

Article

Enhancing Asphalt Binder Performance and Storage Stability with Trinidad Lake Asphalt (TLA)

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Abstract: This study delves into the transformative effects of Trinidad Lake Asphalt (TLA) on asphalt binders, revealing significant improvements in various performance metrics. Our findings indicate that TLA substantially increases binder viscosity and enhances rutting resistance, as evidenced by elevated $G^*/\sin \delta$ values in both original and RTFO-aged states. TLA-modified binders demonstrate superior rheological properties, including improved J_{nr} and percentage recovery, indicating enhanced resistance to permanent deformation and reduced fatigue cracking. However, an increase in TLA content correlates with higher $G^*\sin \delta$ values, suggesting a trade-off with fatigue resistance and a higher susceptibility to cracking. Additionally, while TLA initially improves binder flexibility at low temperatures, excessive content can increase stiffness, adversely affecting stress relaxation properties. Notably, TLA enhances storage stability, ensuring minimal phase separation and excellent homogeneity. These insights underscore the need for the precise control of TLA content to optimize pavement durability. Future research should focus on fine-tuning TLA incorporation with additives like crumb rubber to maximize the structural integrity and longevity of asphalt pavements.

Keywords: TLA; viscosity; rutting resistance; fatigue resistance; low-temperature performance; storage stability



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1. Introduction

Asphalt, commonly known as bitumen, has been utilized as a paving material for over a century. The primary form of asphalt used in today's industry is petroleum asphalt, a byproduct of crude oil refinement. Natural forms of asphalt also exist, such as lake asphalt, which is found in Trinidad and Venezuela, and rock asphalt, which is present in numerous regions globally. The pavement industry is the largest consumer of asphalt, accounting for over 70% of its total usage. Asphalt mixtures, when combined with aggregates, form a durable surface layer on roads, enhancing the comfort of transportation. Given its widespread use, selecting the appropriate type of asphalt for varying climatic conditions has garnered significant interest [1].

Another pressing issue is the increased load on road infrastructures due to the proliferation of electric vehicles (EVs), which are typically heavier than traditional combustion engine vehicles due to their substantial battery weight. This added stress is contributing to a decreased lifespan of pavements. Consequently, there has been a growing focus on enhancing the properties of conventional petroleum-based asphalt to extend pavement service life. Recent years have seen the advent of various modifiers to achieve this goal [2–5]. Among these, Trinidad Lake Asphalt (TLA) is frequently used as an asphalt modifier. TLA is a semi-solid emulsion comprising soluble bitumen, mineral matter, and minor constituents. It is renowned for its consistent properties, high viscosity, density, superior rheological characteristics, and effective blending capabilities with other types of asphalt [6–8]. TLA also exhibits excellent temperature stability, chemical stability, and water stability, making

it highly compatible with petroleum asphalt due to their similar chemical compositions [9]. However, due to its hardness, TLA cannot be used alone in asphalt mixtures and is typically blended with petroleum-based asphalt in specified ratios. TLA can be incorporated into asphalt mixtures flexibly, without degradation or performance loss, even at elevated temperatures. It is especially prevalent in asphalt concrete (AC) and mastic asphalt (MA) pavements and has recently been applied in modern thin bridge pavement systems [10].

Research into the rheological properties of TLA-modified binders has shown that compatibility varies depending on the chemical components and colloid structures involved, leading to distinct performance outcomes [11,12]. One of the most straightforward and commonly used methods to assess modified asphalt performance during production is the Superpave test method. This method is simple and provides clear results. Additionally, storage stability is another crucial criterion for modified asphalt, as mixing different materials can lead to phase separation [8,13].

This study is motivated by the need to better understand how replacing traditional petroleum-based asphalt with TLA affects asphalt performance and stability. Specifically, we're looking to determine the best mix of TLA and a standard asphalt binder, PG 64-22, at different proportions: 10%, 20%, and 30%. We use a well-known testing approach called the Superpave method along with Multiple Stress Creep Recovery (MSCR) method to find out which mixture provides the best performance.

In addition to performance, we are also concerned with how these mixtures hold up over time, especially at high temperatures. This is important because asphalt needs to be stable and perform well under the heat it experiences in real-world conditions. To assess this, we use another testing approach called the cigar tube test, which helps us understand the stability of these mixtures at elevated temperatures.

The goal is to pinpoint the optimal amount of TLA that can be used to replace part of the petroleum-based binder without compromising the asphalt's quality and durability. This is crucial for ensuring that roads last longer and perform better. Figure 1 in the document visually represents how we set up our experiments for this study.

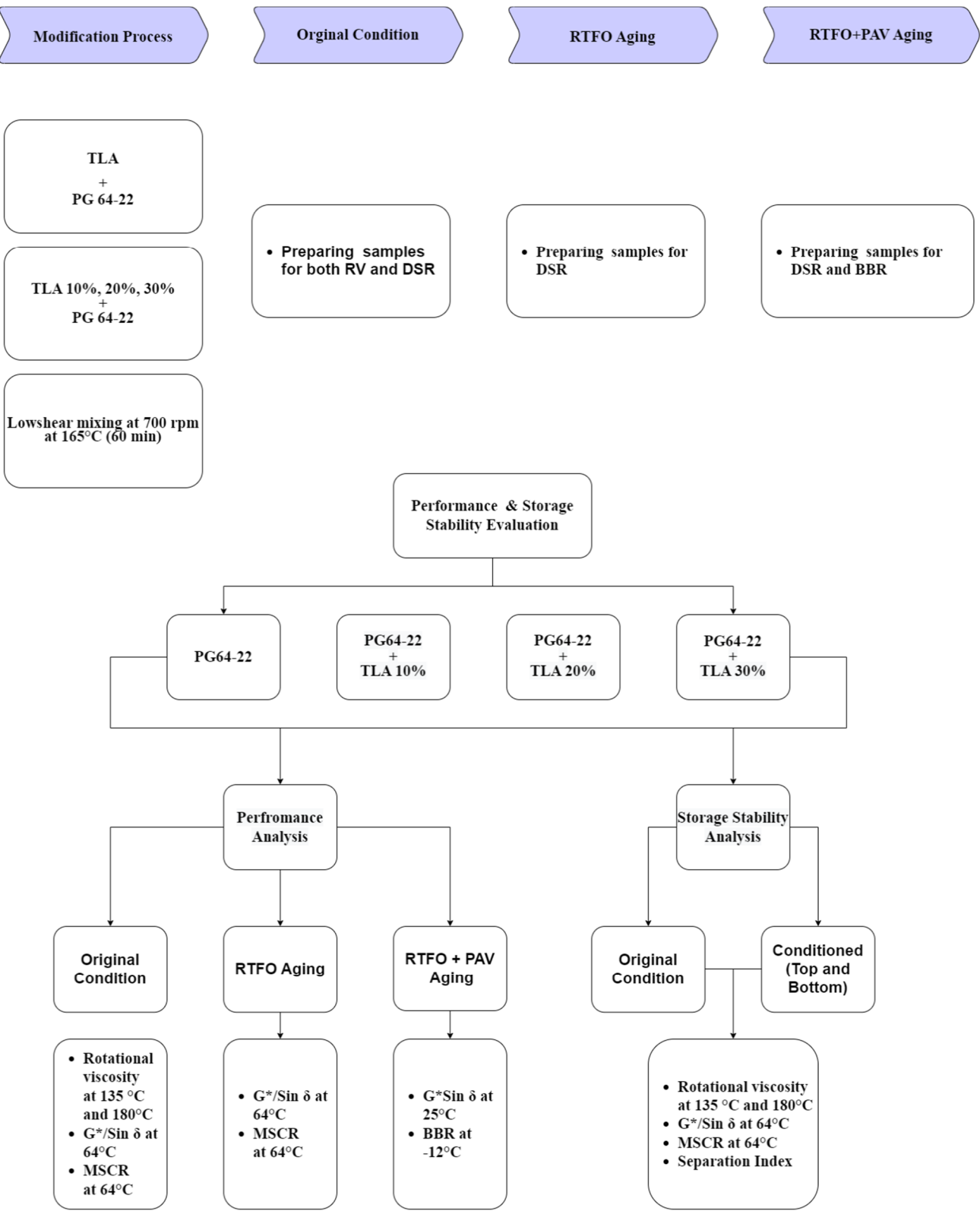


Figure 1. Flow chart of experimental design procedures.

2. Experimental Design

2.1. Materials

In this study, PG 64-22 was chosen as the foundational binder for developing a modified binder incorporating Trinidad Lake Asphalt (TLA). The detailed attributes and speci-

cations of this base binder are presented in Table 1. The modification process utilized TLA in its natural form, characterized by a stable mixture of bituminous material and mineral components. The chemical composition of TLA includes a bituminous content ranging between 53 and 55%, a mineral content of 36–37.7%, hydrated water of minerals at 4.3%, and other organic matter comprising 3.2%. The physical properties of PG 64-22 and TLA are further elaborated in Tables 1 and 2, respectively.

Table 1. Properties of base asphalt binder (PG 64-22).

Aging States	Test Properties	Test Result
Unaged binder	Viscosity @ 135 °C (cP)	754
	Viscosity @ 180 °C (cP)	283
	$G^*/\sin \delta$ @ 64 °C (kPa)	2.10
RTFO aged residual	$G^*/\sin \delta$ @ 64 °C (kPa)	5.25
RTFO + PAV aged residual	$G^* \cdot \sin \delta$ @ 25 °C (kPa)	3400
	Stiffness @ −12 °C (MPa)	185
	m-value @ −12 °C	0.333

Table 2. Properties of Trinidad Lake Asphalt.

Properties	Test Method	Test Result
Penetration (25 °C)	ASTM D5 [14]	1–4
Density	ASTM D70 [15]	1.40–1.42 g/m ³
Softening point	ASTM D36 [16]	199 °F–208 °F
Flash point	ASTM D92 [17]	255 °C–266 °C
Fire point	ASTM D92 (Cleaveland open cup) [17]	305 °C–310 °C

To evaluate the long-term stability of the modified binder, tests were conducted using an aluminum cigar tube in accordance with ASTM D7173 standards [18]. This approach ensures a standardized method to assess the thermal stability and potential aging characteristics of the binder, providing scientifically sound results that can be reliably compared across different studies.

2.2. Production and Sampling of TLA Modified Binders

In this experimental setup, a standard asphalt binder with a performance grade of PG 64-22 is used as the base material. The binder is modified by incorporating Trinidad Lake Asphalt (TLA) in three different percentages: 10%, 20%, and 30%, by weight of the virgin binder. The primary objective of this modification is to enhance the binder's mechanical properties, specifically its resilience and flexibility.

The modification process begins by manually mixing the binder and TLA until a visually homogeneous blend is achieved. To ensure the effective dispersion and intercalation of TLA within the base binder, the mixing temperature is maintained above 150 °C. When the temperature reaches 165 °C, a low-shear mixer is employed, mixing the components at a shear rate of 700 rpm for 60 min while maintaining the temperature at 165 °C. This process promotes a uniformly modified binder and facilitates the effective intercalation of TLA within the binder matrix.

Following the modification, a portion of the binder is subjected to rotational viscosity tests and viscoelastic tests, following standard procedures such as the Dynamic Shear Rheometer (DSR) for Multiple Stress Creep Recovery (MSCR). These tests are crucial for assessing the modified binder's flow and deformation characteristics under varying stress conditions.

The remaining modified binder is poured into cigar cases, each weighing 50 ± 0.5 g, held in a vertical position. The tops of the cigar cases are sealed, and the samples are placed in an oven at a temperature of 163 °C for a conditioning period of 48 ± 1 h. After this

conditioning period, the samples are transferred to a cooler maintained at -10 ± 10 °C for a minimum of 4 h, allowing the molten binder to solidify. The solidified cigar cases are then divided into three equal halves. Each half is placed back into the oven at 163 ± 5 °C until the binder starts to liquefy.

Subsequently, the liquefied modified binder is further homogenized on a hot plate with manual stirring using a spatula to remove any foreign particles. Samples are then extracted from the homogenized binder for viscosity and viscoelastic property assessments, ensuring the accuracy of the testing process according to the experimental protocol detailed in the referenced journal.

To simulate short-term aging, the binder undergoes the Rolling Thin Film Oven (RTFO) test for 85 min at 163 °C, in accordance with ASTM D 2872 standards [19]. RTFO-aged samples are analyzed using DSR for viscoelastic properties and subjected to MSCR tests. This step mimics the aging process that occurs during hot-mix asphalt production and construction phases.

To replicate long-term field aging, the binder is subjected to the Pressure Aging Vessel (PAV) test for 20 h at 100 °C, as outlined in ASTM D 6521 [20]. Post-aging, PAV residue samples are tested at 25 °C using DSR and at -12 °C using the Bending Beam Rheometer (BBR), according to AASHTO T 313 [21]. These tests provide insights into the binder's performance under long-term environmental conditions, such as temperature fluctuations and oxidative aging.

In summary, this comprehensive study employs a multi-stage approach to prepare and evaluate TLA-modified asphalt binders, aiming to gain insights into their thermo-mechanical properties and aging behavior. This sequential process ensures a thorough assessment of the modified binders, facilitating the development of enhanced asphalt materials for infrastructure applications.

2.3. Evaluation of Binder

2.3.1. Superpave Binder Testing

Evaluating the performance of asphalt binders throughout various stages of their lifecycle is essential for ensuring the durability and longevity of road structures. A comprehensive investigation was carried out using three standardized test methods prescribed by the American Association of State Highway and Transportation Officials (AASHTO): the Viscosity test (AASHTO T 316) [22], the Dynamic Shear Rheometer (DSR) test (AASHTO T 315) [23], and the Bending Beam Rheometer (BBR) test (AASHTO T 313).

For rheological evaluation, the Brookfield Rotational Viscometer was utilized in the Viscosity test. A standardized 10.5 g sample of each modified binder type was subjected to viscosity measurements using a number 27 spindle. Assessments were performed at two distinct temperatures—135 °C and 180 °C—to cover a range of conditions that binders may encounter. This method provides critical insights into the fluid-like behavior of binders, which is essential for optimal mixing and compaction processes during construction, ensuring the proper workability and uniformity of the asphalt mix.

The DSR test aimed to capture the viscoelastic characteristics of the binders in their virgin state and after undergoing aging processes: short-term aging (RTFO) and long-term aging (RTFO + PAV). The test was conducted at a frequency of 10 radians per second (approximately 1.59 Hz), which is considered ideal for reflecting the real-world shear-related behaviors of the material. Key parameters such as Complex Shear Modulus (G^*) and Phase Angle (δ) were computed. The parameter $G^*/\sin \delta$ was specifically calculated to assess the material's resistance to rutting, indicating how well the binder can resist permanent deformation under load. Conversely, $G^* \cdot \sin \delta$ was measured at 25 °C to evaluate the potential for fatigue cracking, which is critical for understanding the binder's durability under repeated traffic loading.

The BBR test focused on evaluating the low-temperature performance of the binders using the RTFO + PAV residual samples. Modified binder beams, with dimensions of $125 \times 6.35 \times 12.7$ mm, were subjected to creep stiffness (S) measurements at -12 °C to

simulate cold-weather conditions. A 100 g load was applied, and the central deflection of the beam was monitored for 60 s. This test is crucial for assessing the binder's behavior in terms of thermal-induced stresses, primarily its susceptibility to cracking, which can significantly affect pavement integrity in cold climates.

All tests were conducted in triplicate, and the results were averaged to achieve statistical robustness and reliability. This multifaceted evaluation methodology enabled a comprehensive understanding of the asphalt binders' performance characteristics across various stages of their service life, providing a robust foundation for predicting long-term pavement performance and informing material selection and mix design.

2.3.2. Separation Index/Phase Separation

To investigate the separation index, the analysis was focused exclusively on the upper and lower sections of the aluminum cigar case. Two approaches were employed—one based on viscosity and the other on the $G^*/\sin \delta$ parameter.

For the viscosity-based separation index calculation, Equation (1) was utilized. This equation compares the average viscosity value, $(\text{viscosity})_{\text{avg}}$, with the maximum viscosity value between the upper and lower sections, $(\text{viscosity})_{\text{max}}$. The resulting separation index offers insights into the degree of separation within the modified binder.

$$\text{Separation index} = \frac{(\text{Viscosity})_{\text{max}} - (\text{Viscosity})_{\text{avg}}}{((\text{Viscosity})_{\text{avg}})} \quad (1)$$

Additionally, the separation index was further analyzed using Equation (2), which employs the $G^*/\sin \delta$ parameter. Similar to Equation (1), this equation calculates the separation index ratio by comparing the maximum value, $(G^*/\sin \delta)_{\text{max}}$, to the average value, $(G^*/\sin \delta)_{\text{avg}}$, derived from the upper and lower sections.

$$\text{Separation index} = \frac{(G^*/\sin \delta)_{\text{max}} - (G^*/\sin \delta)_{\text{avg}}}{((G^*/\sin \delta)_{\text{avg}})} \quad (2)$$

By employing these two methods for calculating the separation index, a comprehensive evaluation of the extent of separation in the modified binder was achieved. This dual approach allows for a comparison between the results of the two calculations, thereby providing a deeper understanding of the separation behavior.

The selection of these equations for investigating the separation index is scientifically justified, as they offer quantitative measures to assess the separation phenomenon in the modified binder. By considering both viscosity and $G^*/\sin \delta$, this study aims to provide a thorough understanding of the separation behavior and its implications for binder performance. The use of established equations and referencing previous research sources [24,25] further reinforces the scientific validity of this investigation.

2.3.3. Multiple Stress Creep Recovery (MSCR) Test

The Multiple Stress Creep Recovery (MSCR) test, conducted on a modified asphalt binder using Dynamic Shear Rheometer (DSR) equipment in accordance with AASHTO TP 70 standards [26], is essential for evaluating the rheological properties of the binder. This test is performed on unaged, short-term-aged (RTFO), and storage stability samples. It is executed at two distinct stress levels, 0.1 kPa and 3.2 kPa, with cycles of creep loading and unloading lasting 1 s and 9 s, respectively. Each stress level undergoes a total of ten cycles.

The MSCR test generates two critical parameters: nonrecoverable creep compliance (J_{nr}) and percent recovery (%rec). These metrics quantitatively assess the rutting susceptibility of asphalt binders.

Nonrecoverable creep compliance (J_{nr}) is calculated by dividing the nonrecoverable shear strain by the applied shear stress. J_{nr} serves as an indicator of the material's resistance to permanent deformation, or rutting, under repeated traffic loading. A higher J_{nr} value suggests a greater susceptibility to rutting, thus making it a crucial factor in

material selection for road construction. A lower J_{nr} value, conversely, indicates better resistance to deformation, signifying a more durable binder under traffic-induced stress. The percent recovery (%rec) measures the binder's ability to recover its original shape after deformation, providing insight into its elastic behavior. Together, these parameters enable a comprehensive evaluation of the binder's performance, guiding the selection of materials for enhanced road longevity and safety.

2.4. Statistical Analysis Method

In this study, we utilized Statistical Package for the Social Sciences (SPSS) to perform an Analysis of Variance (ANOVA), followed by Fisher's Least Significant Difference (LSD) test, both conducted at a significance level of $\alpha = 0.05$. The primary purpose of employing ANOVA was to determine whether statistically significant differences existed among the sample means. A significance level of 0.05 indicates that we accept a 5% risk of committing a Type I error, where we might conclude that a difference exists when, in fact, there is none.

Upon identifying significant differences through ANOVA, we implemented Fisher's LSD test to pinpoint the specific groups where these differences occurred. Fisher's LSD calculates the minimum difference required between two sample means to assert that the corresponding population means differ at the specified significance level. Essentially, the LSD acts as a threshold value: if the absolute difference between any two-sample means meets or exceeds the LSD, we can declare that the respective population means are statistically different.

It is important to clarify that stating a '95% chance of each finding being true' is somewhat misleading. Statistically, a significance level of 0.05 means that if the null hypothesis were true (i.e., no real differences exist between the groups), there is a 5% probability of observing the obtained data or more extreme results purely by chance. Therefore, rejecting the null hypothesis at this level provides us with 95% confidence in our results, rather than a 95% probability of the findings being true.

In summary, ANOVA served as an initial tool to detect significant differences in sample means across groups. Upon finding significant results with ANOVA, Fisher's LSD test was employed to conduct pairwise comparisons, identifying which specific groups exhibited differences in their population means [27].

3. Results and Discussion

3.1. Rotational Viscosity

Viscosity is a crucial parameter for evaluating the workability of asphalt binders, especially during the transition from production to construction phases. Figure 2, with standard errors and a linear exponential equation, demonstrates that at 135 °C, before conditioning, a clear trend emerges: the addition of Trinidad Lake Asphalt (TLA) to the virgin asphalt binder leads to an increase in viscosity. This rise is attributed to the inherently high viscosity of TLA. Interestingly, an anomaly is observed where the binder with 20%TLA replacement shows lower viscosity values compared to the 10%TLA-modified asphalt, although these values remain higher than those of the virgin binder. Notably, all modified binders are considered workable at this temperature, as their viscosity values are well below the 3000 cP threshold.

When the temperature is increased to 180 °C before conditioning, the viscosity trend remains consistent with the observations at 135 °C. After conditioning, both the top and bottom portions of the samples were tested at 135 °C and 180 °C. At 135 °C, it was found that the viscosity values at the bottom were higher compared to the original and top portions. Additionally, the top and original condition values were nearly identical. However, as the temperature increased to 180 °C, a significant change in the trend was observed. At this higher temperature, the top portion of the sample, the virgin binder, and the binder modified with 10%TLA showed higher viscosity values compared to the bottom portion, as illustrated with standard errors and the linear exponential equation demonstrated in Figures 3 and 4. This is because TLA has high viscosity and density, and upon heating,

TLA has the tendency to settle more in the bottom portion, leading to a relatively lighter and less viscous top portion initially. However, with prolonged heating, the top portion might experience increased viscosity due to the evaporation and aging effects [6].

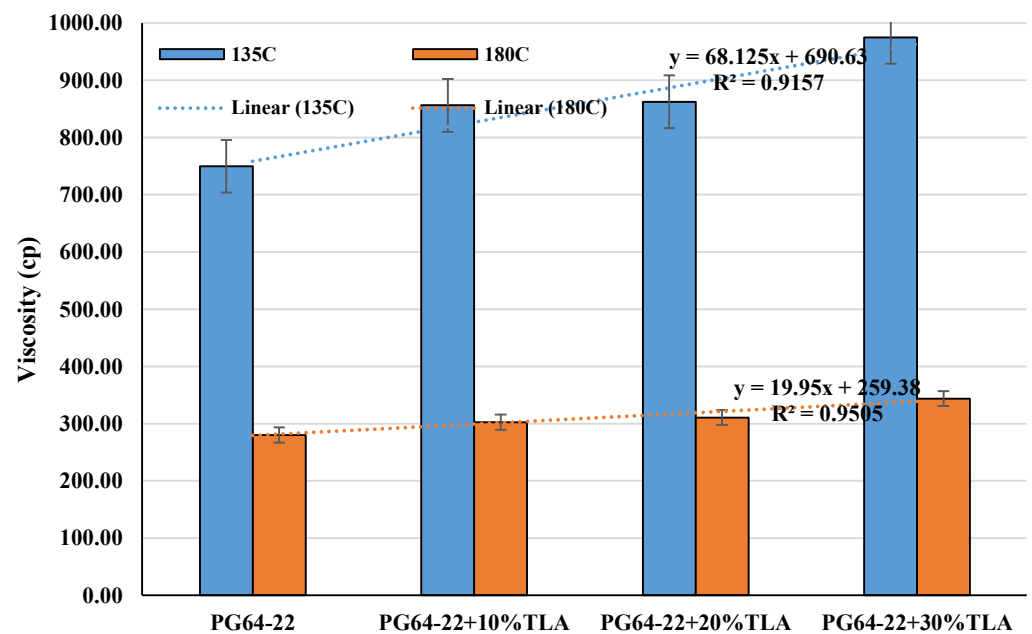


Figure 2. Viscosity at 135 °C and 180 °C of the TLA modified binders at original condition.

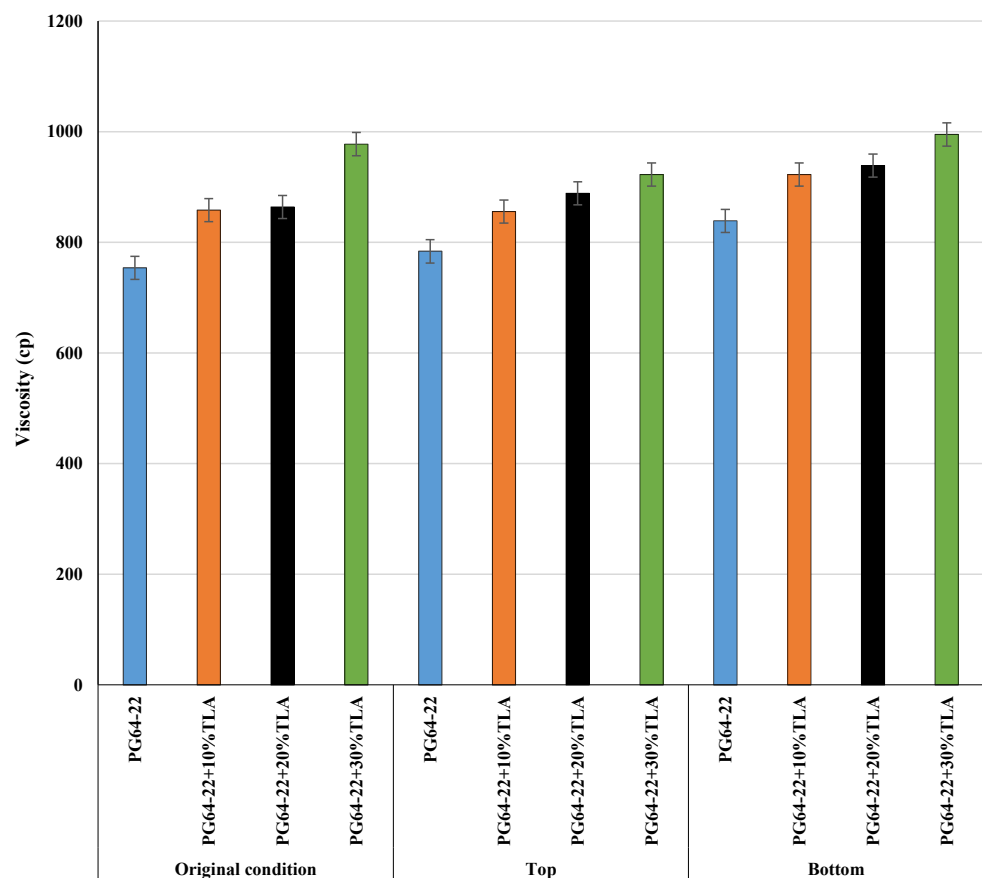


Figure 3. Viscosity at 135 °C of the TLA modified binders after conditioning considering the top and bottom parts.

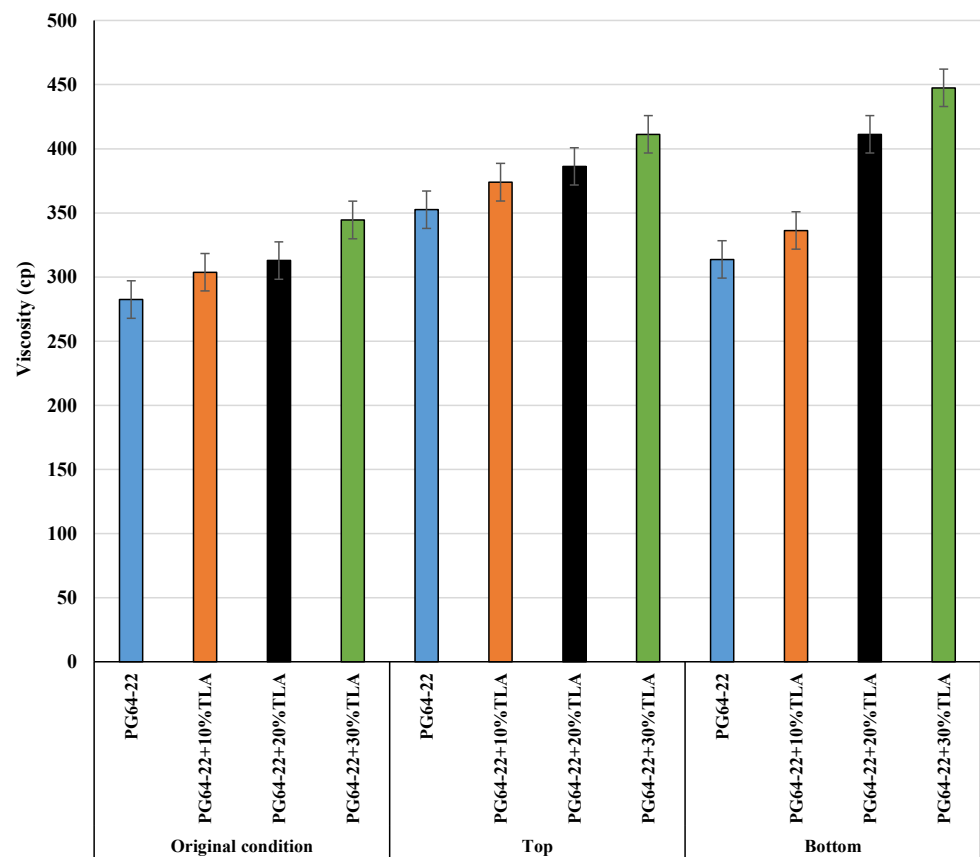


Figure 4. Viscosity at 180 °C of the TLA modified binders after conditioning considering top and bottom parts.

Statistical analysis supports these findings, indicating that the viscosity data among different binder populations are significantly different, as marked by ‘S’ in Tables 3 and 4.

Table 3. Statistical analysis results of the viscosity at 135 °C of TLA modified binders as a function of different combinations at original condition and after conditioning considering only top and bottom parts ($\alpha = 0.05$).

Viscosity at 135 °C													
		Original (%)				Top (%)				Bottom (%)			
	Combinations	PG64-22	PG 64-22 + 10% TLA	PG 64-22 + 20% TLA	PG64-22 + 30% TLA	PG64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA	PG64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA
Original (%)	PG64-22	-	S	S	S	S	S	S	S	S	S	S	S
	PG64-22 + 10%TLA	-	-	N	S	S	S	S	S	S	N	S	S
	PG64-22 + 20%TLA	-	-	-	S	S	S	S	S	S	S	S	S
	PG64-22 + 30%TLA	-	-	-	S	S	S	S	S	S	S	S	S
Top (%)	PG64-22	-	-	-	-	-	S	S	S	S	S	S	S
	PG64-22 + 10%TLA	-	-	-	-	-	-	S	N	S	S	S	S
	PG64-22 + 20%TLA	-	-	-	-	-	-	-	S	S	S	S	S
	PG64-22 + 30%TLA	-	-	-	-	-	-	-	-	S	S	S	S
Bottom (%)	PG64-22	-	-	-	-	-	-	-	-	-	S	S	S
	PG64-22 + 10%TLA	-	-	-	-	-	-	-	-	-	-	S	S
	PG64-22 + 20%TLA	-	-	-	-	-	-	-	-	-	-	-	S
	PG64-22 + 30%TLA	-	-	-	-	-	-	-	-	-	-	-	-

S—Significant, N—Non-significant.

Table 4. Statistical analysis results of the viscosity at 180 °C of TLA modified binders as a function of different combinations at original condition and after conditioning considering only top and bottom parts ($\alpha = 0.05$).

Viscosity at 180 °C													
		Original (%)				Top (%)				Bottom (%)			
	Combinations	PG64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA	PG64- 22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA	PG64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA
Original (%)	PG64-22	-	S	S	S	S	S	S	S	S	S	S	S
	PG64-22 + 10%TLA	-	-	S	S	S	S	S	S	S	S	S	S
	PG64-22 + 20%TLA	-	-	-	S	S	S	S	S	N	S	S	S
	PG64-22 + 30%TLA	-	-	-	-	S	S	S	S	S	S	S	S
Top (%)	PG64-22	-	-	-	-	-	S	S	S	S	S	S	S
	PG64-22 + 10%TLA	-	-	-	-	-	-	S	S	S	S	S	S
	PG64-22 + 20%TLA	-	-	-	-	-	-	-	S	S	S	S	N
	PG64-22 + 30%TLA	-	-	-	-	-	-	-	-	S	S	S	S
Bottom (%)	PG64-22	-	-	-	-	-	-	-	-	-	S	S	S
	PG64-22 + 10%TLA	-	-	-	-	-	-	-	-	-	-	S	S
	PG64-22 + 20%TLA	-	-	-	-	-	-	-	-	-	-	-	S
	PG64-22 + 30%TLA	-	-	-	-	-	-	-	-	-	-	-	-

S—Significant, N—Non-significant.

The variations in viscosity have significant implications for pavement life. Higher viscosity values generally indicate greater resistance to deformation and rutting under high temperatures, enhancing the pavement's durability and longevity. However, excessively high viscosity can lead to challenges in workability and compaction during construction, potentially resulting in inadequate pavement density and increased susceptibility to cracking. The observed differences in viscosity between the top and bottom portions of conditioned samples suggest variations in the binder's homogeneity and stability, which could affect the pavement's performance and structural integrity. Therefore, optimizing the viscosity of asphalt binders through the precise control of additives like TLA is essential for achieving a balance between workability during construction and long-term pavement performance.

This refined understanding of viscosity behavior in asphalt binders underscores the importance of meticulous material selection and process control to ensure optimal performance and durability in road construction projects.

3.2. Rutting Property ($G^*/\sin \delta$)

Higher values of $G^*/\sin \delta$ obtained from the DSR test indicate increased resistance to rutting or permanent deformation at elevated pavement temperatures. In this study, the $G^*/\sin \delta$ values of binders were evaluated both in their original state, immediately after modification, and after Rolling Thin Film Oven (RTFO) aging at a temperature of 64 °C. The evaluations were conducted before conditioning and after conditioning for 48 ± 2 h, considering only the top and bottom parts of the sample for testing.

The results, illustrated with standard errors and linear exponential equations in Figure 5, demonstrate that binders modified before conditioning, in both their original and RTFO-aged states, exhibit increased resistance to rutting as the TLA replacement percentage increases. This indicates that higher TLA content enhances the binder's ability to resist permanent deformation under load.

After conditioning, when the top and bottom portions of the sample were considered separately for testing, the bottom portion exhibited higher resistance to rutting compared to the top portion. This could be attributed to the possible segregation of heavier components at the bottom. Additionally, samples tested before conditioning (i.e., in their original state) exhibited higher resistance to rutting compared to those tested after conditioning, with standard errors and linear exponential equations demonstrating this, as shown in Figure 6. This suggests that the conditioning process may lead to some degradation or softening of the binder, reducing its rutting resistance.

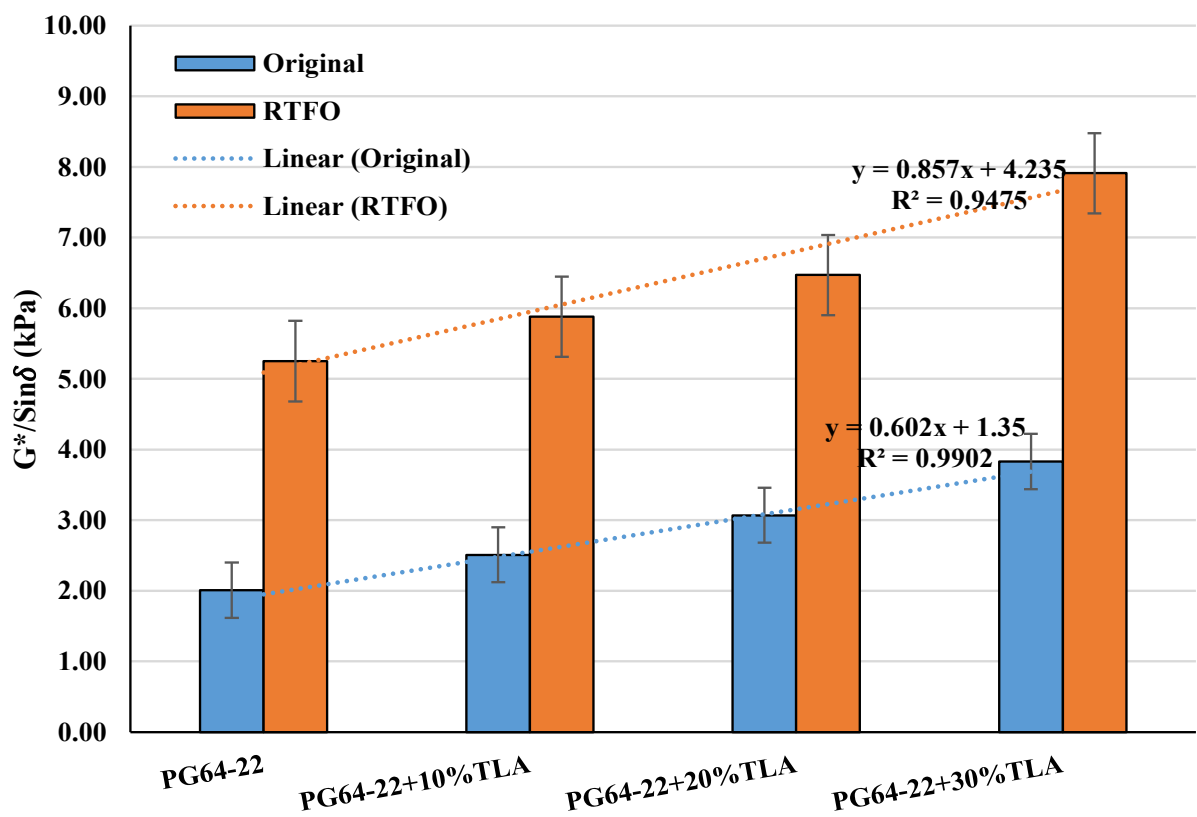


Figure 5. $G^*/\sin \delta$ at 64 °C of the TLA modified binders at Original and RTFO conditions.

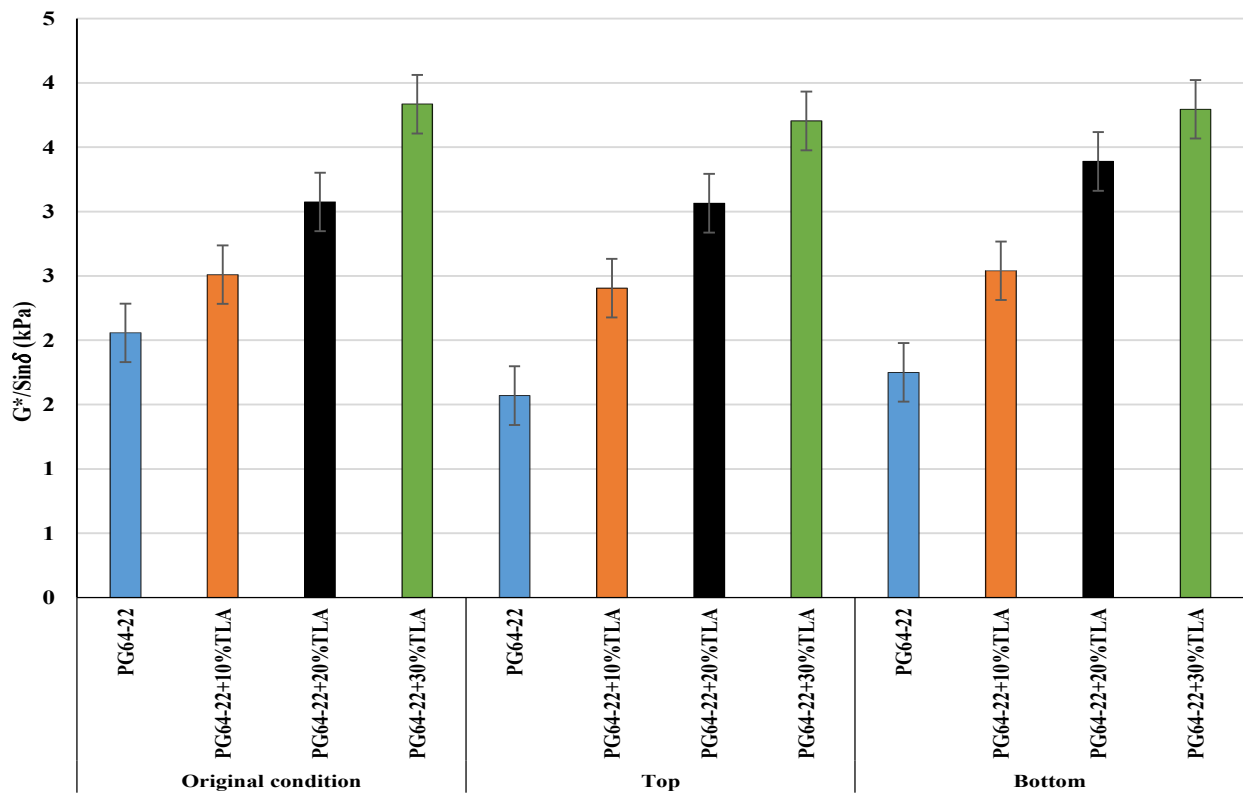


Figure 6. $G^*/\sin \delta$ at 64 °C of the TLA modified binders after conditioning considering top and bottom parts.

The statistical analysis, presented in Tables 5 and 6, further clarifies these results. The increased $G^*/\sin \delta$ values in the original state, particularly for the bottom portion of the conditioned samples, indicate better performance in terms of rutting resistance. This improved rutting resistance contributes positively to pavement life by reducing the likelihood of permanent deformation under repeated traffic loads, thereby enhancing the durability and longevity of the pavement.

Table 5. Statistical analysis results of viscoelasticity at 64 °C of TLA modified binders as a function of Original and RTFO conditions ($\alpha = 0.05$).

Viscoelasticity at 64 °C									
		Original Condition				RTFO Condition			
Combinations		PG 64-22	PG 64-22 + 10% TLA	PG 64-22 + 20% TLA	PG 64-22 + 30% TLA	PG 64-22	PG 64-22 + 10% TLA	PG 64-22 + 20% TLA	PG 64-22 + 30% TLA
Original Condition	PG64-22	-	S	S	S	S	S	S	S
	PG64-22 + 10%TLA	-	-	N	S	S	S	S	S
	PG64-22 + 20%TLA	-	-	-	S	S	S	S	S
	PG64-22 + 30%TLA	-	-	-	-	S	S	S	S
RTFO Condition	PG64-22	-	-	-	-	-	S	S	S
	PG64-22 + 10%TLA	-	-	-	-	-	-	S	N
	PG64-22 + 20%TLA	-	-	-	-	-	-	-	S
	PG64-22 + 30%TLA	-	-	-	-	-	-	-	-

S—Significant, N—Non-significant.

Table 6. Statistical analysis results of viscoelasticity at 64 °C of TLA modified binders as a function of original condition and after conditioning considering only the top and bottom parts ($\alpha = 0.05$).

Viscoelasticity at 64 °C													
		Original (%)				Top (%)				Bottom (%)			
Combinations		PG 64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA	PG 64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA	PG 64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA
Original (%)	PG64-22	-	S	S	S	S	S	S	S	S	S	S	S
	PG64-22 + 10%TLA	-	-	S	S	S	N	S	S	S	S	S	S
	PG64-22 + 20%TLA	-	-	-	S	S	S	S	S	S	S	N	S
	PG64-22 + 30%TLA	-	-	-	-	S	S	S	N	S	S	S	N
Top (%)	PG64-22	-	-	-	-	-	S	S	S	N	S	S	S
	PG64-22 + 10%TLA	-	-	-	-	-	-	S	S	S	N	S	S
	PG64-22 + 20%TLA	-	-	-	-	-	-	-	S	S	S	S	S
	PG64-22 + 30%TLA	-	-	-	-	-	-	-	-	S	S	S	N
Bottom (%)	PG64-22	-	-	-	-	-	-	-	-	-	S	S	S
	PG64-22 + 10%TLA	-	-	-	-	-	-	-	-	-	-	S	S
	PG64-22 + 20%TLA	-	-	-	-	-	-	-	-	-	-	-	S
	PG64-22 + 30%TLA	-	-	-	-	-	-	-	-	-	-	-	-

S—Significant, N—Non-significant.

3.3. Fatigue Cracking Property (Intermediate Failure)

In the evaluation of Superpave binder specifications for asphalt pavements, the parameter $G^* \cdot \sin \delta$ is crucial for assessing fatigue resistance. Lower values of $G^* \cdot \sin \delta$ are typically preferred as they indicate better resistance to fatigue-induced cracking. In this study, the DSR was used to measure $G^* \cdot \sin \delta$ at 25 °C, with standard errors and linear exponential equations as shown in Figure 7.

The results indicated that incorporating TLA with the virgin binder increased the $G^* \cdot \sin \delta$ values, suggesting a significant reduction in fatigue resistance without any notable benefits in terms of reduced stiffness. The addition of TLA led to increased susceptibility to fatigue cracking. All modified binders with different percentages of TLA exceeded the Superpave limit of 5000 kPa for $G^* \cdot \sin \delta$. As the TLA replacement percentage increased, the $G^* \cdot \sin \delta$ values also increased, further exacerbating the susceptibility to fatigue cracking. This trend was statistically analyzed, as shown in Table 7.

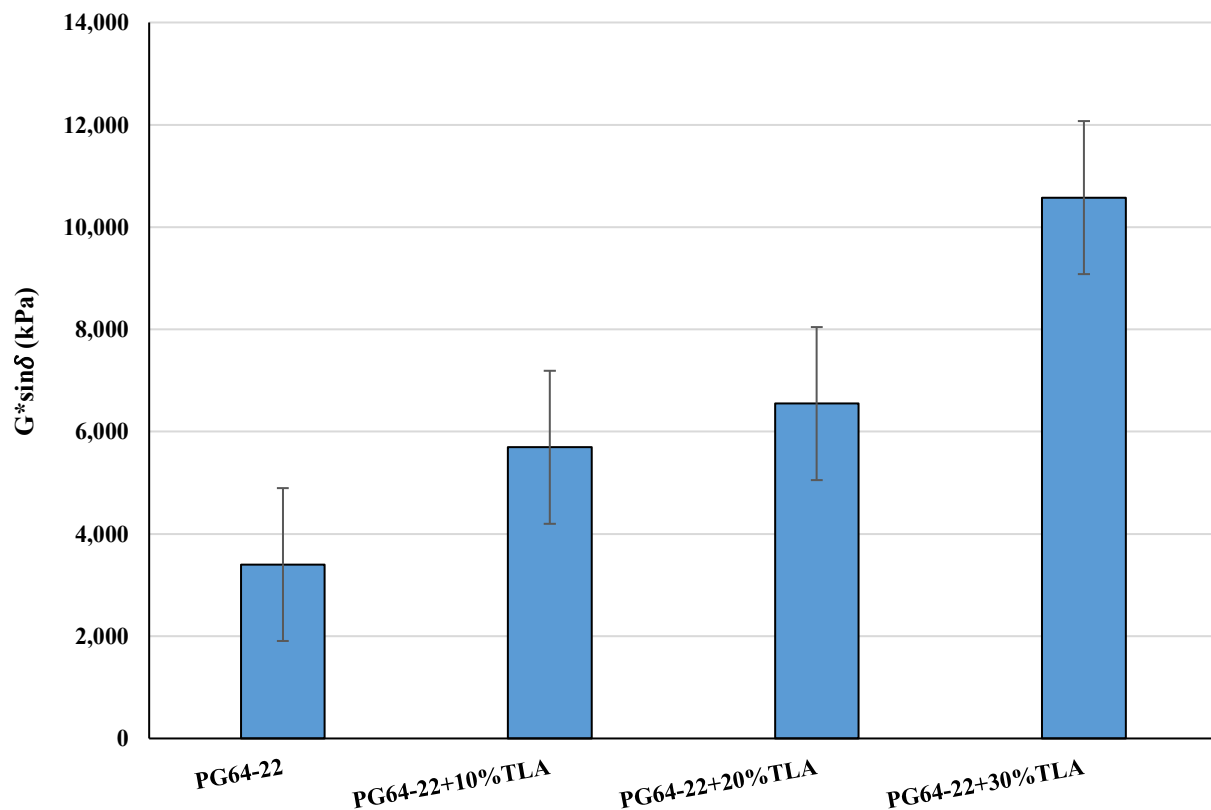


Figure 7. $G^* \cdot \sin \delta$ at 25 °C of the TLA modified binders after RTFO + PAV aged conditions.

Table 7. Statistical analysis results of the $G^* \cdot \sin \delta$ (RTFO + PAV) of CRM binders at 25 °C as a function of different combinations ($\alpha = 0.05$).

Combination	$G^* \cdot \sin \delta$ at 25 °C			
	PG64-22	PG64-22 + 10% TLA	PG64-22 + 10% TLA	PG64-22 + 10% TLA
PG64-22	-	S	S	S
PG64-22 + 10%TLA	-	-	S	S
PG64-22 + 10%TLA	-	-	-	S
PG64-22 + 10%TLA	-	-	-	-

S—Significant, N—Non-significant.

The elevated $G^* \cdot \sin \delta$ values imply that the modified binders are less capable of dissipating stress, making them more prone to fatigue cracking under repeated loading. Consequently, this could lead to a reduction in pavement life, as the materials are more likely to develop cracks over time, compromising the pavement's structural integrity and service life. The statistical analysis supports these findings, demonstrating a clear correlation between higher TLA content and increased $G^* \cdot \sin \delta$ values, thereby indicating reduced fatigue resistance.

3.4. Multiple Stress Creep Recovery (MSCR) Test

J_{nr} and % Recovery Condition for Both Original and RTFO Condition

The experiment evaluated various replacement percentages of TLA modified with virgin asphalt binders, both in their original state and after aging using the RTFO method. The primary metrics for assessment were J_{nr} (creep compliance) and percentage recovery.

The findings indicated that all TLA-modified binders exhibited lower J_{nr} values and higher percentages of recovery compared to virgin binders, both in original and RTFO-aged conditions, with standard errors and linear exponential equations as illustrated in

Figure 8. The reduced J_{nr} values imply a lower risk of fatigue cracking, while the increased percentage recovery suggests an enhanced resistance to permanent deformation or rutting. These improvements are likely due to the enhanced elasticity and rheological properties imparted by the TLA modifiers.

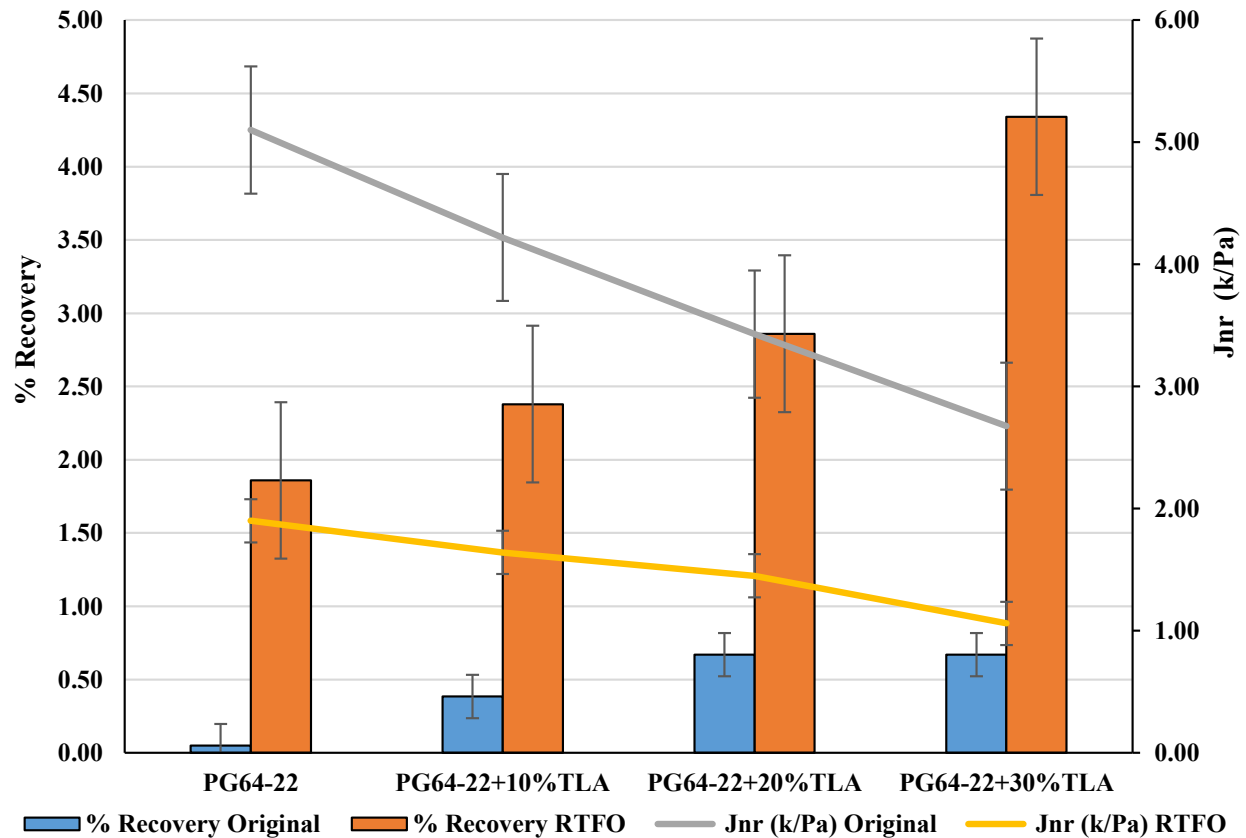


Figure 8. % Recovery and J_{nr} at 64 °C of the TLA modified binders at Original and RTFO condition.

The inclusion of TLA was particularly effective in increasing percentage recovery, thereby enhancing the material's resistance to rutting. Conversely, it led to a reduction in J_{nr} values, indicating a favorable compromise between fatigue resistance and elastic recovery prior to conditioning.

After conditioning and comparing the top and bottom parts of the sample, it was observed that the top portion had lower percentage recovery values compared to the bottom part. J_{nr} values followed a similar trend. Additionally, the percentage recovery values did not show a clear pattern when modified with TLA. Specifically, an initial 10% replacement of TLA resulted in higher percentage recovery values compared to 20%TLA but showed lower values compared to 30%TLA. It was also found that the addition of TLA resulted in lower percentage recovery values compared to the virgin binder, with standard errors and linear exponential equations as shown in Figure 9. The percentage recovery values were almost negligible, rendering statistical analysis impractical after conditioning. Consequently, only J_{nr} values were considered for statistical analysis after conditioning, as seen in Tables 8–10.

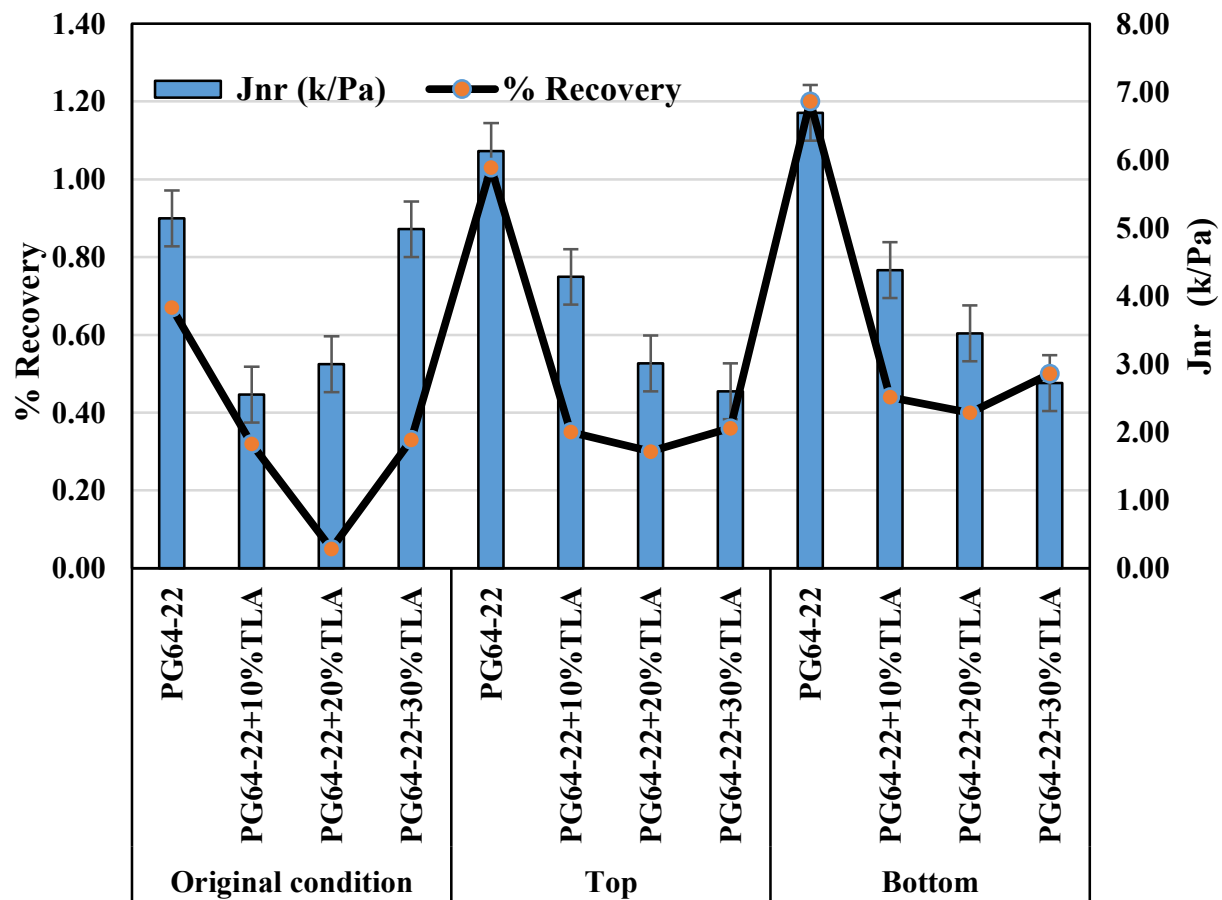


Figure 9. % Recovery and J_{nr} at 64 °C of the TLA modified binders after conditioning considering top and bottom parts.

Table 8. Statistical analysis results of % recovery of TLA modified binders at 64 °C considering Original and RTFO conditions ($\alpha = 0.05$).

% Recovery at 64 °C									
Original Condition					RTFO Condition				
	Combinations	PG64-22	PG 64-22 + 10% TLA	PG 64-22 + 20% TLA	PG64-22 + 30% TLA	PG64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA
Original Condition	PG64-22	-	S	S	S	S	S	S	S
	PG64-22 + 10%TLA	-	-	S	S	S	S	S	S
	PG64-22 + 20%TLA	-	-	-	N	S	S	S	S
	PG64-22 + 30%TLA	-	-	-	-	S	S	S	S
RTFO Condition	PG64-22	-	-	-	-	-	S	S	S
	PG64-22 + 10%TLA	-	-	-	-	-	-	S	S
	PG64-22 + 20%TLA	-	-	-	-	-	-	-	S
	PG64-22 + 30%TLA	-	-	-	-	-	-	-	-

S—Significant, N—Non-significant.

From a scientific standpoint, the lower J_{nr} values of TLA-modified binders suggest a decreased susceptibility to fatigue cracking, which can extend the pavement's lifespan by reducing the frequency of maintenance and repairs. The higher percentage recovery values indicate improved elasticity, which enhances the pavement's ability to return to its original shape after deformation, thus providing better resistance to rutting and increasing the pavement's durability. The balance between lower J_{nr} and higher percentage recovery in TLA-modified binders demonstrates a promising enhancement in both fatigue resistance and elastic recovery, contributing to a longer-lasting and more resilient pavement structure.

Table 9. Statistical analysis results of J_{nr} of TLA modified binders at 64 °C considering Original and RTFO conditions ($\alpha = 0.05$).

J_{nr} at 64 °C								
Original Condition					RTFO Condition			
Combinations	PG 64-22	PG 64-22 + 10% TLA	PG 64-22 + 20% TLA	PG64-22 + 30% TLA	PG 64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA
Original Condition	PG64-22	-	S	S	S	S	S	S
	PG64-22 + 10%TLA	-	-	S	S	S	S	S
	PG64-22 + 20%TLA	-	-	S	S	S	S	S
	PG64-22 + 30%TLA	-	-	-	S	S	S	S
RTFO Condition	PG64-22	-	-	-	-	S	S	S
	PG64-22 + 10%TLA	-	-	-	-	-	S	S
	PG64-22 + 20%TLA	-	-	-	-	-	-	S
	PG64-22 + 30%TLA	-	-	-	-	-	-	-

S—Significant, N—Non-significant.

Table 10. Statistical analysis results of J_{nr} of TLA modified binders at 64 °C considering original condition and after conditioning considering only top and bottom parts ($\alpha = 0.05$).

J_{nr} at 64 °C												
Original (%)					Top (%)				Bottom (%)			
Combinations	PG 64-22	PG 64-22 + 10% TLA	PG 64-22 + 20% TLA	PG64-22 + 30% TLA	PG 64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA	PG 64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA
Original (%)	PG64-22	-	S	S	S	S	S	S	S	S	S	S
	PG64-22 + 10%TLA	-	-	S	S	S	S	S	S	S	S	S
	PG64-22 + 20%TLA	-	-	S	S	S	N	S	S	S	S	S
	PG64-22 + 30%TLA	-	-	-	S	S	S	S	S	S	S	S
Top (%)	PG64-22	-	-	-	-	S	S	S	S	S	S	S
	PG64-22 + 10%TLA	-	-	-	-	-	S	S	S	S	S	S
	PG64-22 + 20%TLA	-	-	-	-	-	-	S	S	S	S	S
	PG64-22 + 30%TLA	-	-	-	-	-	-	-	S	S	S	S
Bottom (%)	PG64-22	-	-	-	-	-	-	-	-	S	S	S
	PG64-22 + 10%TLA	-	-	-	-	-	-	-	-	-	S	S
	PG64-22 + 20%TLA	-	-	-	-	-	-	-	-	-	-	S
	PG64-22 + 30%TLA	-	-	-	-	-	-	-	-	-	-	-

S—Significant, N—Non-significant.

3.5. Thermal Cracking Property (Low Temperature)

The Superpave asphalt binder specification mandates a maximum creep stiffness of 300 MPa, recognizing that lower stiffness values are advantageous for reducing low-temperature stress and preventing thermal cracking. In experiments utilizing the Bending Beam Rheometer (BBR) at −12 °C, it was found that the addition of 10%TLA to virgin binders initially decreased the stiffness compared to the virgin binder alone. This initial reduction in stiffness is likely due to the TLA's ability to enhance the binder's flexibility and improve its stress relaxation properties.

However, increasing the TLA content beyond 10% resulted in higher stiffness values. Notably, incorporating 30%TLA raised the stiffness above the 300 MPa threshold, with standard errors and linear exponential equations as depicted in Figure 10. This increase in stiffness with higher TLA content could be attributed to the additional TLA particles creating a denser and more rigid network within the binder, thus increasing the overall stiffness.

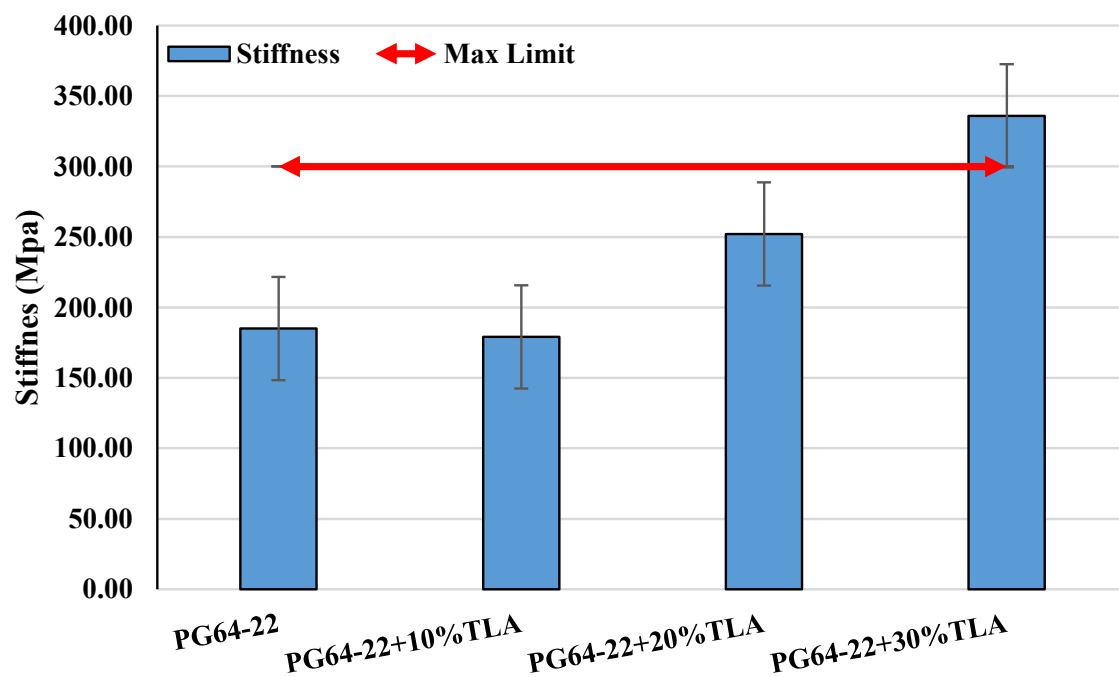


Figure 10. Stiffness at $-12\text{ }^{\circ}\text{C}$ of the TLA modified binders after RTFO + PAV aged condition.

This trend was consistent with the $G^* \cdot \sin \delta$ values at $25\text{ }^{\circ}\text{C}$, and the m-value demonstrated a similar pattern, with standard errors and linear exponential equation as shown in Figure 11. Specifically, only the original binder and the binder modified with 30%TLA met the minimum m-value requirement of 0.30, while the other modified binders failed to achieve this threshold. The m-value represents the rate of change of stiffness with temperature; higher m-values indicate better stress relaxation capabilities. Statistical analysis, detailed in Tables 11 and 12, was conducted to validate these findings.

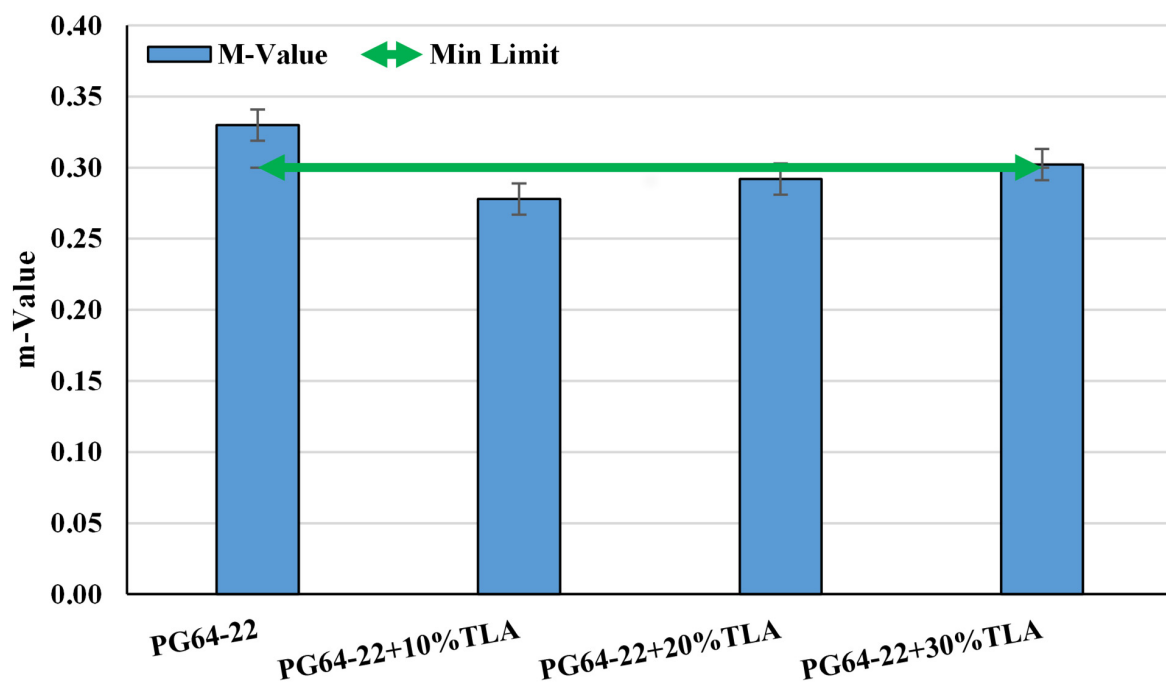


Figure 11. m-value at $-12\text{ }^{\circ}\text{C}$ of the TLA modified binders after RTFO + PAV aged condition.

Table 11. Statistical analysis results of the stiffness (RTFO + PAV) of TLA modified binders at $-12\text{ }^{\circ}\text{C}$ as a function of different combinations ($\alpha = 0.05$).

Combination	Stiffness at $-12\text{ }^{\circ}\text{C}$			
	PG64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA
PG64-22	-	S	S	S
PG64-22 + 10%TLA	-	-	S	S
PG64-22 + 20%TLA	-	-	-	S
PG64-22 + 30%TLA	-	-	-	-

S—Significant, N—Non-significant.

Table 12. Statistical analysis results of the m-value (RTFO + PAV) of TLA modified binders at $-12\text{ }^{\circ}\text{C}$ as a function of different combinations ($\alpha = 0.05$).

Combination	m-Value at $-12\text{ }^{\circ}\text{C}$			
	PG64-22	PG64-22 + 10% TLA	PG64-22 + 20% TLA	PG64-22 + 30% TLA
PG64-22	-	S	S	S
PG64-22 + 10%TLA	-	-	S	S
PG64-22 + 20%TLA	-	-	-	N
PG64-22 + 30%TLA	-	-	-	-

S—Significant, N—Non-significant.

From a scientific perspective, lower creep stiffness at low temperatures indicates better relaxation properties, which can mitigate thermal cracking in pavements. The m-value is also critical; higher m-values are indicative of better stress relaxation capabilities. Therefore, binders that maintain lower stiffness and higher m-values at low temperatures are expected to enhance pavement durability and extend service life by reducing the likelihood of cracking under thermal stress. The experimental results suggest that while the moderate addition of TLA can improve binder flexibility and reduce stiffness, excessive TLA content can lead to increased stiffness, potentially compromising the pavement's performance under low-temperature conditions.

3.6. Storage Stability Results

The storage stability study focused on two key parameters: viscosity and $G^*/\sin \delta$, considering only the top and bottom parts of the samples after the conditioning period. Tables 13 and 14 present the separation percentage values of various modified samples post-conditioning.

The viscosity results indicate minimal phase separation when Trinidad Lake Asphalt (TLA) was introduced as a modifying agent to the virgin binder. The values were almost identical across samples, and increasing the TLA percentage did not significantly enhance phase separation between the asphalt-rich phase and the TLA-rich phase. Additionally, increasing the temperature from $135\text{ }^{\circ}\text{C}$ to $165\text{ }^{\circ}\text{C}$ did not significantly affect phase separation. Notably, the binder modified with PG64-22 + 20%TLA exhibited the lowest phase separation value of 3% at both temperatures.

Similarly, the $G^*/\sin \delta$ study, which assessed the separation index at $64\text{ }^{\circ}\text{C}$, showed comparable results to the viscosity study. The phase separation values were consistent, with the binder modified with PG64-22 + 30%TLA demonstrating the lowest phase separation value of 2% among all combinations.

Table 13. Separation index from viscosity of TLA modified binders.

	Binder	Viscosity		
		Top	Bottom	% Separation
135 °C	PG64-22	783.8	840	3%
	PG64-22 + 10%TLA	855.5	922.5	4%
	PG64-22 + 20%TLA	888.8	938.8	3%
	PG64-22 + 30%TLA	920	995	4%
180 °C	PG64-22	313.8	352.5	6%
	PG64-22 + 10%TLA	336.3	374	5%
	PG64-22 + 20%TLA	386.3	411.3	3%
	PG64-22 + 30%TLA	410	447.5	4%

Table 14. Separation index from $G^*/\sin \delta$ of TLA modified binders.

	Binder	$G^*/\sin \delta$		
		Top	Bottom	% Separation
64 °C	PG64-22	1.57	1.75	5%
	PG64-22 + 10%TLA	2.41	2.54	3%
	PG64-22 + 20%TLA	3.07	3.39	5%
	PG64-22 + 30%TLA	3.71	3.83	2%

These phase separation values have significant implications for pavement performance. Low phase separation indicates better homogeneity of the binder, which translates to more consistent performance and the enhanced durability of the pavement. The reduced phase separation in TLA-modified binders suggests improved compatibility between the virgin binder and TLA, contributing to better dispersion and stability of the modified binder. Consequently, this enhances the binder's ability to resist thermal and load-induced stresses, potentially extending the pavement's lifespan.

The low phase separation values observed can be attributed to the chemical and physical properties of TLA, which promote better interaction and integration with the virgin binder. TLA's inherent compatibility with the asphalt matrix ensures uniform distribution, preventing a significant separation of phases. This uniformity is crucial for maintaining the binder's performance characteristics, ultimately leading to improved pavement resilience and longevity.

4. Summary and Conclusions

The study extensively investigated the impact of incorporating Trinidad Lake Asphalt (TLA) into asphalt binders. Key findings are summarized as follows:

1. **Viscosity:** TLA significantly increases the viscosity of asphalt binders, with higher TLA content generally leading to higher viscosity. Anomalies observed at specific TLA percentages underscore the complexity of these interactions, highlighting the need for precise control of TLA content.
2. **Rutting Resistance:** The addition of TLA enhances the rutting resistance of binders, with increased $G^*/\sin \delta$ values in both original and RTFO-aged states. The bottom portions of conditioned samples showed better performance, suggesting improved compaction or segregation effects. However, conditioning reduces rutting resistance, indicating potential binder degradation.
3. **Fatigue Resistance:** Higher TLA content increases $G^* \cdot \sin \delta$ values, reducing the fatigue resistance of asphalt mixtures and indicating higher susceptibility to fatigue-induced cracking. Statistical analysis confirms the correlation between increased TLA content and decreased fatigue resistance.
4. **Rheological Properties:** TLA-modified binders show improved performance in J_{nr} and percentage recovery, indicating reduced fatigue cracking and enhanced resistance

to permanent deformation. Despite some variability, TLA modification enhances pavement durability.

5. **Low-Temperature Performance:** Adding TLA initially improves binder flexibility and reduces stiffness, beneficial for minimizing low-temperature thermal cracking. However, excessive TLA content increases stiffness, negatively impacting stress relaxation properties.
6. **Storage Stability:** TLA as a modifying agent enhances the storage stability of asphalt binders, demonstrating minimal phase separation and excellent homogeneity. This uniform distribution contributes to improved binder stability and potential for extended pavement lifespan.

Conclusions: The incorporation of TLA in asphalt binders offers significant benefits in terms of viscosity, rutting resistance, rheological properties, and storage stability. However, careful consideration of TLA content is essential to balance workability, fatigue resistance, and low-temperature performance, ensuring the optimal structural integrity and durability of asphalt pavements.

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