia Department of Transportation (GDOT) [20,24,25]. To enhance pavement durability under the region's challenging climatic conditions and increasing traffic demands, GDOT now requires a minimum binder grade of PG 82-22 for surface mixtures such as the Porous European Mix (PEM) the most used surface layer for high-volume roads statewide [26,27]. However, current wet-process GTR modification practices, which typically incorporate 8–12% GTR by binder weight, generally achieve a performance grade of only PG 76-22 [28,29]. This gap highlights a pressing need for research aimed at optimizing GTR dosage and exploring hybrid modification techniques capable of meeting the PG 82-22 requirement while maintaining or improving mixture durability.

This study aims to address these critical knowledge gaps by evaluating two innovative modification strategies to meet GDOT's heightened performance expectations. The first investigates whether increasing GTR content to approximately 15% can elevate the base binder grade from PG 64-22 to PG 82-22. The second examines a hybrid modification approach in which dry-process GTR is combined with polymer-modified asphalt containing Styrene- Butadiene-Styrene (SBS), with the objective of enhancing the performance of PG 76-22 binders to PG 82-22 through synergistic effects. Beyond binder-level improvements, the research also assesses the long-term durability of PEM mixtures incorporating increased GTR contents, recognizing that durability performance is essential for sustainable implementation on high- volume roadways.

By integrating binder rheology, mixture performance, and durability evaluation, this research provides comprehensive insights to support expanded and optimized use of GTR in Georgia's pavement infrastructure. The findings are expected to contribute to environmentally responsible pavement engineering by increasing the beneficial reuse of scrap tires, reducing dependence on costlier polymer modifiers, and enabling the construction of longer-lasting asphalt pavements that conform to GDOT's updated performance specifications.

2. Experimental Program

2.1. Test specimens' preparation

2.1.1. Materials

This study utilized two performance-graded asphalt binders, PG 64–22 and PG 76–22, along with two crumb rubber–based modifiers: Ground Tire Rubber (GTR) and trans-polyoctenamer rubber (TOR). Both binders were supplied by Reeves Construction Company, Georgia. PG 64– 22 served as the base binder, whereas PG 76–22 was a polymer-modified binder incorporating Styrene–Butadiene–Styrene (SBS).

Table 1: Rheological properties of PG 64-22 and PG 76-22 binders.

Aging Condition	**Test Properties**	**AASHTO Standard**	**PG 64-22**	**PG 76-22**
Unaged	Viscosity 135C (cP)	T316	680	1250
	G*/sin δ @ 64°C (kPa)	T315	1.55	4.12
RTFO aged	G*/sin δ @ 64°C (kPa)	T315	4.31	3.58
RTFO + PAV Aged	G*sin δ @ 25°C (kPa)	T315	4242	4548
	Stiffness -12°C (MPa)	T313	252	214
	m-value @ -12°C	T314	0.312	0.314

Table 2: Physical properties of GTR

Properties	**Mass Content (%)**	**Method**
Acetone extract	8.7	PN-92/C04219
Rubber Additives	15.3	TGA
Rubber (SBR, NR)	48.7	TGA
Carbon black	32.7	TGA
Molecular structure	-	Particles
Particle Size	-	Mesh 30

Table 3: Characteristics of Trans-Polyoctenamer Rubber (TOR)

Property	**Value**	**Method**
Mooney viscosity ML (1+4) at 100 C (MU)	Less than 10	DIN53523
Class transition Temp (ºC)	-65	ISO11357-1/-2
Melting Point (ºC)	54	ISO11357-1/-3
Crystallinity (%)	30	DSC (2nd heating)
Thermal Degradation (ºC)	275	TGA

Property	Value	Method
Tensile Strength (MPa)	8.5	ISO 527
Elongation at break (%)	400	ISO 527

Table 1 details the rheological properties of the base asphalt binders (PG 64-22 and PG 76- 22). Table 2 outlines the material composition of the Ground Tire Rubber (GTR), and Table 3 provides the characteristics of the Trans-Polyoctenamer (TOR), with information according to the producer's datasheet.

2.1.2. Sample preparation

All asphalt modification procedures followed a consistent laboratory protocol. The base binders were first heated to 163 °C to ensure complete liquefaction prior to incorporating the modifiers. For PG 64–22–based mixtures, GTR and TOR were incrementally added to the hot binder and blended using a low-shear mechanical mixer operating at 800 rpm for 45 minutes [30]. This method ensured adequate dispersion of rubber particles without inducing excessive shear degradation.

For PG 76–22, which already contained SBS, the same heating process was applied; however, the introduction of GTR and TOR required enhanced blending to promote compatibility with the existing polymer network. Mixing was therefore performed using a high-shear mixer operating at 4000 rpm for 40 minutes [31]. TOR was added after the initial incorporation of GTR to facilitate rubber swelling and polymer interaction within the binder matrix.

All mixtures were blended following identical temperature, time, and shear conditions to ensure uniformity and repeatability across all samples.

2.1.3. Aging process

Asphalt binders naturally undergo aging due to thermal, environmental, and oxidative factors throughout their service life [32]. To simulate these effects, both short-term and long-term aging procedures were conducted in accordance with standardized laboratory protocols [33].

Short-term aging was performed using the Rolling Thin Film Oven (RTFO), following the requirements of AASHTO T 240 and ASTM D2872 [34,35]. Binder samples were poured into RTFO glass bottles and aged at 163 °C with an airflow of 4000 mL/min for a duration of 85 minutes while rotating inside the oven. This procedure replicates the oxidation and volatilization occurring during asphalt mixing and paving operations.

Long-term aging was performed using the Pressure Aging Vessel (PAV) in accordance with AASHTO R 28 [36]. The RTFO-aged binders were placed in stainless-steel pans (50 g per pan)

and exposed to a pressure of 2.1 MPa at temperatures ranging from 100 °C to 110 °C for approximately 20 hours. This process represents the oxidative hardening that occurs during 12–15 years of pavement service.

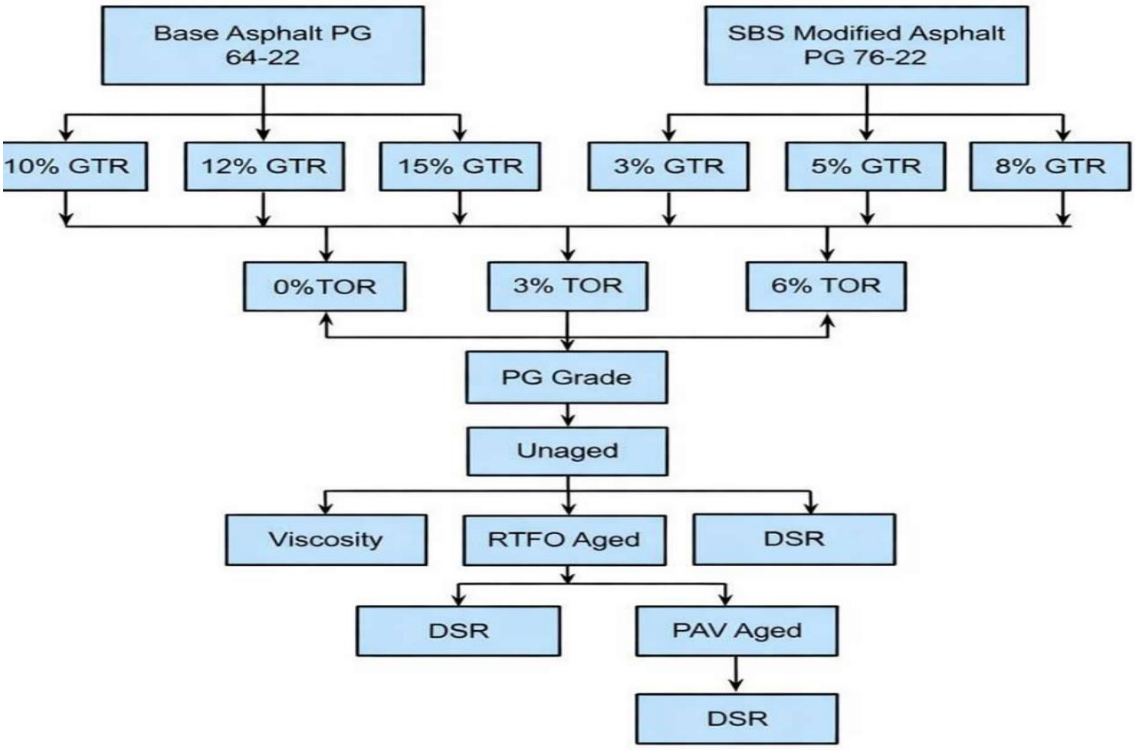
A total of ten pans were aged simultaneously to ensure consistency and adequate sample volume for all subsequent rheological and performance tests.

2.2. Experimental Procedure

This study conducted conventional and advanced laboratory testing on unaged, RTFO-aged, and PAV-aged asphalt binders. The experimental program included RV and DSR tests to evaluate viscosity, stiffness, and viscoelastic performance, while FTIR was used to assess chemical aging, and BBR was performed to determine low-temperature cracking resistance.

A total of 60 asphalt binder samples were prepared from two base binders (PG 64–22 and PG 76–22). For each binder grade, 30 samples were produced using two modifiers (GTR and TOR), with nine modification combinations and three aging conditions. The PG 64–22 blends included 10%, 12%, and 15% GTR each combined with 0%, 3%, and 6% TOR, and the same modification matrix was applied to PG 76–22.

All binder types followed the same preparation, aging, and testing sequence.



FIGURE

2.2.1. Rotational viscometer

Viscosity is a key indicator of an asphalt binder's workability and resistance to flow at elevated temperatures [37]. In this study, the viscosity of unaged, RTFO-aged, and PAV-aged binders was measured using a Brookfield Rotational Viscometer following ASTM D4402 [38]. Tests were conducted at 135 °C and 165 °C to evaluate the influence of GTR and TOR modification on mixing and compaction behavior.

Each sample was conditioned to the target temperature, and a SC4-27 spindle was rotated at 20 rpm to determine the torque required to shear the binder [39]. The instrument automatically calculated viscosity once a stable reading was obtained. All measurements were performed in duplicate, and the mean values were used to compare the effects of modification and aging on binder flow characteristics.

2.2.2. Dynamic shear rheometer (DSR)

The rheological behavior of the modified binders was evaluated using a Dynamic Shear Rheometer (DSR) in accordance with AASHTO T315 [40]. The test characterizes the complex shear modulus

(G*) and phase angle (δ), parameters fundamental for assessing rutting and fatigue performance under the Superpave PG system.

For unaged and RTFO-aged binders, temperature sweep tests were conducted from 46 °C to 88 °C at 6 °C intervals using 25 mm plates. PAV-aged binders were tested with 8 mm plates over 19–31 °C to determine their fatigue susceptibility. The rutting index (G*/sinδ) and fatigue index (G*·sinδ) were computed to assess performance at high and intermediate pavement temperatures [41]. All specimens were conditioned to the test temperature prior to loading to ensure thermal uniformity.

2.2.3. Fourier-transform infrared (FTIR) spectroscopy

Fourier-Transform Infrared (FTIR) spectroscopy was employed to analyze the chemical functional groups associated with binder oxidation. Spectra were collected using a Bruker ATR- FTIR system in the range of 400–4000 cm^{-1} with a resolution of 4 cm^{-1}, following ASTM E1252-98 [42].

For each unaged, RTFO-aged, and PAV-aged binder, the carbonyl (~1700 cm^{-1}) and sulfoxide (~1030 cm^{-1}) absorption peaks were quantified as indicators of aging severity. The spectra were produced by averaging 32 scans to enhance signal clarity, and oxidation indices were calculated to assess the effect of GTR and TOR modification on chemical aging. All measurements were replicated to ensure reliability.

2.2.4. Bending Beam Rheometer (BBR)

Low-temperature performance of the modified binders was evaluated using a Bending Beam Rheometer (BBR) in accordance with AASHTO T313. The test characterizes the creep stiffness (S) and m-value, which together indicate the binder's ability to resist thermal cracking under prolonged low-temperature loading [43].

PAV-aged binders were poured into standardized molds to prepare beams with dimensions of 125 × 12.5 × 6.25 mm. Each specimen was conditioned at the target test temperatures (−12 °C and −18 °C) for one hour before testing to ensure thermal equilibrium. During loading, a constant force was applied to the center of the beam, and the resulting deflection was recorded to compute S(60s) and the corresponding m-value.

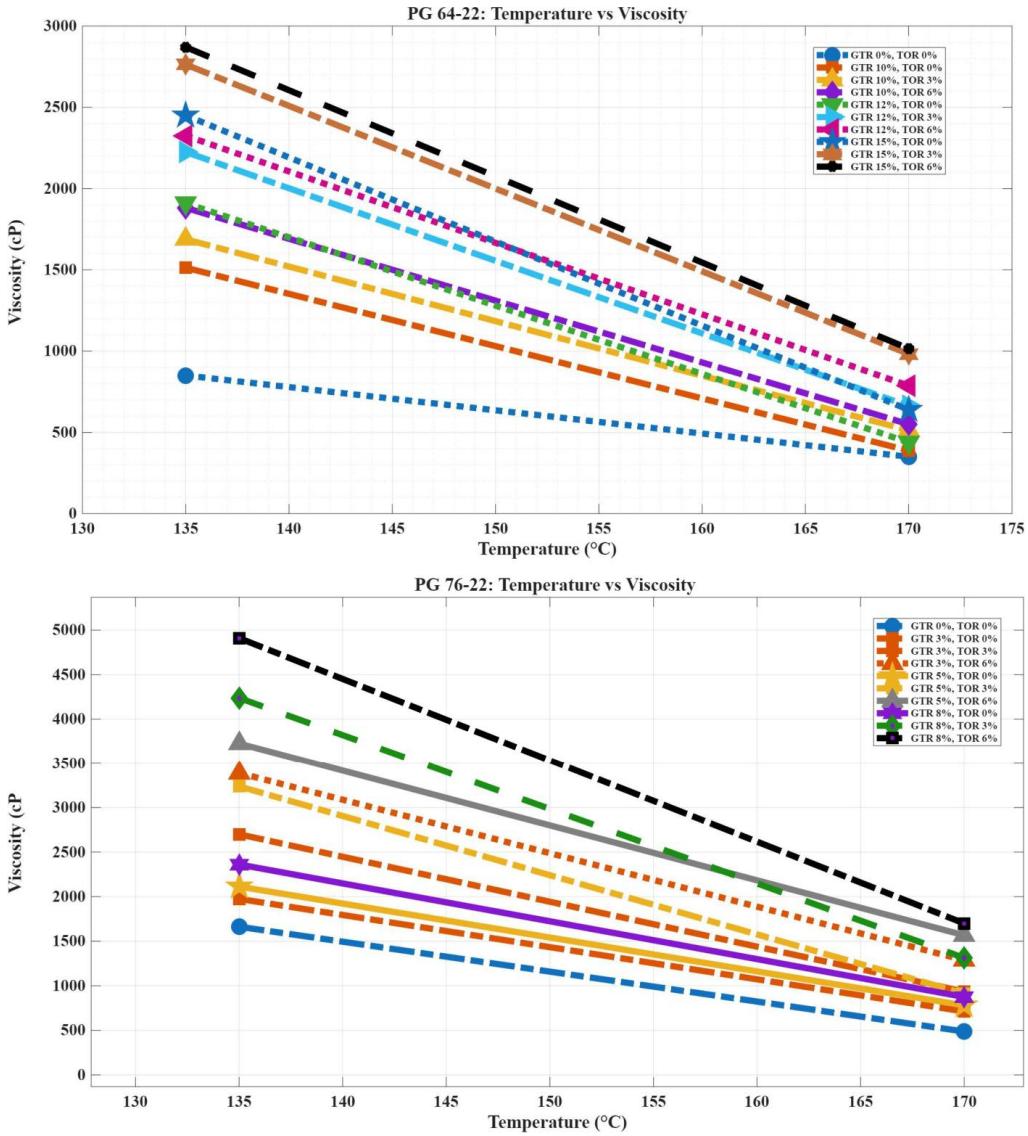
These parameters were used to assess the relaxation capacity and brittleness of the GTR–TOR modified binders at cold climatic conditions. All tests were conducted in duplicate, and the average

results were used to compare the low-temperature cracking susceptibility across the binder modification matrix.

3. Results and Discussion

3.1. Rotational Viscosity (RV)

The rotational viscosity measurements at 135 °C and 170 °C were used to evaluate the workability of the base binders PG 64-22 and PG 76-22 and their GTR/TOR-modified counterparts. For all binders, viscosity decreased with increasing temperature, as expected for the morphologically simple asphalt binders. However, the addition of GTR and TOR significantly altered the absolute viscosity levels and, consequently, the mixing/compaction behavior.



Viscosity characteristics of (a) PG 64-22 and (b) PG 76-22 asphalt binders under high- temperature conditions (135 °C and 170 °C).

For the base PG 64-22, the viscosity at 135 °C was within the acceptable range for conventional asphalt binders, remaining below the Superpave upper limit of 3000 cP at 135 °C. The incorporation of GTR (10–15%) led to a marked increase in viscosity at 135 °C. The 10% GTR-modified PG 64-22 showed a substantial increase in viscosity (on the order of roughly 1.5–2 times the base value, based on the tabulated data), while 12% and 15% GTR further increased viscosity, indicating a strong dependence on GTR content. This trend reflects the swelling of GTR particles in the asphalt matrix, which thickens the binder and enhances its elastic response. At 170 °C, the relative increase in viscosity due to GTR was smaller in percentage terms, suggesting that high temperatures partially mitigate the stiffening effect of GTR and thereby ease mixing.

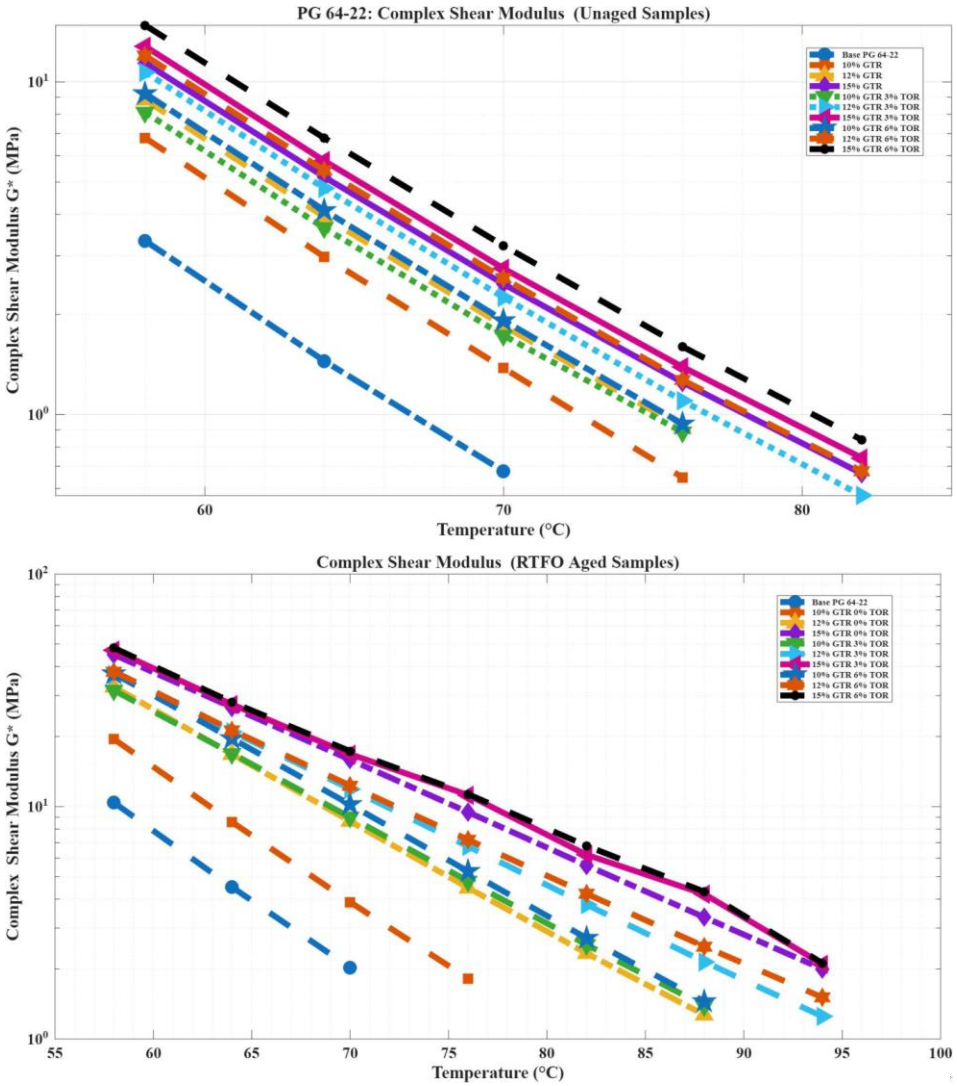
The TOR-modified binders (TOR 3% and TOR 6%) exhibited increased viscosity compared to the unmodified base binder but generally remained less viscous than the corresponding high- GTR blends at the same temperature. When TOR was used in conjunction with GTR, the resulting viscosity lay between that of the base binder and the high-GTR-only blends, indicating that TOR can contribute to network formation and improved elastic response without causing excessive increases in viscosity. The combined GTR+TOR systems therefore provide a compromise between enhanced performance and workable viscosity.

For the PG 76-22 base binder, the initial viscosity at 135 °C was naturally higher than that of PG 64-22, consistent with its higher performance grade. The addition of GTR further increased its viscosity, but the relative change was somewhat smaller than in the PG 64-22 system because the starting viscosity of PG 76-22 was already elevated. TOR-modified PG 76-22 followed a similar pattern to PG 64-22: TOR increased viscosity but not to the same extent as high GTR contents alone. Across all binders, viscosities at 170 °C remained below the critical limits for pumpability, indicating that appropriate mixing temperatures can still be maintained despite the presence of crumb rubber and TOR.

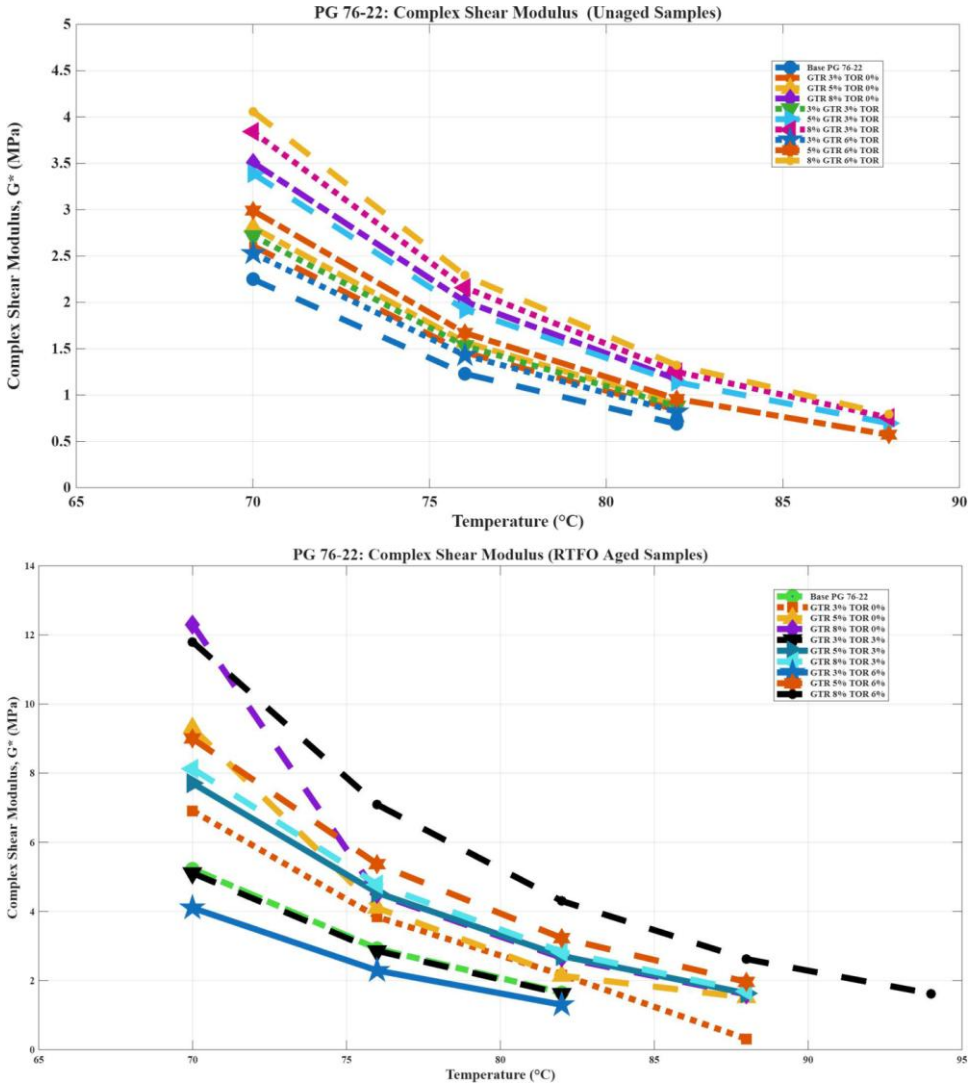
Overall, the RV results show that GTR is more influential than TOR in increasing binder viscosity, especially at 135 °C. This is beneficial for rutting resistance but necessitates careful control of plant mixing and compaction temperatures to avoid constructability issues. TOR additions offer a way to introduce polymer-like benefits with more moderate impacts on viscosity.

3.2. High-Temperature Rheological Behavior (DSR)

Dynamic shear rheometer tests on PG 64-22 and PG 76-22 binders, with and without GTR and TOR, were used to assess their high-temperature rutting resistance via parameters such as complex modulus (G*), phase angle (δ), and G*/sinδ.



(b) Comparison of dynamic shear modulus of PG 64-22 asphalt binder before and after RTFO aging: (a) unaged and (b) RTFO-aged, incorporating GTR and TOR.



(b) Comparison of dynamic shear modulus of PG 76-22 asphalt binder before and after RTFO aging: (a) unaged and (b) RTFO-aged, incorporating GTR and TOR.

For the base PG 64-22, G* decreased and δ increased with temperature, reflecting the typical transition toward more viscous behavior at higher temperatures. The calculated G*/sinδ for the unaged base binder met the Superpave rutting criterion (G*/sinδ ≥ 1.0 kPa) up to a temperature close to its nominal high PG grade. After RTFO aging, the increased stiffness shifted the critical high temperature slightly higher, consistent with oxidative hardening.

The addition of GTR to PG 64-22 significantly increased G* and reduced δ across the tested high-temperature range, resulting in a pronounced increase in G*/sinδ. The 10% GTR binder already showed a clear improvement in rutting resistance, with G*/sinδ values consistently higher than those of the base binder at the same temperature. Increasing the GTR content to 12% and 15%

further increased G* and lowered δ, indicating more pronounced elastic behavior and a better ability to resist permanent deformation under repeated loading. From the tabulated trends, the GTR-modified binders could maintain G*/sinδ above the 1.0 kPa threshold at temperatures several degrees higher than the base PG 64-22, effectively upgrading the high-temperature PG rating.

The TOR-modified PG 64-22 exhibited intermediate behavior between the base and GTR-rich binders. TOR increased G* and decreased δ, particularly at higher dosages, consistent with the formation of a polymeric network within the binder phase. Although the absolute G*/sinδ of the TOR-only binders generally remained below that of the highest GTR contents, the TOR systems still improved rutting resistance relative to the base binder while keeping viscosity increases more moderate. In combining GTR+TOR systems, the effect was essentially additive: higher G*/sinδ and lower δ than with either modifier alone. These blends displayed superior rutting resistance and a more pronounced elastic character, suggesting synergistic interactions between GTR and TOR.

For PG 76-22, the baseline G*/sinδ values at high temperatures were already significantly higher than those of PG 64-22, which is characteristic of a high-PG, polymer-modified or inherently stiff binder. GTR addition further stiffened the binder, but because the underlying binder was already very resistant to rutting, the relative benefit in terms of additional PG grade uplift was smaller than for PG 64-22. Nevertheless, the GTR- and TOR-modified PG 76-22 binders still exhibited higher G*/sinδ and lower δ than the base PG 76-22, demonstrating additional improvements in high-temperature performance, particularly under heavier or more frequent loading conditions.

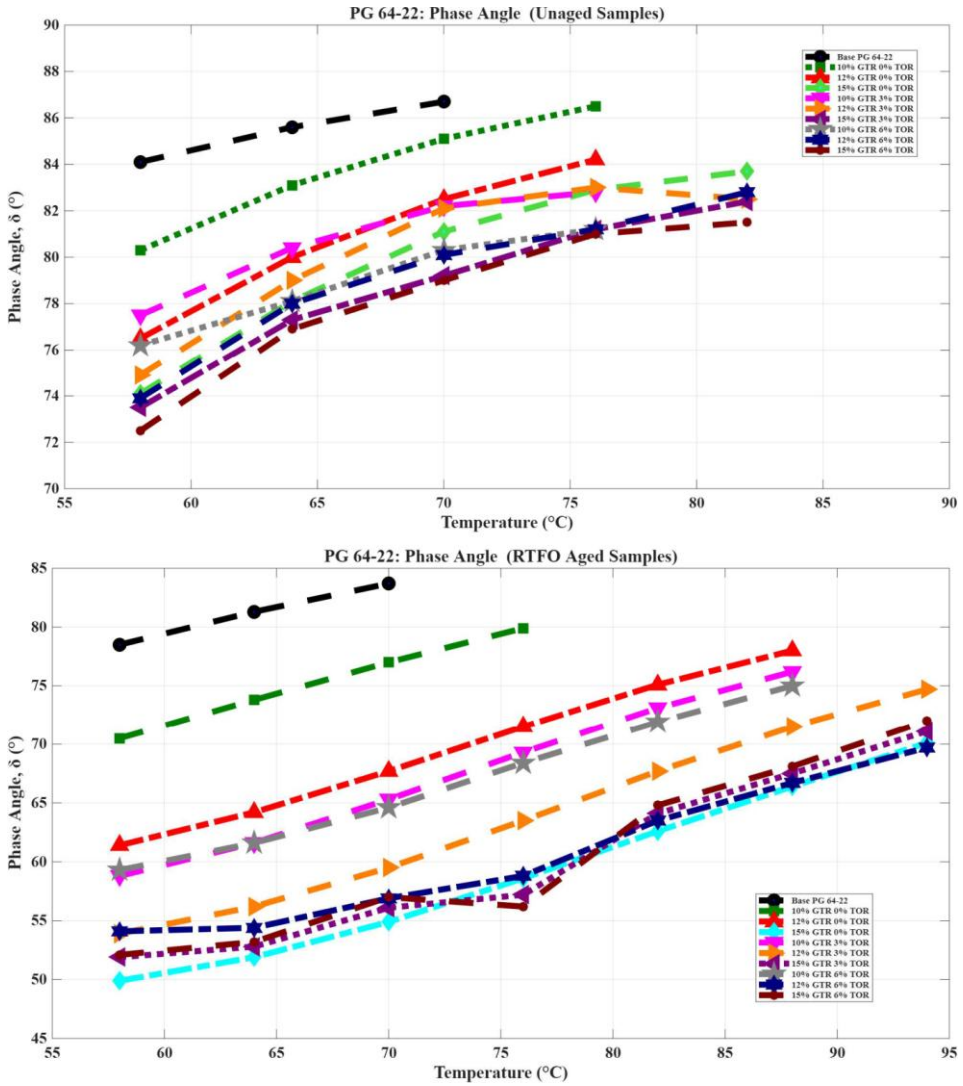
In summary, DSR results confirm that both GTR and TOR improve high-temperature rutting resistance, with GTR providing the stronger effect on G* and G*/sinδ, and TOR primarily boosting elasticity (lower δ) while moderating viscosity increases. PG 64-22 benefits more noticeably from these modifications in terms of PG grade uplift than PG 76-22.

3.3. Intermediate and Fatigue-Related Behavior (G*·sinδ)

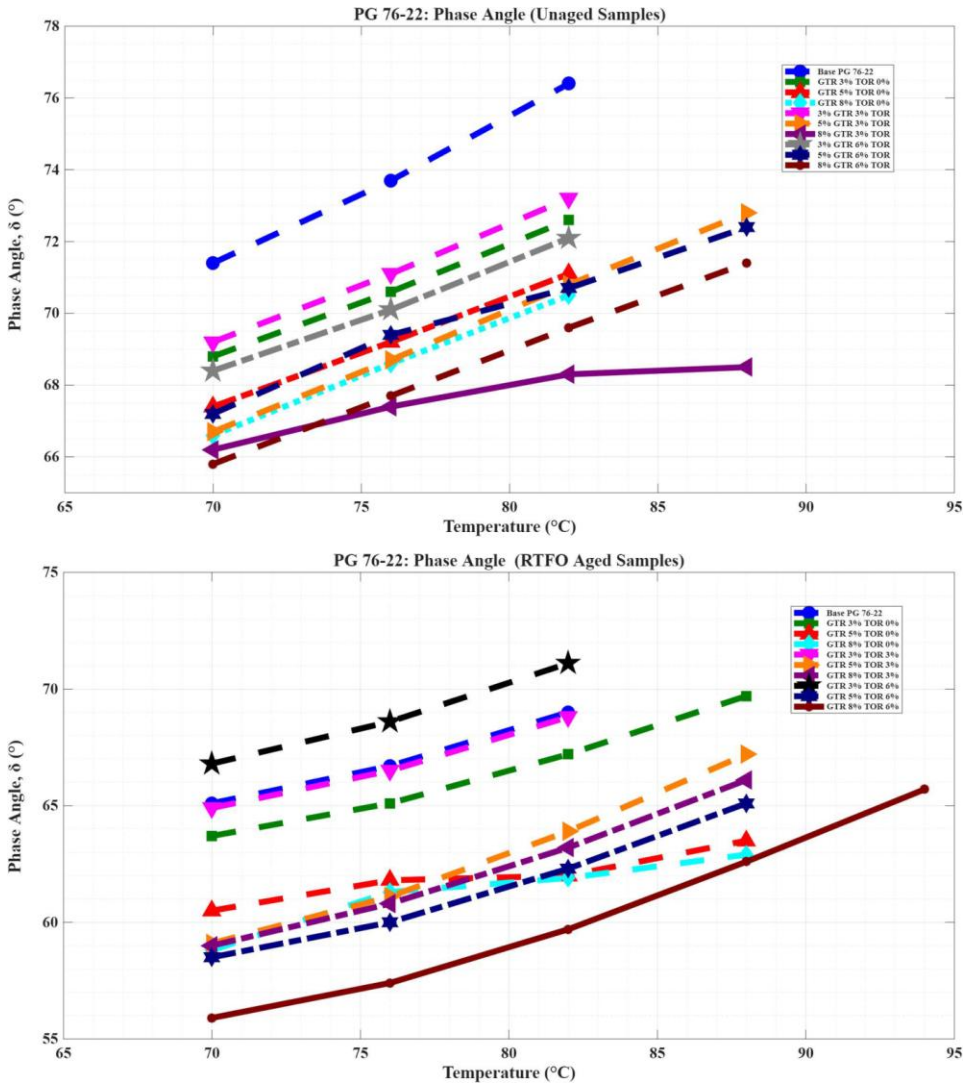
Fatigue cracking in asphalt pavements is predominantly controlled by the viscoelastic behavior of asphalt binders at intermediate service temperatures, where the material is subjected to repeated tensile and shear stresses induced by traffic loading. This behavior is commonly characterized using the Superpave fatigue parameter $G*\sin\delta$, which represents the amount of energy dissipated per loading cycle and serves as an indicator of the binder's susceptibility to fatigue damage. Lower values of $G*\sin\delta$ are generally associated with improved resistance to crack initiation and

propagation, as they reflect a greater capacity for strain accommodation and energy dissipation without fracture.

The incorporation of modifiers such as ground tire rubber (GTR) and trans-polyoctenamer rubber (TOR) alters both the stiffness and phase angle of the binder, thereby directly influencing its fatigue response. Increases in stiffness can elevate $G*\sin\delta$and potentially reduce fatigue resistance, whereas reductions in phase angle indicate enhanced elastic recovery, which may mitigate damage accumulation under cyclic loading. Consequently, the net fatigue performance of modified binders depends on the balance between stiffening effects and improvements in elasticity. Understanding the combined and interactive effects of GTR and TOR at intermediate temperatures is therefore essential for designing asphalt binders that achieve an optimal balance between rutting resistance and fatigue durability, ensuring reliable long-term pavement performance.



(b) Comparison Phase Angle of PG 64-22 asphalt binder before and after RTFO aging: (a) unaged and (b) RTFO-aged, incorporating GTR and TOR.



(b) Comparison Phase Angle of PG 76-22 asphalt binder before and after RTFO aging: (a) unaged and (b) RTFO-aged, incorporating GTR and TOR.

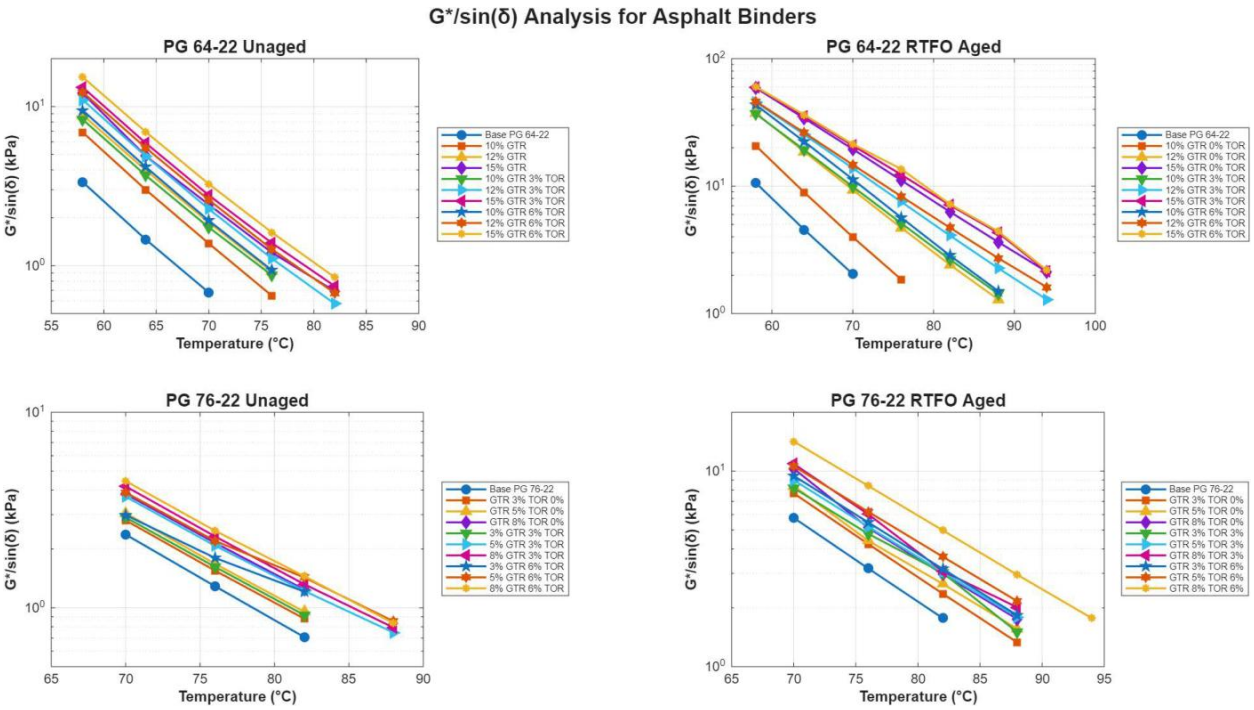
Where intermediate temperature data and fatigue-related parameters ($G^* \cdot \sin\delta$) were measured, the trends indicated that GTR-modified binders tend to increase stiffness at intermediate temperatures and can slightly increase $G^* \cdot \sin\delta$, which may be detrimental for fatigue resistance. However, the decrease in phase angle for GTR- and TOR-modified systems implies greater elastic recovery, which can partially compensate for the stiffening effect. In some of the modified binders, particularly those with moderate GTR contents and TOR, the $G^* \cdot \sin\delta$ values remained within acceptable ranges while still delivering improved rutting resistance.

This suggests that the choice of GTR and TOR dosage is critical: low to moderate modifier contents can provide a balanced performance envelope, whereas very high GTR contents, although

excellent for rutting, may compromise flexibility and fatigue if not carefully accounted for in mixture design.

3.4 Rutting Resistance

Rutting resistance was evaluated using the Superpave parameter $G*/\sin\delta$ to assess the high-temperature performance of the asphalt binders. Figures 9 and 10 present the results for PG 64–22 and PG 76–22 binders, respectively. In general, the incorporation of GTR and TOR significantly improved resistance to permanent deformation across all tested temperatures. As expected, $G*/\sin\delta$ values decreased with increasing temperature; however, modified binders consistently outperformed the corresponding base binders.



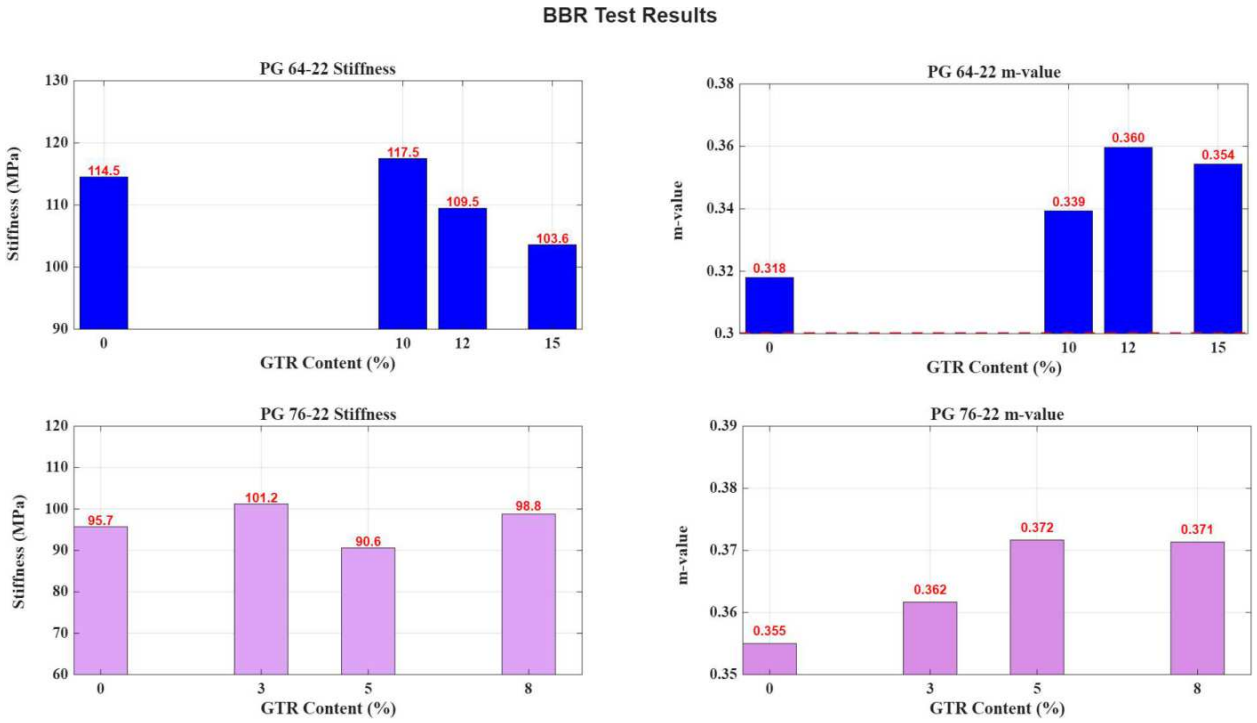
Rutting parameter Comparison of both PG 64-22&76-22 binder Unaged and RTFO Aged, modified with GTR and TOR.

For PG 64–22 binders, GTR was the dominant contributor to rutting resistance, while TOR provided additional enhancement at higher dosages. All modified binders met the Superpave specification at their respective design temperatures in both unaged and RTFO-aged conditions. Aging further increased binder stiffness, indicating improved high-temperature durability. Notably, binders with higher GTR and TOR contents exhibited substantial gains in stiffness, enabling the PG 64–22 binder to achieve performance levels comparable to PG 76–22.

A similar improvement trend was observed for PG 76–22 binders. Despite lower GTR contents compared to PG 64–22 formulations, the modified binders demonstrated enhanced viscoelastic behavior and increased rutting resistance in both unaged and aged states. After RTFO aging, several modified binders exceeded the Superpave requirements at elevated temperatures, qualifying for a higher performance grade (PG 82–22).

Overall, the results confirm that GTR is highly effective in improving rutting resistance, while TOR acts as a complementary modifier that enhances thermal stability. The combined use of GTR and TOR offers a practical and cost-effective approach to upgrading asphalt binder performance under high-temperature loading conditions.

3. 4. Low-Temperature Performance (BBR)



Bending beam rheometer (BBR) tests carried out at low temperatures (e.g., −12 °C and −18 °C, depending on the binder and aging condition) provided the creep stiffness S(t) and m-value at 60 s. These parameters were used to evaluate low-temperature cracking susceptibility.

For the base PG 64-22, the stiffness S at the critical low temperature was below the Superpave limit of 300 MPa, and the m-value exceeded 0.300, indicating acceptable low-temperature performance in line with its PG −22 designation. After RTFO and PAV aging, S increased and m

decreased, reflecting the typical embrittlement due to oxidation. Nevertheless, the base binder generally remained within specification at the design low temperature.

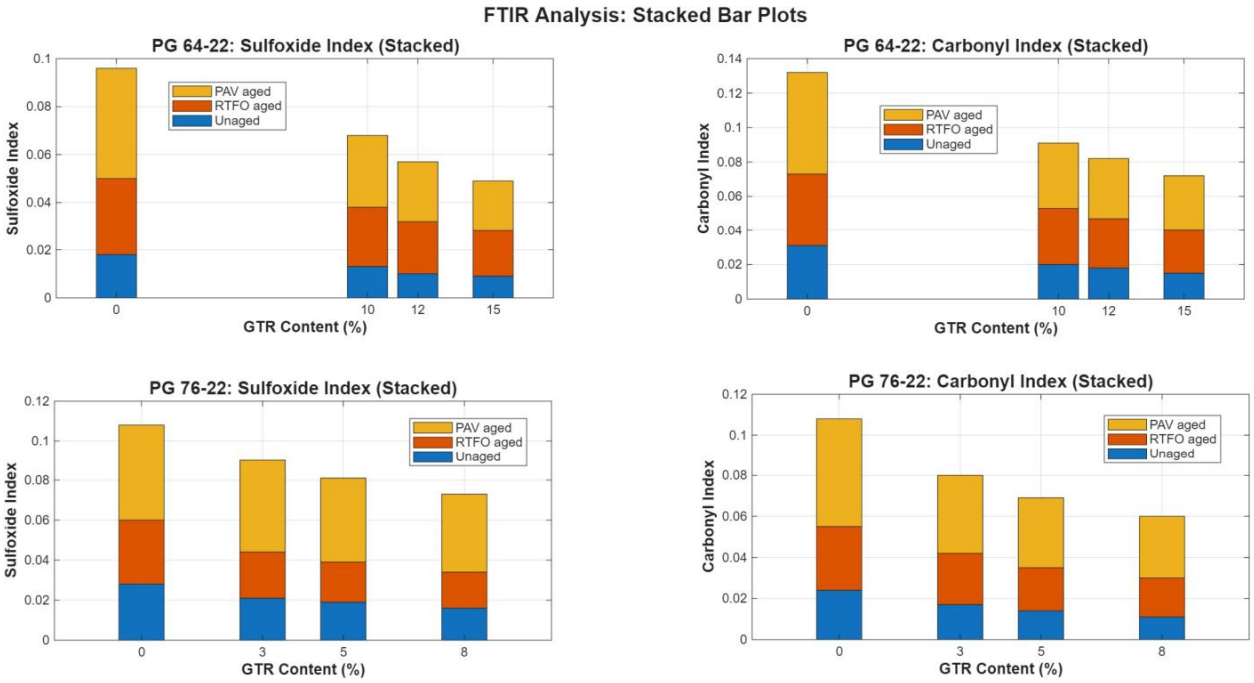
The GTR-modified PG 64-22 binders showed somewhat higher low-temperature stiffness S compared to the base binder, consistent with the increased overall stiffness introduced by crumb rubber. However, the m-values for the GTR blends remained comparable to, or in some cases slightly higher than, those of the base binder. This suggests that while GTR does stiffen the binder matrix, it also contributes to a more complex viscoelastic response that maintains an adequate relaxation rate. In most cases, the modified binders still satisfied $S \leq 300$ MPa and $m \geq 0.300$ at the targeted low temperature, implying that low-temperature cracking performance is not significantly compromised, especially for moderate GTR contents.

The TOR-modified binders exhibited similar or slightly improved m-values relative to the base binder, indicating enhanced relaxation capability. Stiffness S was often comparable to or slightly higher than that of the base binder but typically stayed within specification. For combined GTR+TOR systems, low-temperature performance generally remained acceptable, although the highest GTR contents sometimes pushed S closer to the 300 MPa threshold after long-term aging.

For PG 76-22, the base binder stiffness at low temperature was higher than that of PG 64-22, as expected for a stiffer, high-PG binder. GTR additions further increased S and slightly reduced m, pointing to a potential risk of increased low-temperature cracking if the low-temperature grade is not adjusted accordingly. However, the data indicates that, for the GTR contents used, the binders still met the Superpave low-temperature criteria at the specified design temperature. TOR-modified PG 76-22 tended to maintain better m-values and somewhat mitigate the increase in S, providing a more favorable combination of stiffness and relaxation at low temperatures.

Overall, BBR results show that while GTR and TOR modifications increase stiffness, especially after aging, most blends can still meet low-temperature performance requirements if modifier contents are kept within a reasonable range. PG 64-22 appears more tolerant to GTR addition at low temperature than PG 76-22, which is already relatively stiff.

3.5. FTIR Spectroscopy and Chemical Characterization



FTIR spectra were obtained for the base binders and the GTR/TOR-modified binders under different aging conditions to explore the underlying chemical changes associated with modification and aging.

For the base PG 64-22 and PG 76-22, the main absorption bands corresponded to aliphatic C–H stretching (around 2850–2950 cm^{-1}), aromatic C=C stretching (near 1600 cm^{-1}), and various fingerprint-region bands typical of asphalt binders. With aging (RTFO and PAV), increases were observed in oxidation-related bands, particularly the carbonyl (C=O, around 1700 cm^{-1}) and sulfoxide (S=O, near 1030 cm^{-1}) indices. These increases are consistent with the formation of oxygen-containing functional groups during oxidative aging and explain the associated increase in stiffness observed in RV, DSR, and BBR tests.

For GTR-modified binders, additional features appeared that are characteristic of rubber components, such as bands related to C=C stretching in the rubber backbone and possible S–S or C–S linkages from vulcanized rubber. The intensity of these rubber-related bands increased with GTR content, confirming the effective incorporation and swelling of GTR in the binder phase. In some cases, the FTIR spectra of GTR-modified binders also showed slightly different oxidation patterns after aging, with a reduced relative increase in carbonyl and sulfoxide indices compared to the base binder. This suggests that GTR can act as a sink for radicals or oxygen, partially

retarding oxidation of the asphalt fraction, which aligns with the somewhat moderate aging effects seen in the rheological data for certain GTR contents.

TOR-modified binders showed spectral changes consistent with the presence of a polymeric or oil-rubber component, including enhanced absorption in regions associated with unsaturated hydrocarbons and possibly aromatic structures. The TOR-related bands, although often overlapping with asphalt peaks, contributed to increased absorption in the mid-IR fingerprint region. After aging, TOR-modified binders displayed oxidation patterns comparable to or slightly milder than the base binders, implying some resistance to oxidative hardening.

Combined GTR+TOR systems exhibited both sets of features: rubber-related bands from GTR and polymer/oil-related features from TOR. The FTIR-derived oxidation indices suggested that these systems may have a more complex aging behavior, with some mitigation of oxidation in the base asphalt fraction due to the presence of rubber and TOR. This is consistent with the rheological observations where GTR+TOR blends maintained high rutting resistance while not exhibiting excessively brittle behavior at low temperatures, especially at moderate modifier contents.

3. 6. Integrated Performance Assessment

By combining the RV, DSR, BBR, and FTIR results, a coherent picture of the effect of GTR and TOR on PG 64-22 and PG 76-22 binders emerges.

For PG 64-22, GTR addition significantly upgrades high-temperature performance (higher $G^*/\sin\delta$, higher effective PG high temperature) and improves rutting resistance, at the cost of increased viscosity at mixing and compaction temperatures. TOR offers additional elasticity and contributes to rutting resistance, with more moderate increases in viscosity than GTR. At low temperatures, GTR and TOR modifications generally maintain acceptable S and m-values, particularly at moderate GTR contents, ensuring that low-temperature cracking performance is not drastically compromised.

For PG 76-22, which already possesses high rutting resistance, GTR and TOR provide incremental gains in stiffness and elasticity at high temperature. However, because the base binder is stiffer, care must be taken to avoid excessive low-temperature stiffness, especially at high GTR contents. TOR in PG 76-22 tends to improve elasticity and somewhat temper the increase in low-temperature stiffness compared with GTR alone.

FTIR analyses support the mechanistic interpretation of these rheological behaviors. GTR and TOR introduce additional polymeric and rubbery phases into the binder and can slightly modify the oxidation kinetics of the asphalt fraction, which in turn influences long-term rheological evolution.

Overall, the study demonstrates that GTR and TOR are effective modifiers for enhancing high-temperature performance of PG 64-22 and PG 76-22 binders. For practical applications, moderate GTR contents, possibly in combination with TOR, appear to provide the best balance between rutting resistance, workability, and low-temperature cracking resistance. The rheological improvements are underpinned by clear chemical signatures in FTIR, confirming the formation of a more elastic and complex binder network.

4. Conclusions

4.1 Conclusions

This study investigated the feasibility of using high-dosage ground tire rubber (GTR) as a primary modifier to produce asphalt binders meeting the demanding PG 82-22 specification required by the Georgia Department of Transportation (GDOT). Two modification strategies were evaluated: elevating the grade of a base PG 64-22 binder through high GTR content (up to 15%), and enhancing an SBS-modified PG 76-22 binder through hybrid modification with GTR and the compatibility agent trans-polyoctenamer (TOR).

The key findings are summarized as follows:

1. High-Dosage GTR as a Primary Modifier is Technically Viable: The incorporation of

15% GTR successfully elevated the high-temperature performance grade of a PG 64-22 binder to PG 82. This was evidenced by a significant increase in the rutting resistance parameter ($G^*/\sin\delta$), meeting the target specification. The modified binder also maintained acceptable low-temperature performance (creep stiffness and m-value) within Superpave criteria, demonstrating a balanced performance profile.

2. GTR and TOR Enhance Rheological Properties Synergistically: The addition of GTR

significantly improved the binder's elastic response and resistance to permanent deformation. The use of TOR further enhanced binder compatibility promoted a more homogeneous polymer-rubber network, and contributed to improved long-term durability, as indicated by rheological and FTIR

analysis. In hybrid systems with PG 76-22, GTR and TOR provided incremental performance gains.

3. Workability is Manageable with Process Adjustments: While GTR increased binder

viscosity, particularly at 135°C, all modified binders remained within workable limits for mixing and compaction at elevated temperatures (e.g., 170°C). The viscosity increase associated with TOR was more moderate, suggesting that combined GTR+TOR systems offer a favorable compromise between enhanced performance and practical constructability.

4. Chemical Characterization Supports Performance Benefits: FTIR spectroscopy confirmed

the effective incorporation of GTR and TOR into the asphalt matrix. The modified binders exhibited altered chemical aging patterns, with some evidence that GTR may partially mitigate oxidation of the base asphalt, contributing to retained flexibility after long-term aging.

5. A Sustainable Pathway for Scrap Tire Utilization: This high-dosage approach has the

potential to increase the consumption of recycled tire rubber in asphalt mixtures by over 50% compared to conventional practice. This directly addresses the environmental challenge of scrap tire accumulation while reducing reliance on virgin polymer modifiers.

In conclusion, high-dosage GTR modification, particularly when used in conjunction with compatibility agents like TOR, presents a technically sound, environmentally strategic, and scalable method for producing sustainable, high-performance asphalt binders that meet advanced specifications such as PG 82-22.

5. Recommendations

1. Revise Performance-Based Binder Specifications. Transportation agencies, including GDOT, should update binder specifications to formally recognize and permit high-dosage GTR modifications (e.g., 12-15% by binder weight) as a validated and sustainable pathway to meet demanding performance grades like PG 82-22. This policy change is the fundamental enabler for market adoption.

2. Initiate Pilot Projects with Integrated Performance Monitoring. To bridge the gap between laboratory proof and widespread use, agencies should partner with industry to conduct full-scale

field demonstrations. These pilot projects must include a long-term performance monitoring plan to validate constructability, durability, and lifecycle benefits under real traffic and environmental conditions.

9. Funding Declaration

This work was not supported by any agency

10. Declaration

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics: NA, as this study did not involve human participants or animals.

Consent to Participate: NA, as no human participants were involved.

Consent to Publish: NA, as the manuscript contains no images or identifiable information of human participants.

12. Data availability

Data will be made available on request

References

[1] T. Amari, N.J. Themelis, I.K. Wernick, Resource recovery from used rubber tires, Resources Policy 25 (1999) 179–188.

[2] N. Nayak, D. Apelian, Opportunities and barriers to resource recovery and recycling from Shredder residue in the United States, Jom 66 (2014) 2367–2376.

[3] A. Islam, "Dynamic Modulus of SBS-Modified Asphalt Mixture Added with Ground Tire Rubber Content," College of Graduate Studies: Theses & Dissertations., Georgia Southern University, 2025. doi: https://digitalcommons.georgiasouthern.edu/etd/2966.

[4] A. Gifari, A. Islam, R. I. Babul, E. Ahmed, and S. Alim, "Performance Assessment of GTR Modified Asphalt Concrete: A Comprehensive Study on Mechanical and Durability Properties," in *Proceedings of the 8th International Conference on Civil Engineering for Sustainable Development (ICCESD 2026)*, KUET, Khulna, Bangladesh, Feb. 2026.

[5] A. Islam, A. Gifari, and M. S. Alim, "Evaluation of Low Temperature Rheological Properties of GTR and TOR modified Asphalt binders using Bending Beam Rheometer (BBR)," in *Proceedings of the International Conference on Civil Engineering Research & Innovations (ICCEI 2025)*, RUET, Rajshahi, Bangladesh, Dec. 2025.

[6] A.Islam, "Integrated Traffic Management in Banani." *American Journal of Engineering Research*", 2013

[7] A. Gifari, A. Islam, R. S. Babul, E. Ahmed, and M. S. Alim, "Performance Assessment of GTR Modified Asphalt Concrete: A comprehensive Study on Mechanical and Durability Properties" *in Proceedings of the 8th International Conference on Civil Engineering for Sustainable Development (ICEESD-2026), 5-7 February 2026, KUET, Khulna, Bangladesh*

[8] D. Goevert, The value of different recycling technologies for waste rubber tires in the circular economy—A review, Frontiers in Sustainability 4 (2024) 1282805.

[9] N. Nkosi, T. Nhubu, N.H. Mthombeni, An inventory analysis of waste tyre generation and management in South Africa, Waste Management 194 (2025) 353–365.

[10] S.I. Magagula, K. Lebelo, T.M. Motloung, T.C. Mokhena, M.J. Mochane, Recent advances on waste tires: bibliometric analysis, processes, and waste management approaches, Environmental Science and Pollution Research 30 (2023) 118213–118245.

[11] M. Hashamfirooz, M.H. Dehghani, M. Khanizadeh, M. Aghaei, P. Bashardoost, M.S. Hassanvand, M. Hassanabadi, F. Momeniha, A systematic review of the environmental and health effects of waste tires recycling, Heliyon 11 (2025).

[12] M.L. Mahlangu, Waste tyre management problems in South Africa and the possible opportunities that can be created through the recycling thereof, University of South Africa (South Africa), 2009.

[13] M. Sampath, N. Konikkara, S. David, J.P. Rath, A. SKP, Advancements in sustainable materials for environmentally responsible tyre production: a comprehensive review, RSC Sustainability 3 (2025) 4336–4363.

[14] R. Ghabchi, A. Arshadi, M. Zaman, F. March, Technical challenges of utilizing ground tire rubber in asphalt pavements in the United States, Materials 14 (2021) 4482.

[15] M. Sambucci, D. Marini, M. Valente, Tire recycled rubber for more eco-sustainable advanced cementitious aggregate, Recycling 5 (2020) 11.

[16] D. Lo Presti, Recycled tyre rubber modified bitumens for road asphalt mixtures: A literature review, Constr. Build. Mater. 49 (2013) 863–881.

[17] G. Baumgardner, A.J.T. Hand, T. Aschenbrener, Recycled Tire Rubber–Hybrid GTR Binders and Dry Added GTR–How to use them in Asphalt Pavement Mixtures, United States. Federal Highway Administration. Office of Preconstruction …, 2021.

[18] R. Ma, Y. Li, P. Cheng, X. Chen, A. Cheng, Low-temperature cracking and improvement methods for asphalt pavement in cold regions: A review, Buildings 14 (2024) 3802.

[19] A.M. Saniga, A. Rajish, S. Shankar, R. Vishnu, Optimal pavement maintenance and management strategies for flood affected low volume rural roads, Mater. Today Proc. (2023).

[20] F. March, R. Ghabchi, M. Zaman, P.A. Arshadi, Use of ground tire rubber (GTR) in asphalt pavements: literature review and dot survey, School of Civil Engineering and Environmental Science (CEES), The University of Oklahoma Norman, Oklahoma (2016).

[21] R. Ghabchi, A. Arshadi, M. Zaman, F. March, Technical challenges of utilizing ground tire rubber in asphalt pavements in the United States, Materials 14 (2021) 4482.

[22] R. Ghabchi, A. Arshadi, M. Zaman, F. March, Technical challenges of utilizing ground tire rubber in asphalt pavements in the United States, Materials 14 (2021) 4482.

[23] G. Baumgardner, A.J.T. Hand, T. Aschenbrener, Recycled Tire Rubber–Hybrid GTR Binders and Dry Added GTR–How to use them in Asphalt Pavement Mixtures, United States. Federal Highway Administration. Office of Preconstruction …, 2021.

[24] B. Bui, A. Amekudzi-Kennedy, R. Clark, J. Smith-Colin, S. Amoaning-Yankson, Performance-Based and Evidence-Based Approach to Research Implementation at the Georgia Department of Transportation, Transp. Res. Rec. 2675 (2021) 1031–1039.

[25] Y. Wu, R. Salameh, Y. Tsai, Georgia's Long-Term Pavement Performance Monitoring and Management Plan–Detail Design of Plan, Georgia. Department of Transportation. Office of Performance-Based …, 2020.

[26] Y.-C. Wu, Y. Tsai, Georgia long-term pavement performance (GALTPP) Program–Maintaining Georgia's calibration sites and identifying the potential for using MEPDG for characterization of non-standard materials and methods (Phase 1), Georgia. Department of Transportation. Office of Research, 2016.

[27] Y. Tsai, Z. Wang, X. Zhang, Z. Yang, An enhanced GDOT pavement preservation guide with optimal timing of pavement preservation, Georgia. Department of Transportation. Office of Performance-Based …, 2021.

[28] O. Xu, M. Li, D. Hou, Y. Tian, Z. Wang, X. Wang, Engineering and rheological properties of asphalt binders modified with microwave preprocessed GTR, Constr. Build. Mater. 256 (2020) 119440.

[29] G. Baumgardner, A.J.T. Hand, T. Aschenbrener, Recycled Tire Rubber–Hybrid GTR Binders and Dry Added GTR–How to use them in Asphalt Pavement Mixtures, United States. Federal Highway Administration. Office of Preconstruction …, 2021.

[30] H. Ziari, A. Amini, A. Goli, Investigation of blending conditions effect on GTR dissolution and rheological properties of rubberized binders, Constr. Build. Mater. 242 (2020) 117828.

[31] L.F.M. Leite, B.G. Soares, Interaction of asphalt with ground tire rubber, Pet. Sci. Technol. 17 (1999) 1071–1088.

[32] B. Yang, H. Li, Y. Sun, H. Zhang, J. Liu, J. Yang, X. Zhang, Chemo-rheological, mechanical, morphology evolution and environmental impact of aged asphalt binder coupling thermal oxidation, ultraviolet radiation and water, J. Clean. Prod. 388 (2023) 135866.

[33] W.A. Ogbon, W. Jiang, D. Yuan, J. Xiao, C. Xing, S.C.J. Moya, Comparative analysis of several short-term aging simulation methods and their impact on long-term aging performance of asphalt binders, Constr. Build. Mater. 437 (2024) 136969.

[34] C. Yan, W. Huang, N. Tang, Evaluation of the temperature effect on Rolling Thin Film Oven aging for polymer modified asphalt, Constr. Build. Mater. 137 (2017) 485–493.

[35] S.S. Nagabhushanarao, A.S. Vijayakumar, Chemical and rheological characteristics of accelerate aged asphalt binders using rolling thin film oven, Constr. Build. Mater. 272 (2021) 121995.

[36] B.T. Smith, I.L. Howard, W.S. Jordan III, C. Daranga, G.L. Baumgardner, Comparing pressure aging vessel time to field aging of binder as a function of pavement depth and time, Transp. Res. Rec. 2672 (2018) 223–234.

[37] J. Cai, C. Song, B. Zhou, Y. Tian, R. Li, J. Zhang, J. Pei, Investigation on high-viscosity asphalt binder for permeable asphalt concrete with waste materials, J. Clean. Prod. 228 (2019) 40–51.

[38] M. Zeng, C. Wu, Effects of type and content of mineral filler on viscosity of asphalt mastic and mixing and compaction temperatures of asphalt mixture, Transp. Res. Rec. 2051 (2008) 31–40.

[39] S. Anjan Kumar, U. Sarvanan, J. Murali Krishnan, A. Veeraragavan, Rheological characterisation of modified binders at mixing and compaction temperature, International Journal of Pavement Engineering 15 (2014) 767–785.

[40] H.A. Zahid, S.B.A. Zaidi, N. Ahmad, Eco-efficient modification of asphalt binders and mixtures using elevated ratios of polyethylene terephthalate and crumb rubber waste: a step towards sustainable roads, Innovative Infrastructure Solutions 10 (2025). https://doi.org/10.1007/s41062-025-01961-8.

[41] A. E1252-98, Standard practice for general techniques for obtaining infrared spectra for qualitative analysis, ASTM: West Conshohocken, PA, USA (2021).

[42] S.R. Kommidi, Y.-R. Kim, Dynamic shear rheometer testing and mechanistic conversion to predict bending beam rheometer low temperature behavior of bituminous binder, Constr. Build. Mater. 267 (2021) 120563.

[43] H. Ren, Z. Qian, W. Huang, H. Li, Y. Liu, Low-temperature thermal cracking performance of waterborne epoxy asphalt emulsion mastic based on bending beam rheometer (BBR), Constr. Build. Mater. 334 (2022) 127461.