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# Performance Study on Modified Asphalt Cement Using Trinidad Lake Asphalt (TLA) as a Polymer Modifier

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ABSTRACT

Asphalt binders play a crucial role in pavement performance by providing the necessary viscoelastic properties to withstand traffic loads and environmental stressors. This study investigates the rheological characteristics of Trinidad Lake Asphalt (TLA) blended with penetration grade (PEN 60/70 and PEN 160/220) binders to assess suitability for road applications. Using the Dynamic Shear Rheometer (DSR) test, this study evaluates efforts on varying TLA concentrations as influencing key parameters such as complex shear modulus (G*) and phase angle (δ) across different temperatures and frequencies. The results demonstrate that increasing TLA content enhances rutting resistance by increasing stiffness, but it also impacts fatigue resistance. These findings contribute to the optimisation of asphalt formulations for improved pavement performance under diverse traffic and climatic conditions.

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## 1 INTRODUCTION

Road pavements worldwide rely on the integrity of the asphalt binder to withstand traffic loading and environmental stressors. Asphalt, in combination with mineral aggregates, forms the primary structural matrix of most pavements; however, it is the binder component that provides the deformable and viscoelastic properties essential for performance. Over time, traffic loads, climatic fluctuations, and environmental factors contribute to the aging and deterioration of asphalt pavements, leading to distresses such as fatigue cracking, rutting, and thermal cracking. One established remedy for aged pavements is reclamation, where worn surfaces are milled and recycled into Reclaimed Asphalt Pavement (RAP)[1]. Although RAP is beneficial from sustainability and economic perspectives, the binder within RAP already exhibits significant aging, which can limit the performance of pavements incorporating high RAP content.

One current strategy to improve asphalt binder performance is modification with various additives or polymers. In the United States, a recent survey of state highway agencies revealed that 35 out of 47 agencies plan to expand the application of modified asphalt, recognising their potential in reducing common failure mechanisms such as rutting and fatigue cracking[2]. Efforts to modify asphalt date back to nearly two centuries; by 1982, more than 1,000 technical publications had already documented advances in polymer-modified asphalt or corresponding mixtures, emphasizing a longstanding global interest in improving asphalt performance[3]. Today, polymer modification is widely adopted in modern pavement design to enhance durability and performance under varying traffic and environmental conditions.

Naturally occurring asphalt, such as TLA, has served as a natural asphalt modifier for over 100 years globally. TLA originates from the largest commercially viable natural asphalt lake in the world, known as the La Brea Pitch Lake in Trinidad. It exhibits a high maltene/asphaltene content and distinct compositional structure incorporating a unique mineral component, which can impart desirable properties such as enhanced stiffness and durability to conventional asphalt binders. Numerous studies have reported that small quantities of TLA can noticeably alter the rheological and mechanical performance of blends by improving high-temperature rutting resistance and potentially extending the pavement service life[4-6]. TLA is utilised in the asphalt industry to provide performance-enhancing properties to base bitumen and asphaltic mixes. Indeed, TLA is renowned for its uniform consistency.

One of the most detailed methods for evaluating binder modification is the Dynamic Shear Rheometer (DSR) test. The DSR test is particularly useful because it quantifies both the elastic (recoverable) and viscous (non-recoverable) components of asphalt behaviour through parameters such as the complex shear modulus (G*) and the phase angle (δ). These parameters correlate with critical pavement performance indicators like stiffness, deformation resistance, and fatigue life. Importantly, understanding how G* and δ vary with temperature and loading frequency offers insight into the binder's suitability under real-world traffic speeds and climate scenarios.

Despite the volume of research on polymer-modified asphalt, there remains a need to systematically examine how TLA concentrations in different base asphalt grades, such as PEN 60/70 and PEN 160/220, affect key rheological parameters. Such investigations not only aid in identifying optimal blend compositions but also deepen the broader scientific and practical understanding of natural asphalt modifications. The study was therefore conducted to fill the gaps in evaluating the performance of TLA asphaltic blends across a range of temperatures and loading frequencies using DSR protocols. The findings have direct implications for pavement engineers seeking to extend pavement service life and minimise maintenance costs under diverse operating conditions.

Rheological simulation and modelling have become essential tools in recent years for predicting how asphalt binders behave under actual loading scenarios. The findings of the DSR test, δ and G*, represent how the binder reacts to shear pressures brought on by traffic[7]. For example, a vehicle speed of about 80 km per hour is approximated by a DSR test frequency of 1.59 Hz, enabling laboratory

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characterisation to replicate real-world road circumstances[8,9]. This association aids in bridging the gap between field performance results and lab-scale rheological measurements. In this regard, the potential of modifiers such as TLA to increase elasticity, prevent rutting, and prolong pavement life can be assessed. The development of performance-based specifications and the incorporation of rheological data into pavement life-cycle modeling frameworks are further supported by simulation-based techniques like this one[10,11].

Although prior studies have explored the role of TLA in binder modification, this study uniquely examines the influence of incremental TLA additions across two distinct penetration grades (PEN 60/70 and PEN 160/220)[5,6], with comprehensive rheological profiling across temperature and frequency domains. Studies have typically focused on fixed TLA dosages or single-grade applications without evaluating performance under dynamic loading and thermal variations. By incorporating both complex modulus and phase angle metrics across operational spectra, this research contributes a robust dataset for binder design optimisation under real-world climatic and traffic scenarios[6,12].

Recent work has reframed TLA as a core component in high-performance binder systems, especially in hybrids with elastomers and warm-mix technologies:

(i) TLA + SBS hybrids (PG 64-22) deliver significantly improved rutting resistance (MSCR recovery > 88%, $J_{nr} < 0.01$ kPa$^{-1}$ at higher SBS loadings), while SBS helps mitigate the increased low-temperature stiffness introduced by TLA—suggesting a balanced performance for heavy-traffic, hot-climate applications[13].

(ii) TLA + SIS systems also enhance stiffness and deformation resistance under Superpave protocol testing, further supporting TLA's role as a high-temperature performance booster in elastomer-modified binders[14].

(iii) TLA + Crumb Rubber + Warm-Mix Asphalt (CRM-WMA blends, PG 64-22) manage viscosity and workability effectively, achieving lower viscosity and enhanced high-temperature performance, accompanied by sustainability benefits[15].

(iv) From a durability standpoint, SBS/TLA composite binders show enhanced rheological stability and ageing resistance compared to SBS-only systems[16].

(v) Finally, zero-shear-viscosity (ZSV)–based evaluations of TLA-modified binders reveal that higher ZSV correlates with improved permanent-deformation resistance in mastic asphalt, consistent with TLA's rutting-mitigation properties[17].

## 2 METHODS AND MATERIALS

The methodology involved five main stages: material selection, blend preparation, sample conditioning, rheological testing, and data analysis. This schematic representation (Fig. 1) highlights the systematic approach used to evaluate the rheological performance of TLA-modified binders, ensuring reproducibility and transparency in the testing programme.

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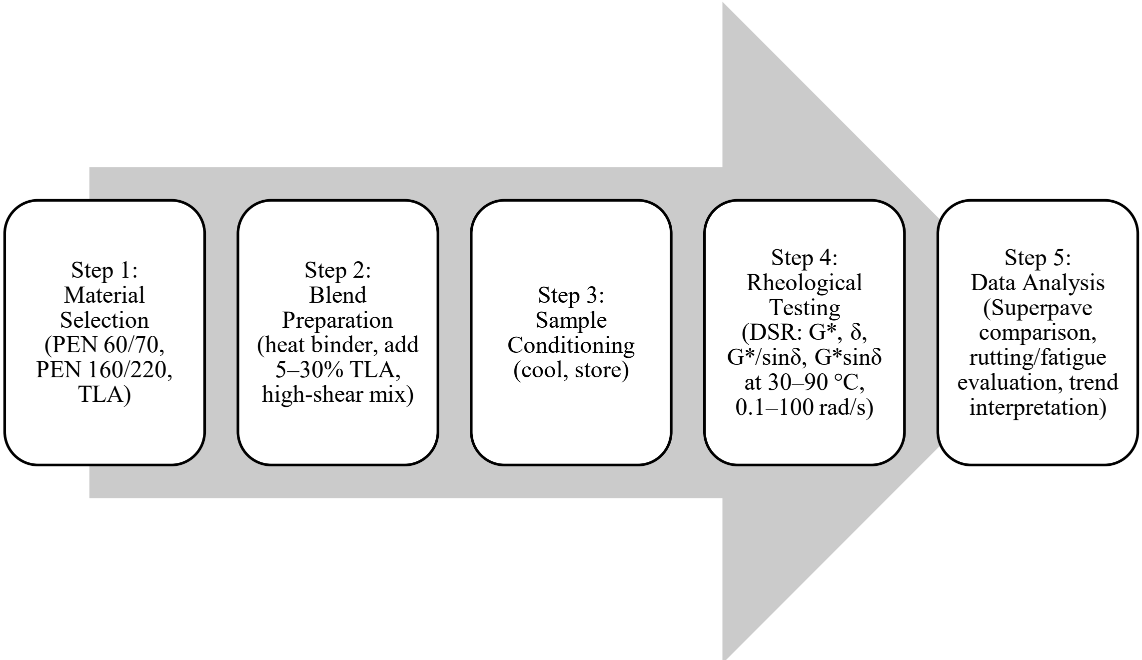


Fig. 1. Experimental process chart for the preparation and rheological evaluation of TLA- modified asphaltic binders.

## 2.1 Materials

Two types of base asphalt binders were selected for this study:

(i) PEN 60/70

(ii) PEN 160/220

The two penetration grades were obtained from the atmospheric/vacuum fractional distillation of crude oil, with modifications made depending on the grade and the relative fractions of gas oil utilised. The choice of these two penetration grades reflects the frequent use of these grades in pavement construction. PEN 60/70 is typically employed in regions experiencing higher temperatures or heavier traffic, while PEN 160/220 is a softer binder suitable for moderate to colder climatic conditions. PEN 160/220 was used according to ASTM D5710 to produce TLA-modified binders.

Trinidad Lake Asphalt was obtained from the Pitch Lake in Trinidad, renowned for its naturally occurring asphalt deposits. The crude pitch is mined in an open-pit manner from the lake, which has a surface span of 100 acres and a central depth of 250 feet. The crude asphalt is a uniform emulsified mixture of bitumen, mineral matter, water, and gas. The crude pitch was mined by tractors with a ripping attachment, which was then transferred to the refining stills containing serpentine coils for heating via steam (300–320 °F). Agitation lines were also used to ensure thorough mixing and consistent product. The still capacity was 100–120 MT and was heated for 16 to 18 hours to remove water present as steam, following which the molten material was strained to remove impurities such as organic debris. The resulting product, TLA, also called Dried Asphalt or Trinidad Epure was a refined, performance-enhancing binder. Its unique composition, notably high in maltene and asphaltenes together with mineral content, has been reported to enhance stiffness and resistance to deformation in asphalt mixtures.

Mineral matter, soluble bitumen, and additional trace elements make up the semi-solid emulsion that is TLA. The following physical attributes are stated in Table 1:

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Table 1. Physical characteristics of TLA

| References | Parameters | Units | Trinidad Lake Asphalt | |
|---|---|---|---|---|
| | | | Min | Max |
| ASTM D5 | Penetration @ 25°C | 0.1 mm | 0 | 5 |
| ASTM D36 | Softening point – $t_{r\&b}$ | °C | 85 | 99 |
| ASTM D92 | Flash point | °C | 150 | - |
| ASTM D2172 | Solubility in Trichloroethylene (Bitumen content) | % | 52 | 62 |
| ASTM D2415 | Ash content | % | 33 | 38 |
| ASTM D70 | Density | g $cm^{-3}$ | 1.0 | 1.5 |
| ASTM D6 | Loss on heating, 50g, 5hrs at 163°C | wt% | - | 2 |
| ASTM D5 | Retained penetration after TFOT | °C | 50 | - |

Source: TTS 590 Refined Trinidad Lake Asphalt (TLA) – Specification

The bitumen component in TLA is 52–62% and has a higher maltene content than conventional bitumen. The mineral matter component is 33–38% and is mainly quartz and clay. The presence of mineral matter provides improved resistance to skid and stiffness to the binder.

TLA, as an asphalt modifier, must be added to base bitumen (proportions vary depending on the grade and specification required, but a typical percentage added is 25%) to achieve a paving grade modified asphalt cement, which is used in the production of the hot mix asphalt (HMA) in the asphalt plant. The main asphalt applications of TLA are in asphaltic, mastic asphalt, and stone mastic asphalt.

## 2.2 Blend preparation

Varying percentages of TLA (0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%) were blended into each base asphalt binder (PEN 60/70 and PEN 160/220) to examine the influence on rheological properties. All percentages were calculated on a weight percent (wt.%) basis to ensure accurate and repeatable blending, while considering the compositional and density differences between TLA and the base binders. The general blend preparation procedure was as follows:

(i) Preheating

Both the base asphalt binder and the TLA were preheated to approximately 160 to 170 °C in an oven for 1.5 to 2 hours until they were sufficiently fluid to pour and then stirred to homogenise the samples.

(ii) Mixing process

A laboratory mixer was used to incorporate the TLA into the base binder. Mixing was performed under controlled temperature (±5 °C of the set-point) for a minimum of 30 minutes at a rotational speed recommended by typical industry practice.

- Mixing Temperature: ~160 to 170 °C
- Mixing Duration: 30 to 60 minutes or until visually homogeneous

  Mixing Speed: ~300 to 500 rpm

(iii) Storage and sample conditioning

After blending, the modified asphalt was poured into airtight containers to minimize oxidation and left to cool at room temperature. Prior to testing, each sample was gently reheated to ensure fluidity without inducing further aging or degradation.

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## 2.3 Rheological testing

### *2.3.1. DSR setup*

The DSR test was used to characterise the viscoelastic behaviour of the TLA-modified binders under varying thermal and loading conditions. The test follows the guidelines of AASHTO T315 and ASTM D7175[18,19].

A parallel-plate geometry with a 25 mm diameter and 1 mm gap was used to test all samples. Measurements were performed under strain-controlled conditions, ensuring that all tests remained within the linear viscoelastic region (LVE), where the material response is independent of strain amplitude[8].

The temperature range was set from 40 °C to 90 °C in 5 °C increments, while frequencies varied primarily between 0.1 and 15.9 Hz to simulate a range of traffic speeds. The key rheological parameters measured were: G* indicating total binder stiffness, and δ (phase angle) reflecting the relative balance between elastic and viscous behaviour. Lower δ values suggest more elastic (recoverable) deformation, while higher values indicate more viscous (permanent) behaviour[7,11,20].

This setup allowed for a detailed characterisation of binder performance under conditions resembling those encountered in real-world pavement applications.

### *2.3.2 Viscosity measurements*

Parallel-plate geometry was also used for viscosity measurements under steady shear or oscillatory conditions, depending on the experimental design. The same temperature range (40 to 90 °C) was employed, with the DSR software controlling shear rates and frequencies:

(i) Viscosity Testing: Measurements were taken at discrete temperatures (40 to 90 °C) to examine how blend viscosity varied, which is directly related to workability during pavement construction.

(ii) Shear Rate/Loading Frequency: 1.59 Hz for a baseline test, with additional frequencies tested as needed to mimic different traffic speeds, was conducted.

### *2.3.3 Determination of the linear viscoelastic region*

Before each series of temperature sweeps, a strain sweep was performed to identify the linear viscoelastic (LVE) region. The selected strain amplitude was kept sufficiently low to ensure that measurements remained within the LVE range, where G* and δ remain independent of strain.

## 2.4 Data analysis

(i) Complex Modulus (G*) and Phase Angle (δ)

Rheological parameters were recorded and plotted against temperature and loading frequency. G* represents the overall stiffness of the material, while δ characterises the balance between elastic and viscous responses.

(ii) Viscosity Trends

Data from the viscosity tests were used to analyse the temperature sensitivity of each blend, vital for assessing workability and predicting high-temperature rutting performance.

# 3 RESULTS AND DISCUSSION

## 3.1 Effect of temperature on complex shear modulus (G*)

Fig. 2 shows the variation of G* with temperature (40–90 °C) at a loading frequency of 1.59 Hz for the PEN 60/70 blends. As the temperature increased, G* decreased in all blends, reflecting a reduction in

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stiffness and load-bearing capacity at higher temperatures. Among the blends, the one containing 30% TLA exhibited the highest stiffness (G* ≈ 2.29 × $10^2$ kPa at 90 °C), suggesting that increased TLA content bolsters high-temperature performance. The enhanced stiffness at higher temperatures can be attributed to the high asphaltene content and mineral content in TLA, which imparts greater elastic-like characteristics to the binder. These results align with prior findings, which suggested that TLA increases binder stiffness at higher temperatures due to its high asphaltene and mineral content[3,19].

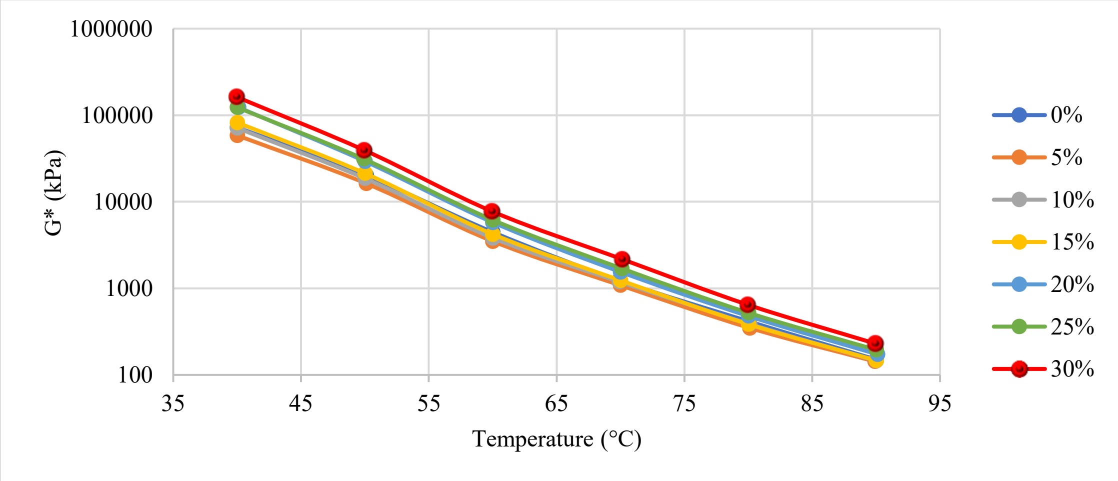


Fig. 2. Temperature-dependent change in the PEN 60/70 blend's G* rheological values at a 1.59 Hz loading frequency.

The PEN 160/220 blends exhibited a similar downward trend in G* with rising temperature, as revealed in Fig. 3. Notably, the blend containing 30% TLA showed a maximum G* of approximately 9.35 × $10^2$ kPa at 90 °C, surpassing the stiffness of lower TLA blends. Although PEN 160/220 binders typically exhibit lower initial stiffness compared to PEN 60/70 grades, the introduction of TLA narrows this gap at higher temperatures. This trend underscores TLA's capacity to improve the high-temperature resistance of softer base binders.

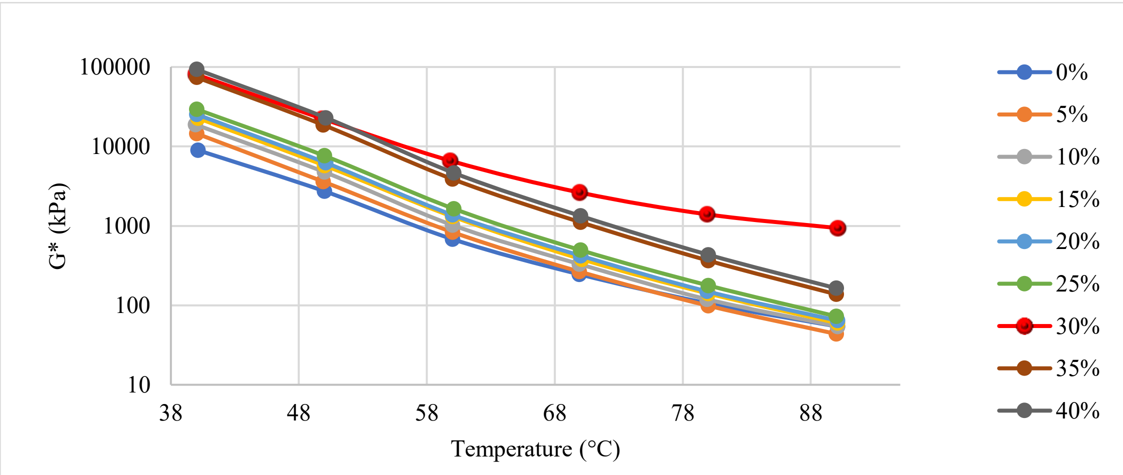


Fig. 3. The variation of the rheological values of G* for the PEN 160/220 blend with temperature at a loading frequency of 1.59Hz.

G* is a key rheological indicator of a binder's stiffness and its ability to resist deformation under cyclic loading. A higher G* value correlates with improved rutting resistance, which is critical for asphalt

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performance in high-temperature environments[4,5]. In this study, the consistent increase in G* with rising TLA content confirms the stiffening effect of TLA due to its rich asphaltene and mineral composition. This enhanced stiffness is beneficial for supporting heavy traffic loads and reducing permanent deformation, particularly in tropical climates[18].

### 3.2 Effect of temperature on phase angle (δ)

The phase angle (δ) provides insight into the relative elasticity (low δ) versus viscous flow (high δ) of the binder. As shown in Fig. 4, δ increased with temperature for the PEN 60/70 blends, indicating a progressive shift toward more viscous behaviour. The blend containing 30% TLA exhibited the lowest δ values at elevated temperatures, implying superior elastic performance and a higher resistance to permanent deformation under these conditions. This trend is consistent with the findings by Habbouche[3] and Hawesah[5], who also observed improved elasticity and rutting resistance in binders modified with natural or synthetic polymers.

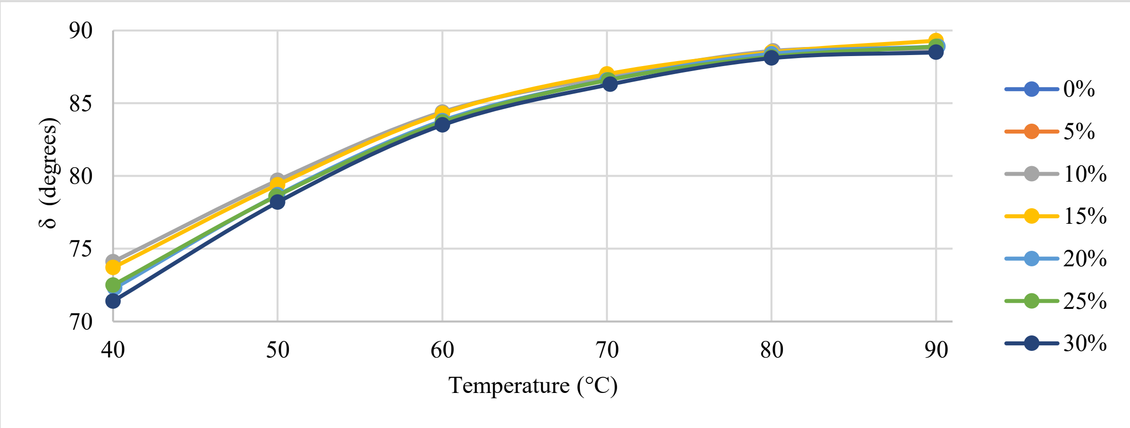


Fig. 4. The variation of δ rheological values for PEN 60/70 TLA blends with temperature at a loading frequency of 1.59Hz.

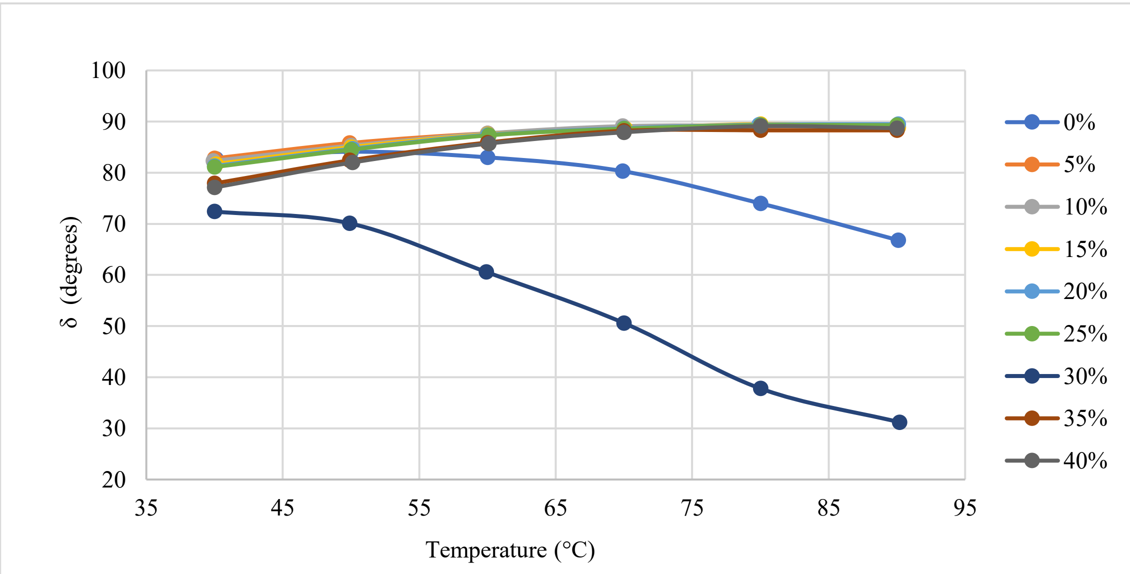


Fig. 5. The variation of δ rheological values for PEN 160/220 TLA blends with temperature at a loading frequency of 1.59Hz.

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In Fig. 5, the PEN 160/220 blends also showed an overall increase in δ with temperature. The most pronounced elastic response (lowest δ) appeared at a 25% TLA concentration, closely followed by 30% TLA at 90 °C. This slight variation suggested there may be an optimum TLA content around 25 to 30% for maximizing elasticity in the PEN 160/220 binder, thereby balancing stiffness and elasticity to mitigate rutting without overly sacrificing flexibility.

δ reflected the viscoelastic behaviour of the binder, where low δ values indicated elastic (recoverable) behaviour, while high values represented viscous (permanent) deformation[3,5]. The ability to maintain low δ values at elevated temperatures was especially important for minimizing rutting. The results of this study demonstrated that increasing TLA content lowered δ, confirming an increase in elastic response. This shift toward elasticity implied that TLA-modified binders were more capable of recovering their original shape under load, which can improve pavement longevity and reduce maintenance cycles[6].

### 3.3 Influence of TLA content on G* at different loading frequencies

Fig. 6 demonstrates how G* for the PEN 60/70 blends evolved with both TLA content and loading frequency (0.1 to 15.9 Hz) at a constant temperature of 60 °C. Higher frequencies, representing faster traffic speeds, typically yielded higher G* values because the binder had less time to relax. At each frequency, incremental additions of TLA consistently raised G*, with 25 to 30% TLA showing the largest gains. These findings validated the role of TLA in reinforcing the binder's resistance to deformation, particularly under rapid loading.

Higher TLA content caused G* to rise at all frequencies, with the steepest increase seen at 15.9 Hz, indicating improved stiffness under conditions of rapid loading. With an $R^2$ value of 0.7531 and an Equation 1, a linear trendline fitted to the 1.59 Hz data showed a moderate positive correlation. This supported the finding that TLA considerably increased the binder's resistance to deformation under typical traffic loading circumstances.

$$y = 12142x + 3273 \tag{1}$$

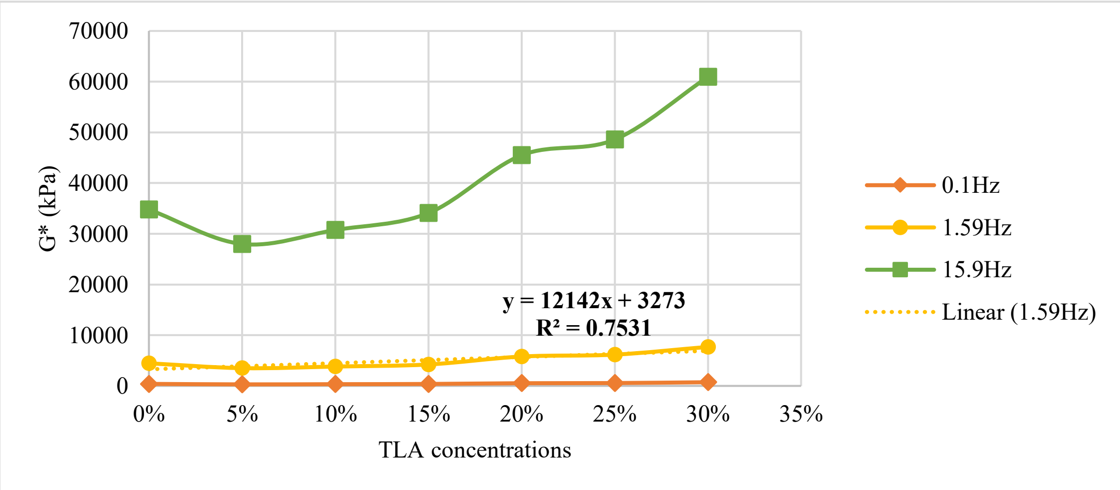


Fig. 6. The effect of increasing TLA concentrations on complex shear modulus (G*) of the PEN 60/70 blend at different frequencies at 60 ˚C.

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TLA functioned as a high-temperature performance enhancer. In hybrid systems, the adding of SBS to TLA-modified binders further elevated stiffness and rutting resistance while moderating excessive rigidity at lower temperatures, indicating complementary mechanisms between TLA's asphaltene-rich fraction and elastomer networks[14]. Similar gains in stiffness and deformation resistance have been reported for TLA+SIS systems under Superpave protocols, supporting the trend we see here for base-binder + TLA blends[13]. Overall, the G*–frequency response in this study was consistent with the emerging view that TLA shifts binder behaviour toward improved high-temperature performance, with polymer additions offering additional balance when desired[13,14,16].

A parallel trend was evident in Fig. 7 for the PEN 160/220 blends at 60 °C. G* rose with both frequency and TLA content, underscoring TLA's stiffening effect. Although the baseline (unmodified) PEN 160/220 was less stiff than PEN 60/70, TLA-modified PEN 160/220 at higher contents showed G* values approaching or surpassing those of neat 60/70 binders. This result was particularly relevant for paving applications where a softer base binder may be preferred for workability, yet high-temperature rutting resistance is also critical.

Equation 2, with an $R^2$ value of 0.6374, indicated a moderate correlation, was obtained by fitting a linear trendline to the 1.59 Hz data. G* readings gradually rose as TLA concentration increased, with larger increases of over 25%, indicating a stiffening effect brought on by TLA's high asphaltene and mineral content. According to the trend, TLA improved rutting resistance in softer base binders, even though more scatter was seen for PEN 160/220 than for the PEN 60/70 blends.

$$y = 12145x + 12.727 \tag{2}$$

### 3.4 Influence of TLA content on phase angle (δ) at different loading frequencies

Fig. 7 illustrates how δ varies with frequency for the TLA-modified PEN 60/70 blends at 60 °C. Generally, δ decreased at higher frequencies, indicating a more elastic response when loading times were short. Elevated TLA levels further reduced δ, suggesting that TLA addition augments the elastic component of the binder. Such elasticity can be beneficial in delaying fatigue cracking, as the binder can better recover deformations between load cycles.

δ for TLA-modified binders is comparatively constant as TLA concentration increases, especially at lower loading frequencies (0.1 Hz and 1.59 Hz), as portrayed in Fig. 7. A very weak linear link is indicated by a linear regression fitted to the 1.59 Hz data, which has a slope of -1 and an $R^2$ value of 0.0854. On the other hand, δ shows a modest negative trend at higher frequencies (15.9 Hz), indicating more elasticity under quicker loading conditions. Even though the overall decrease in δ is slight, it supports the idea that adding TLA improves elastic responsiveness, especially at higher stress frequencies.

The reduction (or slower increase) in phase angle δ with added TLA at higher frequencies indicates a modest shift toward a more elastic response, which aligns with reports of improved strain recovery in TLA-containing systems. Studies on TLA+SBS hybrids have shown lower δ values and higher MSCR recovery than the base binder, demonstrating enhanced elastic contributions at traffic-relevant loading rates[13,16]. Likewise, TLA+SIS systems show the same directional effect under Superpave testing, reinforcing the link between TLA-driven structure and reduced phase lag[14]. The δ trends observed in this study, therefore, matches previously reported improvements in recoverable deformation for TLA-based high-performance binders.

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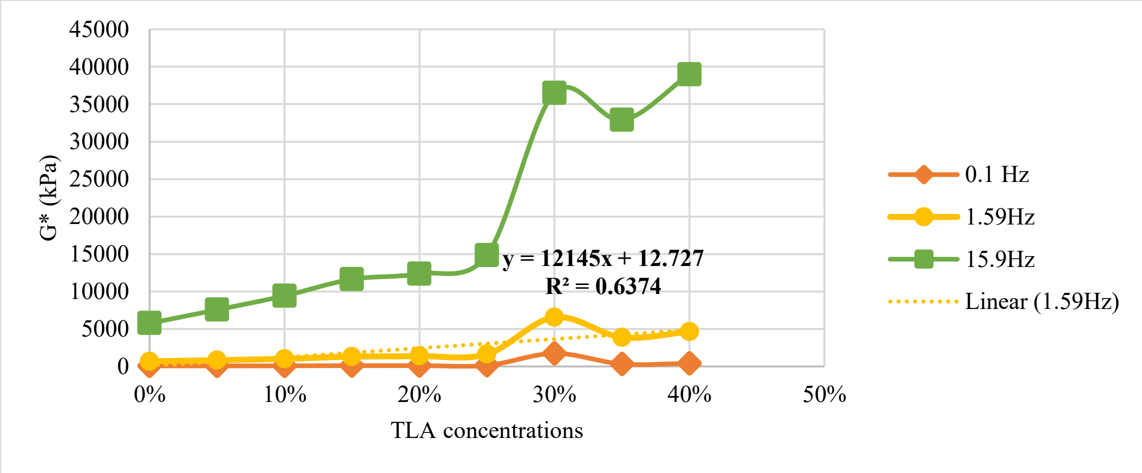


Fig. 7. The effect of increasing TLA concentrations on complex shear modulus (G*) of the PEN 160/220 blend at different frequencies at 60 ˚C.

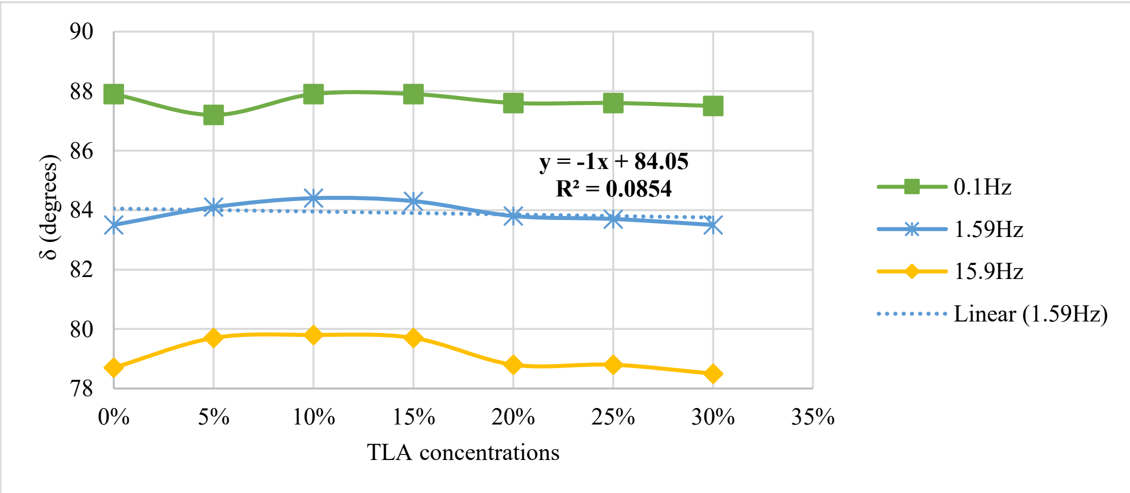


Fig. 8. The influence of increasing amounts of TLA concentration on phase angle of PEN 60/70 TLA at 60˚C for varying load frequencies.

In Fig. 9, the PEN 160/220 blends demonstrate a similar frequency-dependent decline in δ. Notably, blends containing 25% or 30% TLA display phase angles comparable to, or even lower than, neat PEN 60/70 at high frequencies. This finding confirms that with adequate TLA modification, a softer base binder like PEN 160/220 can achieve elasticity levels that rival stiffer base binders, enhancing the blend's overall resistance to permanent deformation.

Although δ generally decreases as TLA increases, there was a noticeable dip at 30% TLA, which was followed by a recovery. Equation 3, with an $R^2$ value of 0.065 was obtained by fitting a linear trendline to the 1.59 Hz data, suggesting a weak and statistically insignificant linear relationship. In spite of this, the general pattern of δ dropping as TLA levels rise is consistent with the anticipated increase in binder elasticity. More research is necessary because the 30% anomaly might be the result of material heterogeneity or thermal interaction effects.

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$$y = -16.333x + 86.911 \quad (3)$$

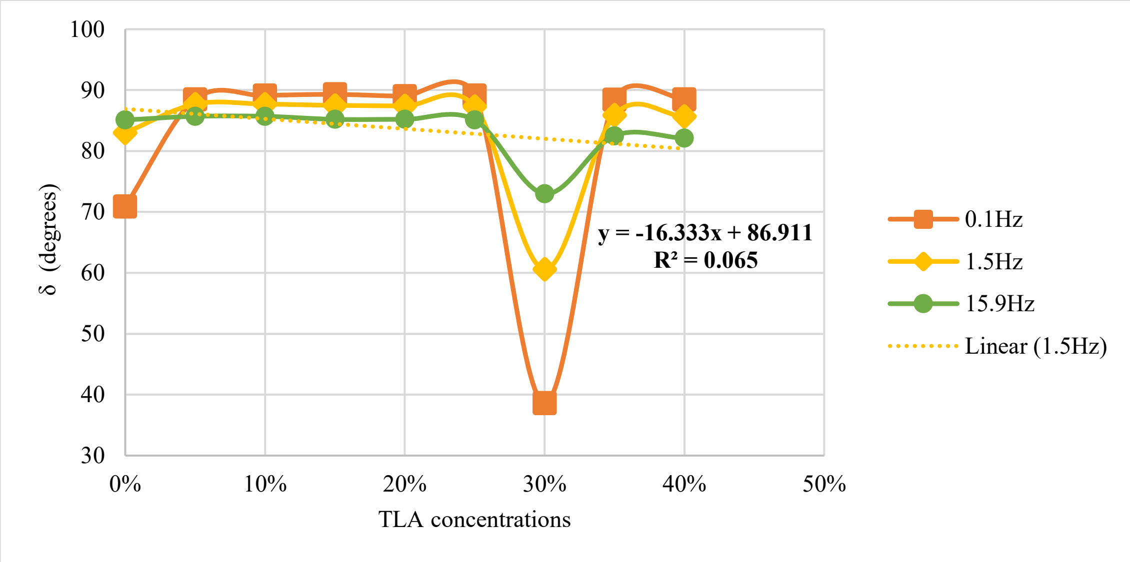


Fig. 9. The influence of increasing amounts of TLA concentration on phase angle (δ) of PEN 160/220 TLA at 60 ˚C for varying load frequencies.

### 3.5 Effect of loading frequency on viscosity

Fig. 10 shows how viscosity changes with loading frequency for PEN 60/70 blends at 60 °C. At all levels of TLA concentrations, viscosity increases with frequency, aligning with the elastic nature observed in the G* and δ results. Higher TLA contents result in notably higher viscosities, reflecting the increased internal friction and reduced chain mobility related to the high asphaltene content. This observation is in line with Maharaj[6], who noted that TLA modification increases binder viscosity, which may require higher mixing and compaction temperatures during field application. From a practical standpoint, this implies that TLA-modified binders may require slightly higher compaction temperatures or specialised handling during pavement construction.

The effect of frequency on viscosity for PEN 160/220 blends at 60 °C is revealed in Fig. 11. Although the baseline viscosity is lower than that of the PEN 60/70 binder, the adding of TLA substantially raises the viscosity, thereby narrowing the gap. This reinforces the possibility of tailoring the base binder grade with strategic amounts of TLA to match specific traffic and climate requirements.

The shear-thinning behaviour observed in this study (viscosity decreasing as loading frequency increases) is typical of structured, modifier-rich binders and has been reported for TLA-containing systems. Recent works show that while TLA raises viscosity relative to the neat binder, hybrids incorporating warm-mix and crumb-rubber technologies can offset workability challenges while retaining high-temperature benefits[14]. These findings are consistent with our frequency-dependent viscosity curves: TLA increases resistance to flow at lower frequencies (heavier loading), yet the system remains amenable to mix and compaction management using WMA-type strategies reported in the literature[14].

### 3.6 Effect of temperature on viscosity

Fig. 12 illustrates the sensitivity of PEN 60/70 TLA blends to temperature (40 to 90 °C) at a loading frequency of 1.59 Hz. As the temperature rises, the viscosity decreases sharply, reflecting the reduced resistance to flow at higher temperatures. Nonetheless, the viscosity of blends with higher TLA content

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remains comparatively elevated at each temperature point, indicating that TLA extends the usable high-temperature range of the binder.

The strong temperature sensitivity (viscosity decreasing with temperature) observed across our TLA blends mirrors prior reports on TLA-modified and TLA-polymer hybrid binders. In the literature, TLA raises the viscosity baseline and improves high-temperature stability, while WMA or polymer additives are incorporated to moderate mixing and compaction temperatures without sacrificing rutting performance[13,15]. Our temperature-viscosity responses therefore fit within the reported processing envelope for TLA-based systems: higher viscosity at service temperatures that supports rut resistance, coupled with established approaches to control plant-level workability[13,15,16].

Similarly, Fig. 13 shows a notable reduction in viscosity as temperature increases for PEN 160/220 blends. At 90 °C, higher TLA concentrations still retain sufficient viscosity to resist permanent deformation, an essential property in hot climates where pavement surfaces can easily reach these elevated temperatures. These observations further corroborate TLA's capability to increase the high-temperature performance of relatively softer base binders.

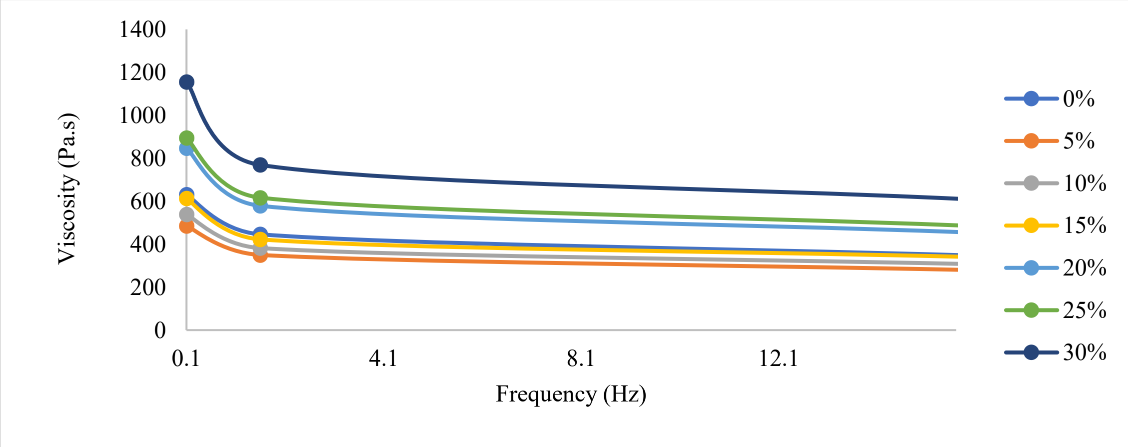


Fig. 10. The effect of increasing frequency on the viscosity of PEN 60/70 TLA blend at 60˚C.

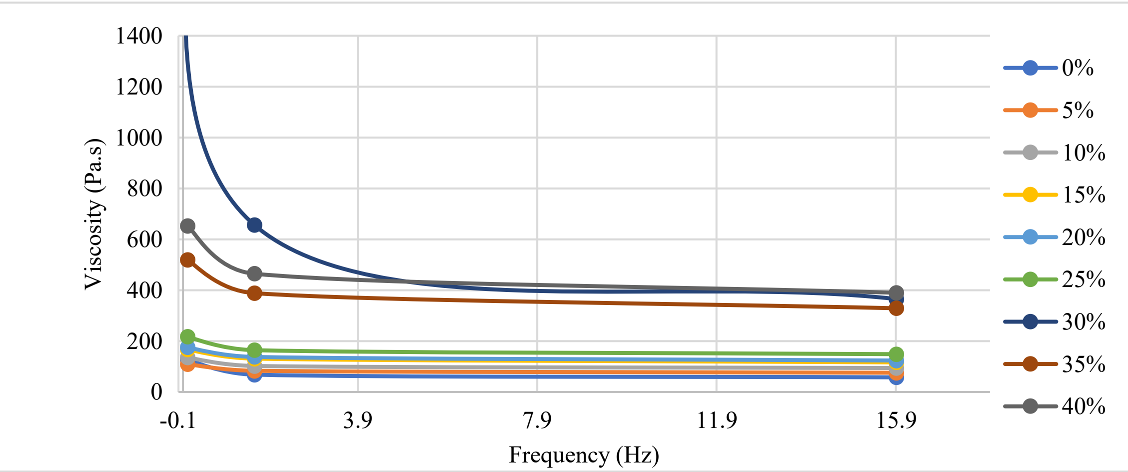


Fig. 11. The effect of increasing frequency on the viscosity of PEN 160/220 TLA blend at 60˚C.

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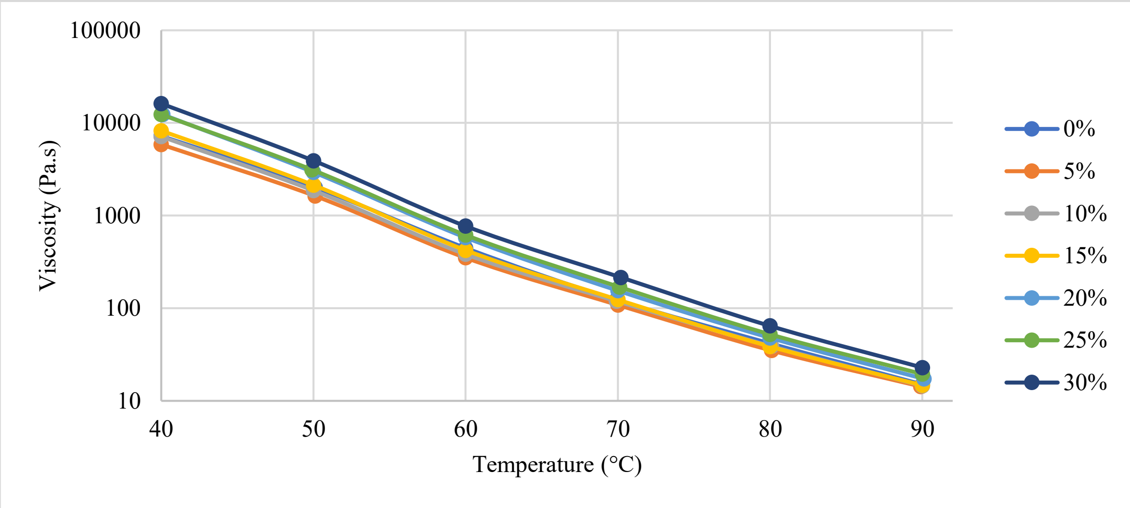


Fig. 12. The effect of increasing temperature on the viscosity of PEN 60/70 TLA blend at 1.59Hz.

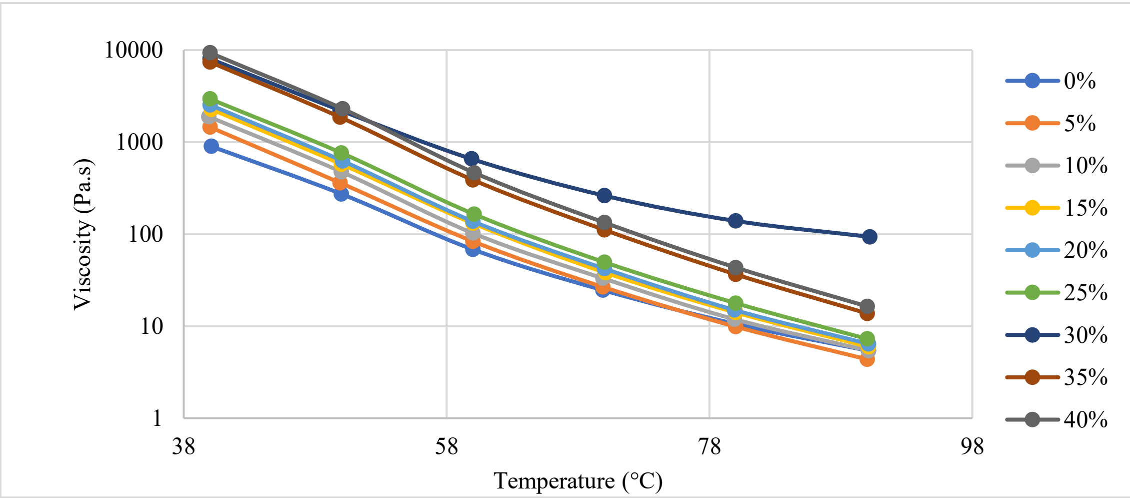


Fig. 13. The effect of increasing temperature on the viscosity of PEN 160/220 TLA blend at 1.59Hz.

The findings confirm that incorporating TLA into both PEN 60/70 and PEN 160/220 penetration-grade binders enhances high-temperature stability and elastic response. As the TLA concentration increases, G* rises and the δ decreases, indicating a more elastic and stiff material capable of resisting permanent deformation (rutting). These rheological improvements, however, must be balanced against potential constructability issues, as higher stiffness can complicate mixing and compaction processes.

From an overarching perspective, these results address the initial objectives by demonstrating that TLA modifications can be systematically tuned, typically within the 25 to 40% range, to achieve improved pavement performance. Temperature and frequency sweeps further highlight that TLA extends the useful temperature range for each binder, offering significant benefits in climates with elevated pavement temperatures and under heavy or fast-moving traffic. In practical terms, using TLA-modified binders supports the development of longer-lasting roads and reduces maintenance needs, aligning well with the

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objective of this study, that is, evaluating sustainable and effective asphalt modification strategies for modern pavement demands.

### 3.7 Effect of TLA concentration on viscosity

Fig. 14 illustrates the variation of viscosity with TLA concentration across different loading frequencies at 60 °C. At all frequencies, viscosity increases with higher TLA content, reflecting reduced binder workability due to higher asphaltene and mineral combinations. The most notable increases occur beyond 20% TLA. A linear regression applied to the 1.59 Hz data yielded a trendline of Equation 4 with an $R^2$ value of 0.7531, indicating a strong positive relationship. This confirms that TLA significantly affects binder viscosity, particularly at standard traffic loading frequencies, and highlights the need for careful dosage selection to balance performance with constructability.

The monotonic increase in viscosity with TLA concentration in both base binders aligns with reports that TLA's asphaltene and mineral fraction increases binder body and internal friction. Prior studies suggest two practical pathways when higher TLA levels raise processability concerns: (i) pairing TLA with elastomers (e.g., SBS) to improve high-temperature grade and storage stability while balancing intermediate-temperature response[13,16]; and (ii) using CRM and WMA additives to reduce viscosity at production temperatures while maintaining improved deformation resistance[15]. Our concentration-viscosity trends are therefore in line with these recommended strategies for high-T performance and constructability.

$$y = 1213.8x + 327.22 \quad (4)$$

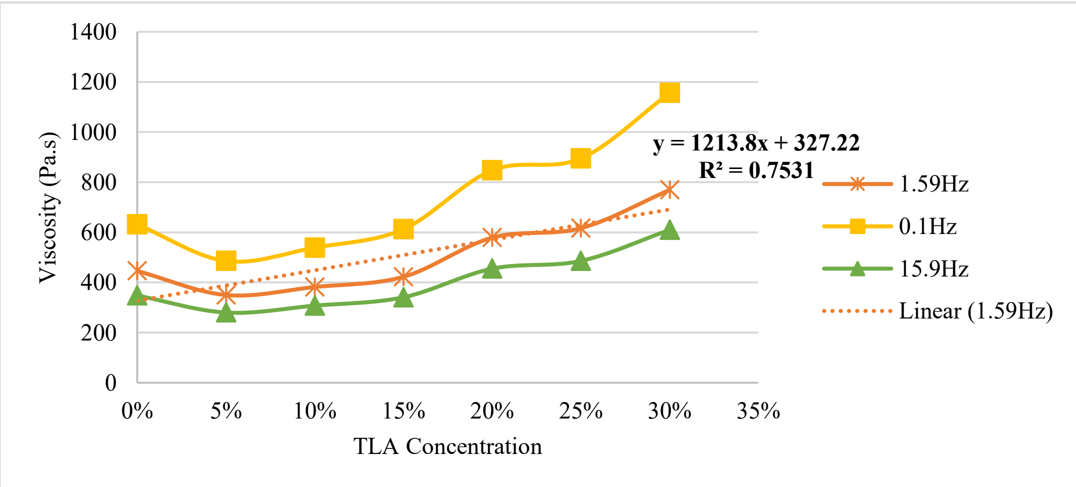


Fig. 14. Viscosity vs TLA Concentration at 60ºC and 1.59Hz for PEN 60/70 binder.

For PEN 160/220 mixes, viscosity increases gradually with TLA content at 60 °C, as seen in Fig. 15, with a noticeable increase of around 30%. The 1.59 Hz data was subjected to linear regression, which produced Equation 5 with an $R^2$ value of 0.5323, suggesting a moderately positive connection. This demonstrates that TLA has a substantial impact on binder viscosity, particularly when it exceeds 25%. To maintain field workability, higher compaction temperatures and better mixing techniques may be necessary.

$$y = 1401.8x - 18.313 \quad (5)$$

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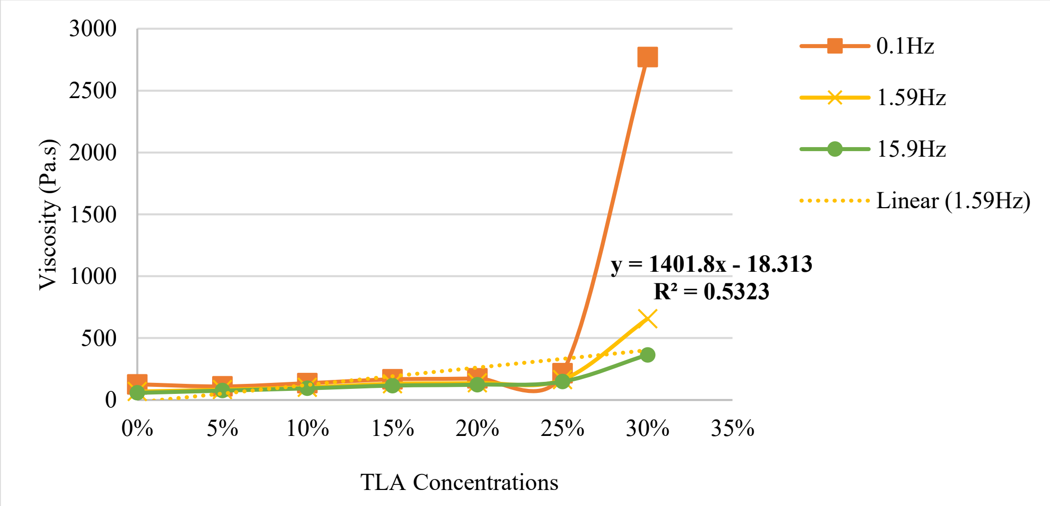


Fig. 15. Viscosity vs TLA Concentration at 60 ºC and 1.59Hz for PEN 160/220 binder.

### 3.8 Comparative summary of rheological trends

To summarise the impact of TLA concentration on important rheological parameters, Table 2 presents trendline analyses for both PEN 60/70 and PEN 160/220 binders at 60 °C and 1.59 Hz. The findings support a dose-dependent response by showing significant trends to moderate correlations between viscosity and G*. Phase angle (δ) displayed less statistically significant trends, with slight declines. The use-of TLA as a rheological modifier is validated by the equations and associated $R^2$ values, which also support the observed performance increases.

**Table 2.** Trendline equations and $R^2$ values for G*, δ and viscosity as a function of TLA concentration for PEN 60/70 and PEN 160/220 binders (evaluated at 60 °C, 1.59 Hz)

| Property | Binder | Trendline (1.59 Hz) | $R^2$ Value | Interpretation |
|---|---|---|---|---|
| G* | PEN 60/70 | y = 12142x + 3273 | 0.7531 | Strong positive correlation |
| G* | PEN 160/220 | y = 12145x + 12.727 | 0.6374 | Moderate-strong correlation |
| δ | PEN 60/70 | y = -1x + 84.05 | 0.0854 | Weak trend; minor δ reduction |
| δ | PEN 160/220 | y = -16.333x + 86.911 | 0.065 | Very weak trend; non-linear dip at 30% |
| Viscosity | PEN 60/70 | y = 1213.8x + 327.22 | 0.7531 | Strong positive correlation |
| Viscosity | PEN 160/220 | y = 1401.8x – 18.313 | 0.5323 | Moderate correlation; steeper post-25% |

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The rheological behaviour of TLA-modified asphalt binders (PEN 60/70 and PEN 160/220) at 60 °C and 1.59 Hz for a range of TLA concentrations (0 to 30%) is summarised in the graphical abstract (Fig. 16). Higher TLA content results in an increase in the complex shear modulus (G*), which indicates improved binder stiffness and rutting resistance. PEN 60/70 continuously shows higher G* values than PEN 160/220. Additionally, viscosity rises, especially around 20% TLA, indicating decreased workability at higher dosages. In contrast, a shift toward more elastic behaviour is indicated by a decrease in the phase angle (δ), which is most noticeable in the PEN 160/220 blends. TLA's function in enhancing high-temperature performance and elastic recovery is highlighted by the logarithmic scale on the y-axis, which also shows the magnitude variations across rheological parameters.

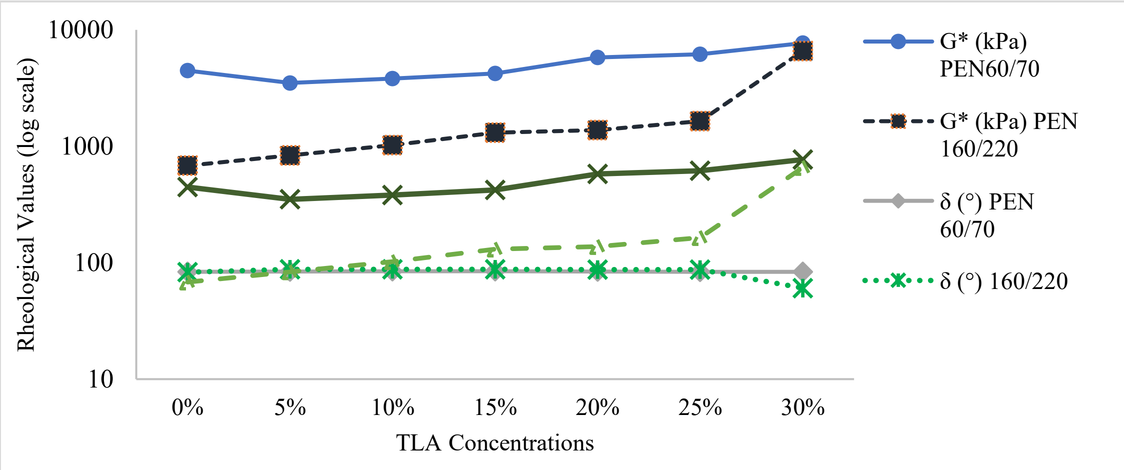


Fig. 16. Graphical abstract showing the effect of TLA concentration on complex shear modulus (G*), phase angle (δ), and viscosity for PEN 60/70 and PEN 160/220 binders at 60 °C and 1.59 Hz.

Taken together, higher G* and modestly lower δ with increasing TLA corroborate recent reports that TLA raises high-temperature performance and permanent-deformation resistance. Studies on SBS/TLA composites showed improved rheology and aging behaviour compared with SBS alone, reinforcing TLA's value in long-term performance contexts[16]. Zero-shear-viscosity (ZSV) analyses of TLA-modified binders further link elevated ZSV to lower permanent deformation in mastic asphalt, consistent with our overall trend envelope[17]. Where viscosity increases become a constraint, the literature demonstrates that WMA and CRM can recover workability while preserving the TLA-driven gains in rutting resistance[15]. These converging lines of evidence support the robustness and practical relevance of our results.

### 3.9 Comparative insight

Synthetic modifiers such as Styrene-Butadiene-Styrene (SBS) and Gilsonite are widely employed to improve asphalt performance by enhancing elasticity, thermal susceptibility, and fatigue resistance. However, these synthetic alternatives may involve higher costs, supply chain risks, or environmental concerns[3]. In contrast, TLA, being a naturally occurring modifier, offers consistent rheological enhancements, as demonstrated in this study, particularly in high-temperature stiffness (G*) and elastic recovery (low δ). Prior research has shown that TLA-modified binders can perform comparably to SBS-modified asphalt under rutting and fatigue conditions[15], making it a valuable and sustainable substitute in pavement applications.

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### 3.10 Broader implications and limitations

The findings of this study have meaningful implications for sustainable pavement design, especially in hot and tropical regions. TLA, as a naturally occurring asphalt modifier, offers an environmentally favourable and locally available alternative to synthetic polymers such as SBS and EVA[3,20]. The performance gains observed, especially improvements in rutting resistance and elastic recovery, highlight TLA's suitability for pavements subjected to high-temperature stress and heavy traffic loads, where binder durability is paramount[4-6]. Additionally, TLA usage can support circular economy goals by minimizing reliance on imported, petroleum-based modifiers.

Despite its benefits, some limitations exist. TLA increases binder stiffness, which may require elevated mixing and compaction temperatures during construction, potentially affecting energy use and workability[6]. The current study was limited to laboratory-scale rheological testing; further validation through long-term field trials are necessary to confirm durability under environmental aging and actual traffic loading. Moreover, this study does not explore the interaction of TLA-modified binders with different aggregate types or moisture sensitivity, which are critical factors in field performance. These aspects represent key areas for future research.

## 4 CONCLUSION

The incorporation of TLA into both PEN 60/70 and PEN 160/220 binders enhances binder stability and elasticity at high pavement service temperatures, typically ranging from 60 °C to 90 °C, where rutting and deformation risks are most critical. The study demonstrates that TLA concentrations in the range of 25 to 30% provide optimal improvements in rutting resistance while maintaining acceptable workability and fatigue performance. These rheological insights offer valuable guidance for selecting binder types and dosages in regions with high pavement temperatures or heavy traffic loads. Moreover, they support strategic formulation decisions aimed at extending pavement service life and reducing maintenance frequency.

In a broader context, the use of TLA as a natural modifier contributes to sustainable infrastructure development, particularly in countries with access to natural asphalt resources. It presents a viable, cost-effective alternative to synthetic polymer modifiers such as SBS, EVA, and crumb rubber. Nevertheless, practical implementation must consider potential constructability challenges associated with increased binder stiffness.

Future research should include long-term field performance evaluations, compatibility studies with various aggregates, and comparative assessments against synthetic modifiers using life-cycle cost analysis and performance modelling frameworks.

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## CONFLICT OF INTEREST

There was no conflict of interest.

## AUTHORS' CONTRIBUTIONS

Conceptualization: S. Ramlal & R. Maharaj
Data curation: N/A
Methodology: S. Ramlal, & V. Harry
Formal analysis: S. Ramlal, A. Clark, V. Harry, R. Maharaj
Visualisation: N/A

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Software: N/A
Writing (original draft): S. Ramlal, A. Clark, R. Maharaj
Writing (review and editing): S. Ramlal, A. Clark, R. Maharaj
Validation: N/A
Supervision: S. Ramlal & R. Maharaj
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Project administration: N/A

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