Temperature Susceptibility of Asphalt Binders for Climate Change

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INTRODUCTION

Paved roads will need to increase by 25 million road lane-kilometres by 2050, under the Energy Technology Perspectives 2012 (Dulac 2013). This has led to an increased demand in stability and durability of binder products. Flexible pavement has been incorporated into the transportation system of Trinidad and Tobago. This type of pavement structure is most common because of how fast local commuters can access the roadways.

The duty of asphalt binder is to bind the fine and coarse aggregates of the surface layer. Asphalt is defined as a dark brown to black cementitious material in which the predominating constituents are bitumen which occur in nature or are obtained in petroleum processing (ASTM 2016). TLA is a naturally occurring asphalt deposit found in the Pitch Lake of south-west Trinidad. Its consistency is attributed to its constant soluble bitumen content when refined. Individual components of TLA work in combination to produce improved stability and durability of pavements (Widyatmoko et al. 2005). In 1870, Trinidad Lake Asphalt (TLA) recorded its first use as an asphalt binder. Despite the benefits offered by TLA, the demand for paved roads exceeded the supply of lake asphalts in the late 1800s (Horan 2003). This shortfall led to the use of petroleum asphalts as the substitute for TLA in the pavement wearing course in the early 1900s.

Petroleum asphalts are commonly regarded as a waste product from the refinery process of crude oil. The properties of refined bitumen are dependent on the refinery operations and the composition of the crude oil at the source. Refined bitumen is characterised by its visco-elastic behaviour which dominates many facets of road performance. The rheological behaviour of refined bitumen is predominantly influenced by temperature and applied loads, which is evidenced between two extremes: purely viscous and purely elastic (Horan 2003). An asphalt binder should be elastic for dissipation of energy at low temperatures without fatigue cracking and viscous at high temperatures to prevent rutting. At ambient temperatures, bitumen is a stable semi-solid. However, exponential increase in traffic and significant variations in daily and seasonal temperatures have shown some limitations in asphalt binder performance (Pareek et al. 2012).

The Trinidad and Tobago Meteorological Office has recorded significant increases in the mean annual temperature, with an increase around 0.6 °C since 1960; an average of 0.13 °C per decade (Mc Sweeney et al. 2010). Climate change causes deterioration of the hydrological cycle, economy and of pavement structures (Viola and Celauro 2015). Within this study, under the broad topic of climate change, its temperature impact is the main focus. NCHRP Report 750 (Meyer et al. 2014) draws upon several climate models and future emissions scenarios and identifies that as average temperatures increase, an increase in the frequency and duration of extreme temperatures is also projected.

Accurate prediction of the temperature profile in pavements greatly aids pavement engineers in the design process (Yavuzturk et al. 2005). Thermal environmental conditions, to which pavements are exposed, significantly impact pavement stability and long-term performance. Cracking, rutting, and potholes are common distresses associated with flexible pavements. In general, climate change will not introduce new consequences for the pavement, but increases the likelihood and scale of deterioration of catastrophic failure (Willway 2008). The vulnerability of a pavement to temperature impacts of climate change is determined by pavement materials and pavement design. Susceptibility of binders to high temperatures are seen in hot months (summer) where air temperatures exceed 30 °C. The surface temperature of asphalt pavements may increase by 50 °C or more, which may reach or exceed the softening point of asphalt (Shen 1999).

The purpose of this study is to analyse and compare TLA modified bitumen and RLP modified bitumen blends to determine their temperature susceptibility to regional high temperature increases. This investigation was carried out on TLA 60-70 penetration bitumen and polymer modified bitumen. This study is limited to short term ageing which is representative of production, transport and compaction of the bituminous pavement layer. Short-term ageing is identified by high temperatures which indicate high oxidation rates (Hofko et al. 2017). The Thin Film Oven Test (TFOT) simulates short term ageing for the intent of this report. Short term ageing of bitumen significantly affects the durability of asphalt mixtures. The objectives of this research paper are to examine and analyse traditional and fundamental properties of TLA modified bitumen and polymer modified bitumen blends. Long term ageing is not investigated by this paper.

TEST PROGRAM

Materials and preparation. The base asphalt binder; refinery bitumen of 60-70 penetration grade was obtained from Trinidad Lake Asphalt by the evaporation of lighter hydrocarbons. The base asphalt was mixed with varying percentages of modifiers to evaluate the traditional and fundamental properties. The ratio of raw TLA and Rubber Latex Polymer to the based 60-70 asphalt is shown in Table 1. The percentages represent the TLA or polymer by weight of bitumen. All blends were prepared at a temperature of 150 °C. It was ensured that all modifiers were thoroughly mixed with the 60-70 bitumen to achieve homogenous blends.

Table 1. Blending of TLA and Rubber Latex Polymer to 60/70 bitumen.

% TLA Blending								
Sample ID	TLA20	TLA25	TLA30	TLA35	TLA40			
Blend %	20%	25%	30%	35%	40%			
% Rubber Latex Polymer Blending								
Sample ID	RLP2	RLP2.5	RLP3	RLP4	RLP5	RLP6	RLP7	RLP10
Blend %	2%	2.5%	3%	4%	5%	6%	7%	10%

Traditional Testing. Penetration and Specific Gravity tests were performed to investigate the experimental properties of the blends. The penetration test was performed in accordance with ASTM D5-06: Penetration of Bituminous Materials. The Specific Gravity of each asphalt binder sample was performed according to ASTM D 70-03: Specific Gravity of Semi-Solid Bituminous Materials. Linear regression analysis was performed to measure the strength between the dependent variable Y (Specific Gravity) and the independent variable X (percent Modifier). The test for significance of regression is done to determine whether a trend is present between the dependent variable and a subset of independent variables. The test significance was $P \leq 0.05$.

Short-term Ageing. Short term ageing was done on 50% of the asphalt binder samples. It was aged in compliance to ASTM D1754 – 09: Standard Test Method for Effects of Heat and Air on Asphaltic Materials using Thin Film Oven Test (TFOT). Binder samples were placed in the oven at 163^{0}C for five hours to simulate short term ageing of asphalt pavements during production and compaction.

Dynamic Shear Rheometer (DSR) Frequency Testing. The determination of the Complex Modulus (G*), the phase angle, torque and applied frequency was acquired by implementation of ASTM D7175 – 15: Standard Test Method for determining the rheological properties of Asphalt Binder Using a Dynamic Shear Rheometer. Dynamic oscillatory testing was strain-controlled with a gap of 1.00mm. The test temperatures of each sample were 40 °C, 45 °C and 50 °C which are representative of peak pavement temperature for temperature increase in Trinidad; where rutting is predominant. This temperature range was adopted from the Long-Term Pavement Performance (LTPP) Model (Sun 2016) which were defined as follows:

$$T_{d(min)} = -1.56 + 0.72T_{a(min)} - 0.0041Lat + 6.26 \log (d+25)$$

$$T_{d(max)} = 54.32 + 0.78T_{a(max)} - 0.0025Lat + 15.14 \log (d+25)$$

The total depth of the asphalt surface layer was assumed to be 40mm (4.0cm) with the highest pavement temperature at the centre of the layer (20mm). It is at this location where the pavement temperature was computed for a worst-case scenario of an increase of 10 °C due to increases in atmospheric temperature.

RESULTS AND DISCUSSION

Traditional properties. Penetration Testing was conducted on all asphalt binder blends to investigate the response of the base asphalt to varying percentages of modifier content. As shown in Figure 1, the measured penetration value decreased with an increase in modifier content resulting in logarithmic decay. The based bitumen modified with maximum 40% raw TLA, experienced a 56% decrease in penetration. While bitumen modified with 10% polymer (the maximum percentage studied) experienced a 27% decrease in penetration. There is a greater increase in stiffness of the base asphalt with the addition of TLA. Adequately, stiff binders allow for minimal deformation under applied loads whereas excessively stiff binders experience cracking. The determination of the modifier content which produces the required stiffness is critical to the durability and adapted pavement management system.

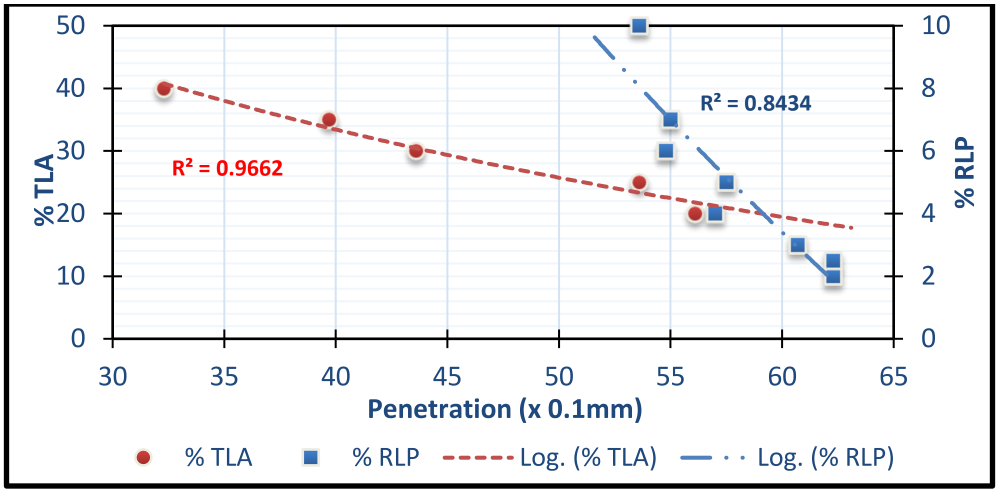
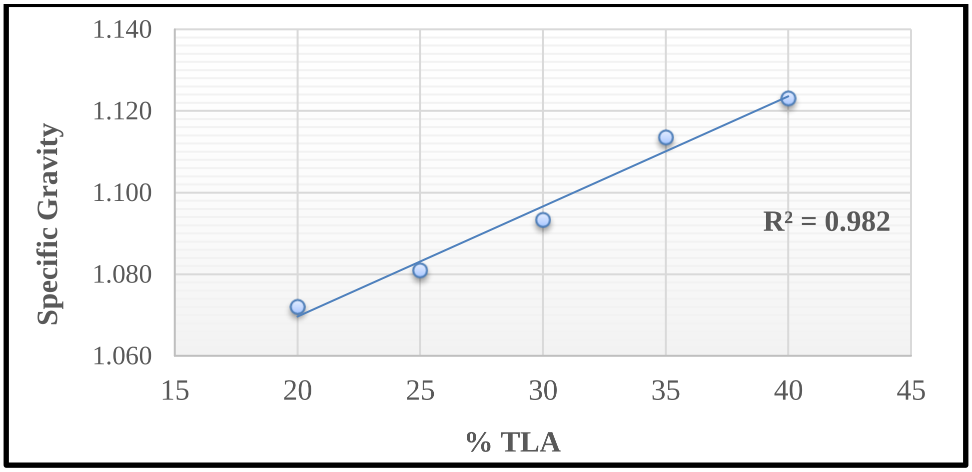
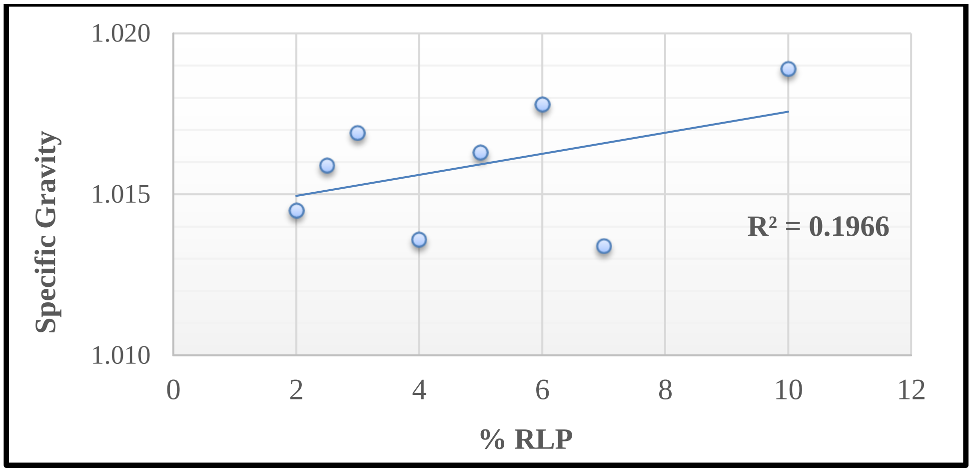


Figure 1. **Penetration of unaged TLA and RLP.**

Figure 2 shows the specific gravity of the unaged TLA and RLP blends. Although, the reported best fit line shows a linear relationship for both sets of modified samples, the general trend of the data points was noted. TLA modified blends showed an increase in Specific Gravity with increasing percentages of TLA, showing an increase in the density of the modified samples with increasing modifier content. Data points were evenly and closely distributed around the regression. This distribution suggests a homogenous and general compatibility mixing between the 60-70 bitumen and TLA.



(a)



(b)

Figure 2. Average specific gravity of (a) unaged TLA and (b) RLP blends.

Alternatively, polymer modified blends generated a regression line with a gentler slope when compared to TLA modified blends. This shows that the increase in density of the polymer blends occurred at a slower rate than TLA blends. However, data points were unevenly distributed about the regression line, with a noticed decrease in density with an increase in polymer percentage for some samples (e.g. 4% and 6% blends). This may be attributed to some extent of incompatibility between 60-70 bitumen and polymer. Air bubbles within the mix and an incomplete burning of the rubber fines could have influenced the sporadic distribution of data points and noticed decrease in density with increase in polymer. If the density of a pavement is too low, air voids are interconnected and premature distresses may occur (Blankesnship 2009). Implementing required compaction during mixing and pavement construction inhibits the likelihood of reduced density.

As shown in Table 2, TLA modified blends p-value was recorded as 0.00001. It can be suggested that the increase in TLA significantly changes the specific gravity properties of the blend. For polymer modified blends, the p-value was recorded as 0.88554. Unlike TLA blending, RLP did not significantly change the specific gravity properties of the blend when the percentages were increased.

Table *2.* Specific Gravity Model Summary.

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate	P-value
Percentage of TLA added	0.99740	0.99481	0.99351	0.00299	0.00001
Percentage of polymer added	0.05633	0.00317	-0.13923	0.00226	0.88554

Complex Modulus (G^*) and Phase angle (δ). Essential properties of the base asphalt, specifically the complex modulus (G*) and the phase angle (δ) were determined by rheological tests with frequency sweeps over a range of frequencies between 0.1 to 15.91 Hz. Plots of G* and δ versus frequency at 50^0C for the base asphalt at blends of 40% TLA and 10% RLP are shown in Figures 3 and 4.

TLA shows a noticeable increase in the stiffness (G*) and a decrease in viscoelastic response (δ) of the 60/70 pen bitumen for both TFOT aged and unaged blends. Figure 3 shows that G* increases with increasing frequency while Figure 4 shows that δ values decrease with increasing frequency for increasing concentration of TLA. This implies that stiffness is increased but the response becomes more elastic (δ values tends to 0^0) as the frequency increases. In addition, RLP shows relative increase in both G* and viscoelastic response, δ for both TFOT aged and unaged blends. This result demonstrates an increase in stiffness and viscosity with increasing frequency and concentration of RLP.

It must be noted that the viscoelastic response values decrease from 60/70 pen bitumen to TLA blends to RLP blends; an indication of increased elasticity. Additionally, TLA blends had the highest G* values followed by an arrangement of 60/70 pen bitumen and RLP blends. As expected, TLA increases the stiffness of the base asphalt.

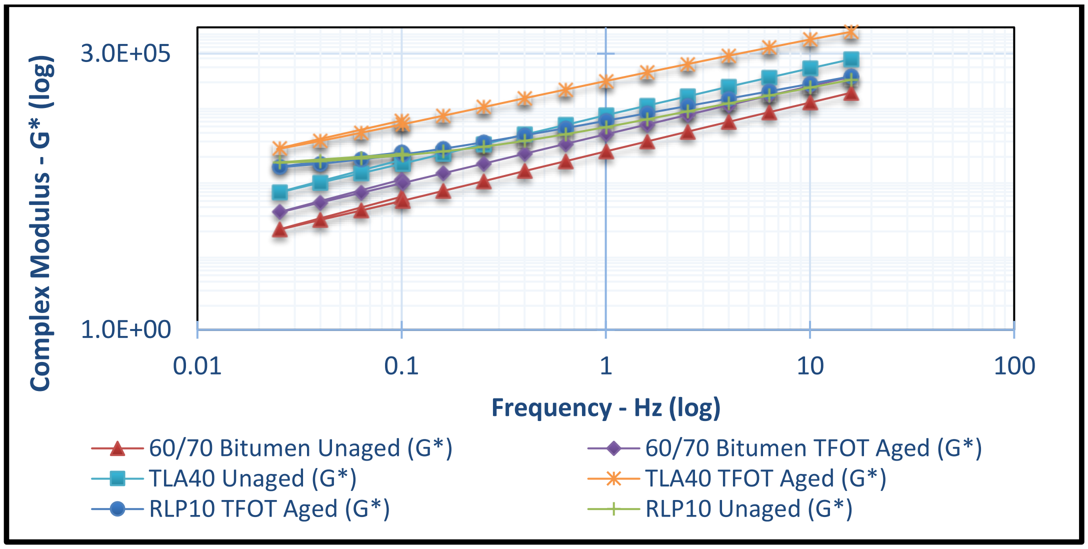


Figure 3. Complex modulus (G*) at 50 ^{0}C.

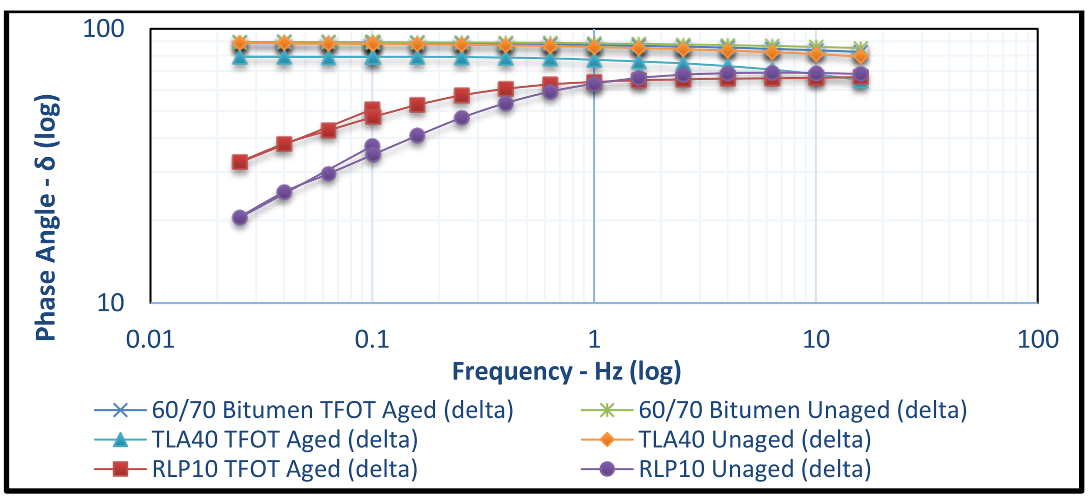


Figure 4. Phase angle (δ) at 50 ^{0}C.

Viscosity vs Elasticity. With the purpose of evaluating the effect of TLA and RLP on viscosity and elasticity, a plot of the fatigue cracking parameter (G*sinδ) against the rutting parameter (G*/sinδ) for 40% TLA and 10% RLP at test temperatures and frequencies is shown in Figure 5. Unaged blends for TLA binders demonstrated more linearity when compared to TFOT aged TLA binders. The curvature of the aged blends at higher values of G* is indicative of a loss in stability of both viscous and elastic components as G* increases. This implies that the probability of rutting and cracking increases as the asphalt becomes stiffer with reduced ability to rebound after load deformation. Additionally, unaged polymer blends demonstrated similar linearity when compared to TFOT aged polymer blends. This implies that viscosity and elasticity of polymer blends are independent of age.

It is noteworthy to mention, that RLP stabilised the 60/70 pen bitumen when compared to the response of TLA modified binders. Evidence of this is the reduction in curvature from TLA to RLP blends. An increase in the stability of the base asphalt represents increased stability of the asphalt surface layer for intended traffic loads and temperature variation.

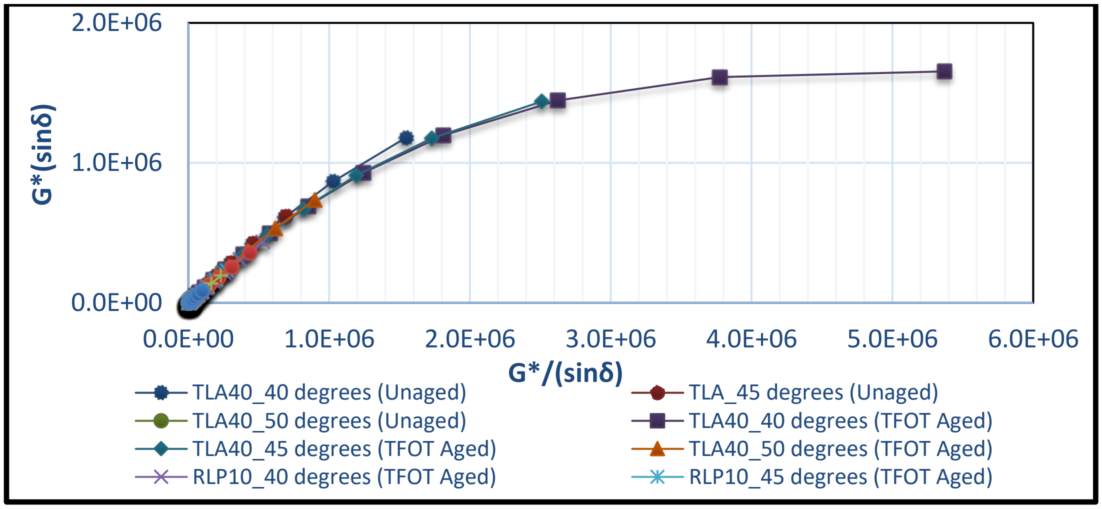


Figure 5. **G*(sin δ) and G*(sin δ) at test temperatures and frequencies.**

Elasticity vs Temperature. Figure 6 shows the rutting parameter, G*/sinδ for 40% TLA and 10% RLP at the test temperature range. G*/sinδ represents the elasticity response of the asphalts. An increase in temperature for both TFOT aged and unaged samples, reported a decrease in the elasticity. This implies that the base asphalt and all blends become less viscous and less elastic with an increase in temperature, regardless of age. TLA blends exhibited more elasticity than RLP blends and the base asphalt over the temperature range. In addition, the recorded decrease in elasticity for increasing temperature was greatest for TFOT aged TLA. This implies that rutting would be most significant in TLA modified asphalt, with increasing temperature.

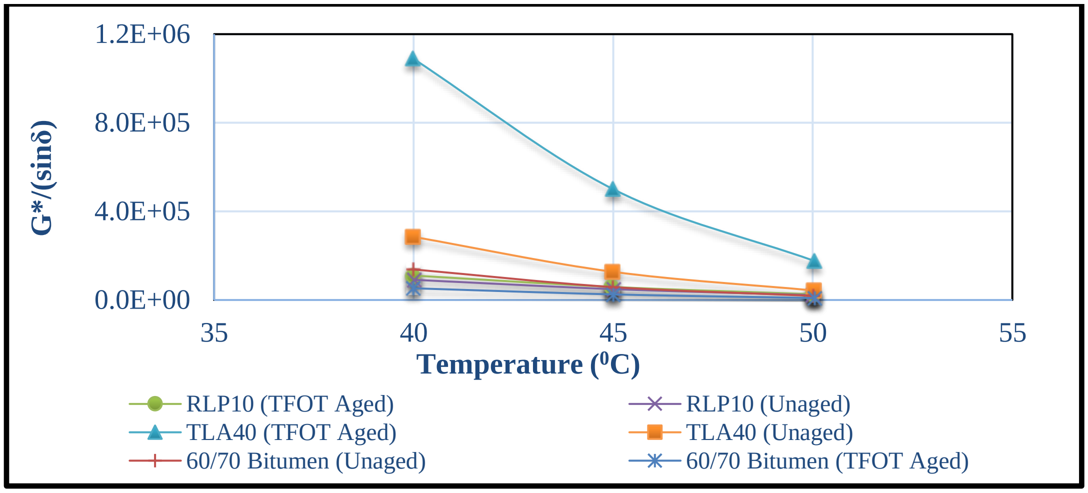


Figure 6: Elasticity of binder and blends.

CONCLUSIONS

This study was conducted to evaluate temperature susceptibility of asphalt binders. The findings presented and analysed suggest that polymer modified blends may be the better suited for present and potential pavement temperatures in Trinidad and Tobago. Although, TLA is readily available in Trinidad, it's implementation as a binder modifier for tropical climates may decrease the performance of the pavement after short-term ageing since stiffness (G*) increases with increasing load frequency and elasticity is significantly reduced for increasing temperatures. Additionally, RLP stabilised the 60/70 pen bitumen when compared to the response of TLA modified binders for the analysis of the fatigue cracking parameter (G*sinδ) against the rutting parameter (G*/sinδ).

It is recommended that the study be extended to include the determination of the yield energy for the base asphalts and corresponding blends. Yield energy quantifies the energy needed to cause permanent deformation of the asphalt pavement surface.

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