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Investigating Asphaltic Performance: Rheological Evaluation of Rutting and Fatigue Resistance in Trinidad Lake Asphalt (TLA)-Petroleum-Based Binders

Shiva Ramlal[a], Amy Clark [b,Ψ], Vitra Ramjattan-Harry[c] and Rean Maharaj[d]

[a] Research and Technical Services Unit, Lake Asphalt of Trinidad and Tobago (1978) Ltd, Brighton, La Brea, Trinidad and Tobago, West Indies; Email: sramlal@trinidadlakeasphalt.com

[b,c,d] Process Engineering Unit, The University of Trinidad and Tobago, Esperanza Road, Point Lisas 540517, Trinidad and Tobago, West Indies; Emails: amy.clark@utt.edu.tt; vitra.harry@utt.edu.tt; rean.maharaj@utt.edu.tt

[Ψ] - Corresponding Author

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Abstract: *The performance and longevity of asphalt pavements are crucial to transportation infrastructure, affecting road durability, safety and maintenance costs. This study explores the rheological properties of Trinidad Lake Asphalt (TLA) and Petroleum-Based Binders (TPB) to assess their influence on rutting and fatigue resistance. Using Dynamic Shear Rheometer (DSR), the viscoelastic behaviour of TLA-TPB blends was examined across a range of temperatures and oscillatory frequencies. The results showed that increasing TLA concentrations could enhance rutting resistance but might reduce fatigue cracking resistance. It is thus essential for optimising asphalt formulations to suit tropical climates, ultimately improving pavement durability and reducing long-term maintenance costs. The findings revealed a performance trade-off, where higher stiffness could benefit rutting resistance but might reduce flexibility and long-term fatigue durability. An optimal TLA concentration range of 20-30% was proposed, balancing both rutting performance and acceptable fatigue behaviour. This study sheds important insights on pavement formulation strategies under tropical conditions, where temperature extremes and loading variability will demand resilient binder performance.*

Keywords: *Asphalt, rutting and fatigue, Dynamic Shear Rheometer, pavement, Trinidad Lake Asphalt*

1. Introduction

The longevity and performance of asphalt pavements are critical factors in transportation infrastructure, directly influencing road safety, maintenance costs and overall economic sustainability (Asphalt Institute, 2014). Asphalt binders play a crucial role in determining pavement durability, as they provide the necessary adhesion between aggregates while also resisting traffic loads and environmental stressors (Huang, 2004). However, over time, asphalt pavements experience significant degradation due to factors such as vehicular traffic, temperature fluctuations and oxidative aging (Airey, 2003; You et al., 2018). Two predominant forms of pavement failure are rutting and fatigue cracking, both of which compromise structural integrity and serviceability. Understanding and mitigating these forms of distress are key objectives in pavement engineering research.

Notably, a Dynamic Shear Rheometer (DSR) test frequency of 0.1-15.9 Hz allows laboratory studies to accurately replicate field loading circumstances because it roughly resembles the loading frequency produced by a vehicle moving at about 80 km/h (Bahia and Anderson, 1995; AASHTO, 2003). This relationship between actual traffic-induced stress responses and lab-based rheological data aids in bridging the gap between experimental results and pavement performance in the real world. This relationship has been further strengthened by developments in computational modelling, which have made it possible to incorporate rheological characteristics into life-cycle prediction and mechanistic-empirical pavement design models. More precise predictions of rutting, fatigue, and other distress mechanisms over time are now possible thanks to simulation techniques that can take site-specific factors like temperature changes, load repetitions and binder aging into account. Under a variety of simulated traffic and climate conditions, the effects of modifiers like TLA on enhancing binder elasticity, preventing permanent deformation and prolonging pavement service life can be thoroughly assessed in this context.

Rutting is the permanent deformation of asphalt pavements, primarily caused by repeated traffic loading and excessive temperatures. It occurs when the asphalt binder softens and deforms under sustained pressure, leading to depressions in the wheel path. This type of failure is particularly common in warm climates where elevated temperatures reduce binder stiffness, increasing the likelihood of plastic flow and accumulation of deformation. To enhance rutting resistance, asphalt binders must exhibit sufficient stiffness while maintaining elasticity to recover from applied loads. The rutting parameter, often characterised by the complex modulus (G^*) and phase angle (δ), is a key performance indicator in assessing a binder's resistance to deformation. Studies have shown that modifications to asphalt binders, such as the addition of polymers or natural bitumen sources, can enhance their resistance to rutting by improving their viscoelastic properties (Asli et al., 2012; Bailey and Philips, 2010; Zargar et al., 2012).

Fatigue cracking occurs when an asphalt binder loses its flexibility due to aging, oxidation, or repeated bending stresses. Over time, the binder's ability to dissipate strain energy diminishes, leading to the formation of cracks that propagate through the pavement structure. This type of distress is more prevalent in colder climates or under conditions where frequent loading cycles impose high tensile stresses on the pavement. The resistance of an asphalt binder to fatigue cracking is commonly evaluated through its $G^*\sin\delta$ parameter, which quantifies the ability of the binder to withstand repeated loading cycles without undergoing structural failure. Research has indicated that increasing the stiffness of an asphalt binder, while beneficial for rutting resistance, may inadvertently reduce its fatigue resistance, highlighting the need for an optimal balance in binder formulation (Du et al., 2018).

To address these challenges, various modification techniques have been developed to enhance the performance of asphalt binders. One widely researched approach involves the use of TLA, a naturally occurring asphaltic material sourced from the Pitch Lake in Trinidad and Tobago. TLA is known for its high asphaltene content and exceptional durability, making it a valuable additive for improving binder stiffness and rutting resistance. However, while TLA has been shown to enhance the rigidity of asphalt mixtures, excessive concentrations may reduce the binder's ductility, increasing susceptibility to fatigue cracking (Vigneswaran et al., 2024; Rambarran et al., 2022).

In contrast, TPB, derived from the fractional distillation of crude oil, exhibit lower stiffness compared to TLA but offer better flexibility. The integration of TLA and TPB in asphalt formulations presents an opportunity to optimise binder performance by leveraging the advantages of both materials. Studies have suggested that blending TLA with TPB in specific proportions can yield an asphalt binder with improved resistance to both rutting and fatigue, although the exact balance between stiffness and flexibility remains a subject of ongoing research (Maharaj et al., 2015).

Previous studies have extensively examined the rheological behaviour of asphalt binders modified with polymers, fillers and other additives to improve their resistance to pavement distress including waste-oil rejuvenation (Maharaj et al., 2015), fly-ash and toner fillers (Mohamed et al., 2017; Rambarran et al., 2022), clay-nanocomposite reinforcement (Singh et al., 2021), and crumb-rubber polymer modification (Maharaj et al., 2019). The Strategic Highway Research Program (SHRP) and the Superpave Performance Grading System have established performance-based specifications that define desirable binder properties under varying climatic and loading conditions (Yang et al., 2024). While these studies have provided valuable insights into binder modification strategies, there remains a lack of comprehensive research on the rheological characterisation of TLA-TPB blends, particularly under tropical environmental conditions.

Most existing research focuses on polymer-modified asphalts, with limited emphasis on natural asphalt modifications and their comparative advantages over synthetic alternatives (Zhu et al., 2014). Additionally, the interplay between TLA concentration, temperature variations and oscillatory loading frequency remains an underexplored area, particularly in the context of developing optimal formulations for high-temperature regions. This gap in knowledge underscores the need for further investigation into the viscoelastic properties of TLA-TPB blends, with the aim of identifying compositions that optimise both rutting and fatigue resistance.

In the Caribbean, where year-round high temperatures (26-34 °C) and humidity (>75 %) speed up oxidative aging and plastic flow, rutting and fatigue cracking continue to be the most common distress mechanisms for asphalt pavements (Climate Change Knowledge Portal, n.d.; Weather Atlas, n.d.). Although TLA is widely used as a natural stiffening agent, excessive usage of it can reduce ductility due to its high asphaltene content (Maharaj et al., 2015). There is a knowledge gap on TLA blend performance in tropical marine conditions because previous research on the blends was mostly focused on temperate areas.

Therefore, the objective of this investigation is to (i) measure the rheological response of TLA–TPB blends under temperature–frequency regimes in the Caribbean and (ii) determine the ideal TLA concentration that strikes a balance between fatigue resistance and rutting. For pavement engineers looking for long-lasting binder formulations for island road networks, the study provides beneficial guidance.

2. Literature Review

2.1 TLA versus Polymer-modified Asphalts

Although polymer modifiers like crumbs and styrene-butadiene-styrene (SBS) may significantly improve the elasticity of the binder, they usually increase the cost of the material by 30 to 50%, which is more than most small-island economies can afford (Airey, 2003; Malluru et al., 2025). Thus, TLA is a locally produced substitute that has demonstrated high-temperature stability and good storage qualities (Vigneswaran et al., 2024). However, Walters and Bahia (2019) advised that if the TLA dosage is more than about 35% wt, the binder is susceptible to moisture-induced degradation, highlighting the necessity of striking a balance between durability and stiffness increases. Further investigation shows that anti-stripping techniques like hydrated-lime substitution (Mohammed et al., 2023) or amine-based liquid additives (Wang and Wang, 2021) can partially or completely counteract moisture damage at high TLA dosages, suggesting that dosage ceilings may be removed when such treatments are used.

2.2 Climatic Considerations for the Southern Caribbean

The average global horizontal irradiance in TT is approximately 5.4 kWh, the yearly rainfall ranges from 1,600 to 2,200 mm, and the relative humidity can vary by more than 75% (Solargis, 2021; Climate Change Knowledge Portal, n.d.). While extended rainy seasons encourage moisture removal of aggregates, continuous UV exposure speeds up oxidative hardening (Zhang et al., 2023). Because there are no freeze-thaw cycles, pavement damage is mostly caused by rutting and wear from prolonged high temperatures. A binder-design approach specifically designed for high-temperature, high-humidity service conditions in the Caribbean is motivated by these combined stressors.

2.3 Research Voids

Only a few investigations describe both rutting (G*/sin δ) and fatigue (G*sin δ) indices on similar specimens, even though TLA has been used for a century. Comprehensive rheological records for TLA–TPB blends under tropical temperature–frequency spectra are also rare (Du et al., 2018). Furthermore, nothing is known about moisture-susceptibility testing and field-scale validation (Qin et al., 2023). The present investigation addresses these data gaps and creates performance envelopes that are pertinent to the region by mapping binder response over 40-90 °C and 0.1-15.9 Hz.

3. Method and Materials

The study utilised TLA sourced from the Pitch Lake in Trinidad and TPB obtained from petroleum fractionation. Blends of 60/70 and 160/220 TPB were prepared with varying TLA concentrations. Rheological characterisation was conducted using an ATS RheoSystems DSR at temperatures ranging from 40-90°C and frequencies of 0.1-15.91 Hz.

The frequency range of 0.1-15.91 Hz was selected based on previous studies indicating that lower frequencies simulate long-term loading conditions while higher frequencies represent short-term vehicular impacts (Mohamed et al., 2017). Temperature variation from 40°C to 90°C was chosen to reflect tropical environmental conditions prevalent in Trinidad and Tobago. The sample preparation followed ASTM D5 for penetration and ASTM D36 for softening point to ensure consistency across blends. The source and specifications of the TLA and TPB samples used in this investigation are shown in Table 1.

4. Results and Discussion

TLA-modified 60/70 and 160/220 binders' rutting resistance (G*/sinδ) at 60°C is shown in Figure 1 for three loading frequencies (0.1 Hz, 1.59 Hz and 15.9 Hz). Although the extent of improvement varies by frequency, rutting resistance rises with TLA content across all frequencies and both binder types. The 60/70 blend's stiffer base characteristics are confirmed by noticeably higher G*/sinδ values as compared to 160/220. The effect of TLA on rutting resistance is most noticeable at 15.9 Hz, which mimics high-speed automobile traffic (~80 km/h). The importance of frequency in performance grading is highlighted by the significantly lower G*/sinδ values at 0.1 Hz, which is indicative of slower traffic or idle conditions.

According to these results, higher TLA concentrations improve load-bearing ability, especially when traffic loads are frequent and substantial, as they are on tropical highways.

Table 1. Source and Specifications of TLA and TPB Samples Utilised in the Study

TEST	UNITS	METHOD	TLA		TPB 160/220		TPB 60/70	
SOURCE			Natural product mined from the Pitch Lake. Obtained from the Lake Asphalt of Trinidad and Tobago Limited		By-Product of the Petroleum Fractionation Process.		By-Product of the Petroleum Fractionation Process.	
			Min.	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
Specific Gravity	g/g	ASTM D70	-	-	Report		Report	
Density	g/cm^3	ASTM D70	1.0	1.5	-	-	-	-
Softening Point	°C	ASTM D36	85	99	35	-	46	-
Penetration at 25 °C, 100g, 5 s	0.1 mm	ASTM D5	0	5	160	220	60	70
Ductility at 25°C, 5 cm/min	cm	ASTM D113	-	-	100	-	100	-
Flash point (Cleveland open cup)	°C	ASTM D92	150	-	220	-	230	-
Solubility	%	ASTM D7553/D2172	52	62	99.0	-	99.0	-
Retained Penetration after thin-film oven test	%	ASTM D5	50	-	37	-	52	-
Ductility at 25°C, 5cm/min, after thin-film oven test	cm	ASTM D113	-	-	100	-	50	-
Ash Content	%	ASTM D2415	33	38	-	-	-	-

For the 60/70 blend, a slight reduction in rutting resistance was observed at low TLA concentrations (5-10%) under medium and high frequencies (1.59 Hz and 15.9 Hz). This may be attributed to partial disruption of the base binder's microstructure before sufficient asphaltene reinforcement from TLA is achieved. At these lower dosages, the stiffening effect of TLA may not be fully realised, leading to temporary decreases in G*/sinδ. Once concentrations exceed 15-20%, the reinforcing network becomes dominant, resulting in the strong positive trend seen at higher dosages. This non-linear effect underscores the importance of adopting an optimal TLA threshold, as sub-optimal dosages may inadvertently weaken rutting resistance.

For the 60/70 binder, G*/sinδ at 15.9 Hz rose from 3.55E+04 KPa at 0% TLA to 6.22E+04 KPa at 30% TLA, reflecting a 75.3% increase. At 1.59 Hz, values increased from 4.49E+03 KPa to 7.74E+03 KPa (72.4% increase), and at 0.1 Hz, an 83.1% increase was observed (from 3.97E+02 KPa to 7.27E+02 KPa). In the case of the 160/220 binder, rutting resistance at 15.9 Hz increased by 559.6%, from 5.79E+03 KPa to 3.82E+04 KPa. At 1.59 Hz, the increase was even more dramatic—997.7%, from 6.87E+02 KPa to 7.54E+03 KPa. At 0.1 Hz, a rise of an exponential 3204.8% was recorded from 8.45E+01 KPa to 2.79E+03 KPa. These findings confirm that higher TLA content significantly boosts binder stiffness under dynamic loading, with especially pronounced effects at high frequencies. This supports a targeted TLA range of 20-30% for optimising rutting resistance across various traffic speeds.

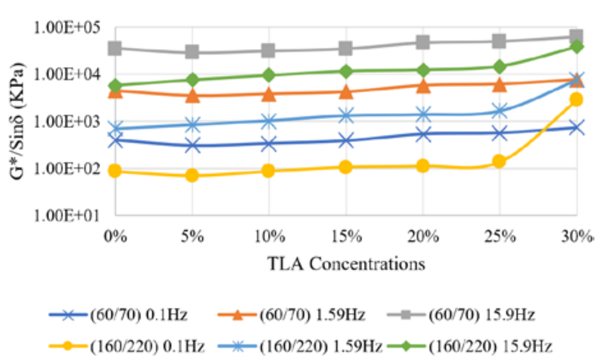

Figure 1. Rutting Resistance (G*/sinδ) of TLA-modified 60/70 and 160/220 Asphalt Binder Blends as a function of TLA oncentration, evaluated at 0.1 Hz, 1.59 Hz and 15.9 Hz frequencies at 60°C.

G*sinδ values rise with TLA concentration for both types of binder, suggesting a reduction in fatigue resistance (see Figure 2). This tendency, where high-frequency loading speeds up binder stiffness and brittleness, is most noticeable at 15.9 Hz. The fatigue parameter values are significantly lower at lower frequencies (0.1 Hz), which mimic static or slow-moving loads, indicating greater flexibility. These results demonstrate how fatigue performance is sensitive to binder formulation and stressors caused by traffic. Crucially, they emphasise the necessity of striking a balance between possible fatigue penalties and rutting resistance improvements, particularly in situations with large TLA dosages and fast traffic loads.

For the 60/70 binder, G*·sinδ increased from 3.96E+02 kPa at 0% TLA to 7.26E+02 kPa at 30% TLA under 0.1 Hz, yielding an 83.3% improvement. A slight 0.5% decrease was observed at 1.59 Hz, from 5.75E+03 kPa to 5.72E+03 kPa. At 15.9 Hz. However, the improvement was more pronounced—rising from 3.41E+04 kPa to 5.97E+04 kPa, a 75.1% increase, indicating enhanced resistance to deformation under rapid loading. The 160/220 binder, known for its softer baseline performance, exhibited even greater gains. At 0.1 Hz, G*·sinδ increased from 7.54E+01 kPa to 1.09E+03 kPa, marking a 1345.6% increase. At 1.59 Hz, values climbed from 6.77E+02 kPa to 5.72E+03 kPa, a 744.9% increase, and at 15.9 Hz, the most dramatic increase of 507.0% was observed—rising from 5.75E+03 kPa to 3.49E+04 kPa.

These results emphasise that TLA concentrations between 20% and 30% significantly enhance fatigue resistance across all frequencies, with particularly outstanding improvements in softer base binders like 160/220. The frequency-dependent response highlights the efficacy of TLA-modified blends in mitigating fatigue-related distress under both slow and high-speed traffic conditions.

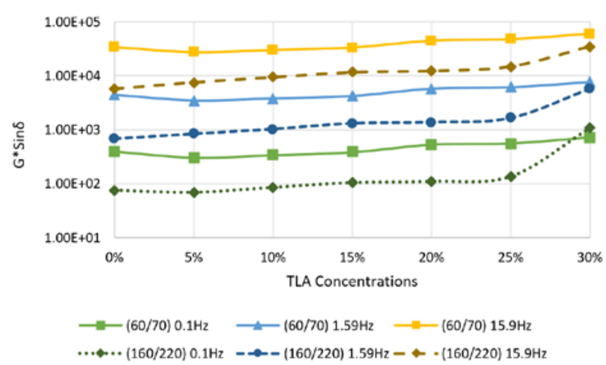

Figure 2. Fatigue Resistance (G*sinδ) of TLA-modified 60/70 and 160/220 Asphalt Binder Blends as a function of TLA concentration across three frequencies (0.1 Hz, 1.59 Hz and 15.9 Hz) at 60°C.

From Figure 3, it shows that for all blends, G*/sinδ values fall exponentially with rising temperatures, which is in line with asphalt binders' thermal softening behavior. Binders, particularly those with a higher TLA concentration, show greater rigidity at lower temperatures, which helps them resist rutting. But as the temperature gets closer to 90°C, the blend variations become less noticeable, and even the stiffer binders perform worse. Additionally, even at high temperatures, the 30% TLA–160/220 blend maintained comparatively high G*/sinδ ratios, suggesting improved thermal stability. These results highlight how crucial it is to optimise binder formulations for high-temperature resilience, particularly in tropical regions that are subject to frequent heating cycles and extended heat exposure.

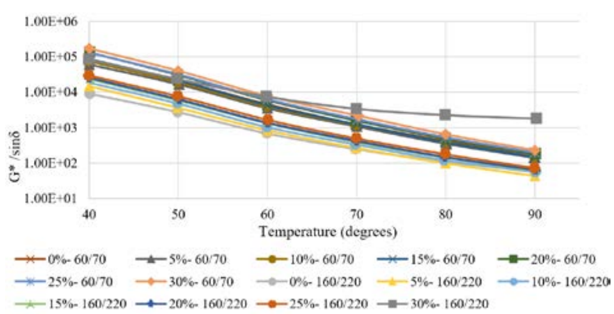

Figure 3. Rutting Resistance (G*/sinδ) of TLA-modified 60/70 and 160/220 Binder Blends across a Temperature range of 40°C to 90°C at 1.59 Hz

In temperate regions, pavement distress from high temperatures is often limited to short seasonal peaks, but in Trinidad's tropical climate, pavement layers are exposed to sustained elevated temperatures (≈ 26-34 °C) and high humidity year-round. This persistent thermal and oxidative stress accelerates aging and increases susceptibility to plastic flow. In our rheological tests conducted at 80–90 °C, the TLA-TPB blends maintained higher G*/sin δ values than many modern temperate-region binders documented in recent studies (Guo et al., 2025; Martinez-Toledo et al., 2024; Mior Sani et al., 2025). These findings suggest that the adopted model must emphasise high-temperature stiffness and elastic resilience over broad thermal flexibility. This justifies the selection of a 20–30 % TLA dosage specifically tailored for tropical pavement conditions.

The impact of temperature on fatigue cracking resistance (G*sinδ) for different TLA concentrations in both 60/70 and 160/220 binders is shown in Figure 4. There is a definite inverse relationship: for all mixes, G*sinδ falls with increasing temperature. According to this pattern, higher temperatures increase binder flexibility and lessen the likelihood of fatigue cracking. Because of their greater flexibility, blends with lower TLA concentrations provide superior fatigue resistance at lower temperatures (40–60°C). Even the stiffer blends with increased TLA content, however, start to exhibit improved ductility at higher temperatures (80–90°C), which reduces the performance difference between formulations. The findings confirm that binders need to be tuned for the entire diurnal thermal range found in tropical areas and that temperature has a significant impact on fatigue performance.

Although rheological characteristics were assessed in this investigation over a full range of oscillatory frequencies (0.1, 1.59 and 15.9 Hz), the comparative figure shown in Figure 5 concentrates on the 15.9 Hz condition. Because it produced the most noticeable difference in performance indices (G*/sinδ and G*sinδ) across TLA concentrations, this frequency was chosen for graphical emphasis to clearly illustrate the trade-offs between fatigue resistance and rutting. With a wheel speed of about 80 km/h, the 15.9 Hz frequency represents a short-term, high-speed traffic loading scenario. As such, it is extremely important to pavement performance in heavily frequented roads. Despite being tested and discussed as well, 1.59 Hz equivalent to standard field loading frequencies used in Superpave and AASHTO protocols had less noticeable trends and is therefore excluded from this comparative visualisation (see Figures 3 and 4). However, throughout the investigation, 1.59 Hz data are utilised to support temperature-dependent interpretations and are still crucial for comprehending binder behaviour under normal operating settings.

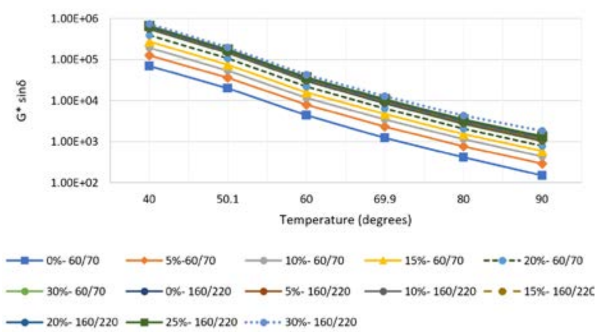

Figure 4. Fatigue Resistance (G*sinδ) of TLA-modified 60/70 and 160/220 Binder Blends across Temperatures from 40°C to 90°C

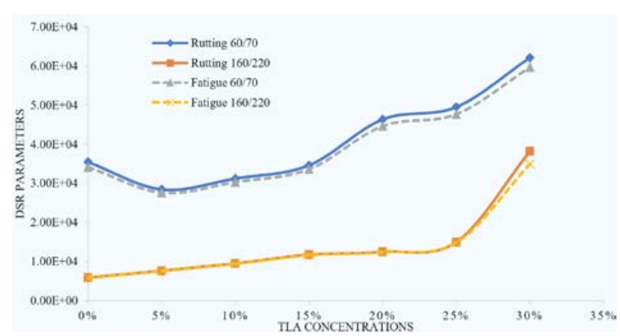

Figure 5. A Comparative Overview of the Effect of TLA Concentration on Rutting (G*/sinδ) and Fatigue (G*sinδ) Resistance at 15.9 Hz for Both the 60/70 and 160/220 Binder Blends.

This high-frequency condition is particularly useful for urban highways with continuous traffic levels since it replicates rapid vehicle loading at highway speeds (~80 km/h). In all blends, the results show a strong positive association between rutting resistance and rising TLA concentration; at 30% TLA, the 60/70 binder achieved the highest G*/sinδ values. On the other hand, fatigue resistance (G*sinδ) rises with TLA content as well, but more slowly, especially for the 160/220 blend. The trade-off between stiffness and flexibility is further illustrated by this figure: high concentrations of TLA (over 30%) may decrease fatigue durability even while it improves rutting resistance. The image demonstrates the ideal performance window of 20-30% TLA, when rutting resistance gains are highest without resulting in a significant fatigue penalty.

At 60°C and 15.9 Hz, TLA-modified binders demonstrated measurable improvements in both rutting and fatigue resistance. For the 60/70 blend, rutting resistance (G*/sinδ) increased by 75.2%, rising from 3.55E+04 KPa to 6.22E+04 KPa at 30% TLA. Fatigue resistance (G*sinδ) similarly increased by 75.1%, from 3.41E+04 KPa to 5.97E+04 KPa, indicating greater stiffness and a potential reduction in flexibility. In contrast, the 160/220 blend exhibited a 559.6% increase in rutting resistance (from 5.788E+03 KPa to 3.82E+04 KPa) and a 507.6% increase in fatigue resistance (from 5.746E+03 KPa to 3.49E+04 KPa). These quantitative results validate the role of TLA in significantly enhancing binder stiffness and rutting performance, particularly for softer base binders, while also underscoring the need to balance fatigue considerations. This supports the recommendation of a 20-30% TLA concentration as an optimal range.

The black curves illustrate the rheological behaviour of different TLA-TPB blends at 60°C. A shift toward higher G* and lower δ suggests increased stiffness and elasticity with rising TLA concentrations (see Figures 6 and 7). However, excessive TLA addition may negatively impact fatigue resistance, as predicted by Superpave specifications (C-SHRP, 1995). This suggests that while TLA can enhance load-bearing capacity, excessive use may lead to premature cracking under repeated loading, requiring precise formulation adjustments for optimal binder performance.

For the 160/220 blend, the black curves Figure 7 reveal a marked contrast between the unmodified binder (0% TLA) and the heavily modified blend (30% TLA). At 0% TLA, the binder exhibits lower stiffness, consistent with its softer baseline properties. By contrast, at 30% TLA, the shift toward significantly higher complex modulus (G) and reduced phase angle (δ) indicates pronounced stiffening and elasticity. This sharp difference highlights how increasing TLA concentration fundamentally alters the viscoelastic response of softer base binders, improving rutting resistance but at the cost of reduced ductility and potentially lower fatigue tolerance.

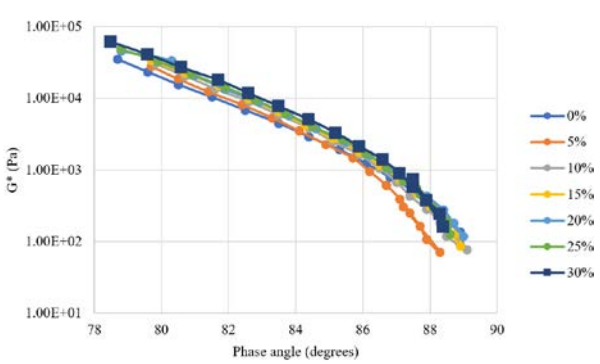

Figure 6. Black Curves for TLA (60/70) at 60˚C

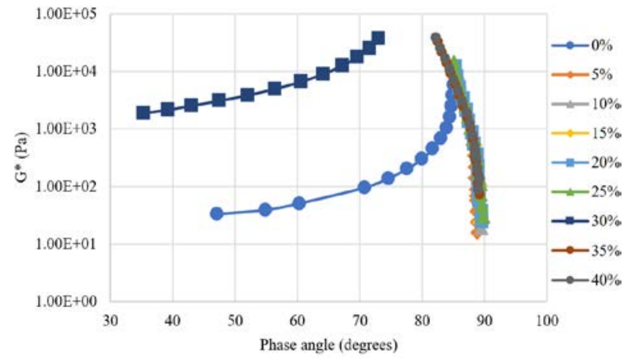

Figure 7. Black Curves for TLA (160/220) Blend at 60˚C

5. Conclusion

This study highlights the rheological evolution of TLA-modified petroleum-based binders across a range of loading frequencies and temperatures. It was discovered that TLA concentrations ranging from 20% to 30% greatly improved rutting resistance, especially under high-temperature and high-frequency circumstances. Nevertheless, this results in greater G*sinδ values, suggesting a potential reduction in fatigue resistance, particularly at larger TLA dosages. These findings highlight the necessity of choosing a TLA dosage in pavement design that balances performance.

Based on the research objectives and rheological evidence, an ideal TLA concentration of 20-30% is recommended, as this range maximises rutting resistance while maintaining acceptable fatigue resistance under tropical conditions. To further confirm the endurance of these modified blends under Caribbean climate conditions, further research should include field-scale cyclic fatigue testing, moisture conditioning, and aging simulation. These observations are especially pertinent to the development of asphalt solutions that endure longer in hot, tropical climates.

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Authors' Biographical Notes:

Shiva Ramlal *holds a Master of Business Administration (MBA) in Business Administration and Management (Distinction) from Edinburgh Business School, Heriot-Watt University and a Bachelor of Science in Chemistry and Management with a minor in Analytical Chemistry from the University of the West Indies, St. Augustine Campus, where he graduated with First Class Honors. He currently serves as the Head of the Research and Technical Services Unit (TLA), with a focus on applied research and innovation in materials science and sustainable development.*

Amy Clark *is a Project Assistant at The University of Trinidad and Tobago (UTT) and a Master of Science (MSc) candidate in Energy Engineering (Renewable Energy). She holds a BSc in Process Engineering and a Diploma in Chemical Engineering from UTT. Her work centers on converting MSc theses into peer-reviewed manuscripts through technical editing, data validation, and alignment with international publication standards. Her research interests include renewable energy integration, asphalt modification, rheological characterisation, and sustainable materials engineering.*

Vitra Ramjattan Harry *is an Engineering Laboratory Technician at The University of Trinidad and Tobago. She holds a Master of Science (MSc) in Reservoir Engineering and a Bachelor's degree in Process Engineering, both from The University of Trinidad and Tobago. With over 12 years of experience in academic and technical support roles, her expertise spans laboratory operations, experimental design, and applied process research. She has co-authored 11 publications to date, reflecting her continued commitment to advancing knowledge in the fields of engineering and energy sciences.*

Rean Maharaj *holds a Bachelors (B.Sc.) Degree in Chemistry, specialising in Analytical Chemistry, a Master of Philosophy (M.Phil.) degree in the field of Applied Physical Chemistry and a Ph.D. in Process and Utilities Engineering. Professor Maharaj joined academia in 2006 and is attached to the Process Engineering Programme at the University of Trinidad and Tobago. He currently has an active research agenda focusing on areas such as material science, waste management and renewable energy systems.*

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