

Original Research Paper

Rutting and Fatigue Cracking Susceptibility of Polystyrene Modified Asphalt

Nazim Mohamed, Demitri Ramlochan and Rean Maharaj

University of Trinidad and Tobago, Process Engineering Department,
Point Lisas Industrial Estate, Point Lisas, Trinidad and Tobago, Tobago

Article history

Received: 10-03-2017

Revised: 31-05-2017

Accepted: 01-06-2017

Corresponding Author:

Nazim Mohamed
University of Trinidad and
Tobago, Process Engineering
Department, Point Lisas
Industrial Estate, Point Lisas,
Trinidad and Tobago, Tobago
E-mail: nazim.mohamed@utt.edu.tt

Abstract: The absence of studies investigating the influence of waste Polystyrene (PS) on the performance characteristics of rutting resistance and fatigue cracking resistance of the indigenous asphaltic materials Trinidad Lake Asphalt (TLA) and Trinidad Petroleum Bitumen (TPB), has hindered the possible use of PS as a performance enhancer as observed with other asphalts from different sources thus also developing a sustainable approach for the disposal of PS. The influence of PS on TLA and TPB was investigated by measuring the rheological properties of complex modulus (G^*) and phase angle (δ) of prepared blends and calculating the fatigue cracking resistance and rutting resistance parameters ($G^* \sin \delta$ and $G^*/\sin \delta$ respectively). The addition of PS to TLA resulted in an increase in the fatigue cracking resistance as well as the rutting resistance compared to the pure TPB binder. Despite having improvements in rutting resistance due to PS addition, the fatigue cracking resistance of the TPB parent binders were superior compared with the PS modified TPB blends. The incremental increase in temperatures for TPB and TLA based blends resulted in gradual improvements in their fatigue cracking resistances but gradual deterioration in the rutting resistance of the modified blends. The conclusions were identical for both the Research Program Super pave specification and the Strategic Highway Research Program specifications. There is strong rheological evidence of the possibility to utilize waste PS as an asphalt performance enhancer for both TLA and TPB thus creating a sustainable strategy for the reuse of waste PS.

Key words: Rutting Resistance, Fatigue Cracking Resistance, Polystyrene, Modified Asphalt, Trinidad Lake Asphalt, Trinidad Petroleum Bitumen

Introduction

Asphalt is considered a viscoelastic material; they behave partly like an elastic solid (recoverable deformation after loading) and partly like a viscous liquid (non-recoverable deformation after loading) which exhibits brittle and hard properties in cold environments and is relatively soft in hot environments. It is currently still the most utilized material used in road pavements worldwide however its shortcomings have been characterized mainly by high temperature fatigue cracking and rutting (or permanent deformation) at high temperature, resulting in a deterioration of the performance qualities of the material (Bahia *et al.*, 1998; Yu *et al.*, 2009). Rutting and fatigue cracking are key rheological and performance indicators employed in asphalt technology. Rutting is the permanent

deformation of asphaltic based pavements whereas fatigue cracking occurs when the pavement becomes brittle after losing resilience due to small molecule volatilization and/or oxidation of organic functional moieties (Navarro *et al.*, 2004). Fatigue cracking manifests itself in the early life of an asphaltic pavement and as the cracks develop and the exposed areas become susceptible to the elements, the rutting process is enhanced (Mezger, 2006). The improvement in service life and performance of road pavements has received much research attention as it offers significant economic value and any modifications of asphaltic blends are designed mainly to increase the pavement service lifespan and performance of the asphalt pavement (Sienkiewicz *et al.*, 2012)

The use of waste polymeric materials as modifiers for the improvement of performance of asphalt pavement

material has been promising (Muhammad, 2016; Sienkiewicz *et al.*, 2012). A recent study (Rokade, 2012) incorporating waste polymeric materials in flexible highway pavements demonstrated that the added waste polymeric materials improved the engineering properties of base asphaltic material and also provided a low cost solution to the environmental and ecological threat resulting from by the rapid increase in disposal of waste polymeric materials (Rokade, 2012). Studies incorporating various waste polymeric materials into indigenous Trinidad Lake Asphalt (TLA) and Trinidad Petroleum Bitumen (TPB) have demonstrated promising (Maharaj *et al.*, 2009a; 2009b; Maharaj and Singh-Ackbarali, 2011; Maharaj *et al.*, 2015). These studies highlighted the very important fact that the influence of polymeric additives on performance characteristics of the resultant modified asphalt is dependent on the source and chemical composition of the parent binder: Its performance characteristics cannot be generalized as different asphaltic materials may interact with additives differently. The potential of the use of PS as a modifier for Trinidad asphalts must be experimentally studied as TLA and TPB vary significantly in terms of their composition. TLA, an internationally well established commercial product and a source of superior quality asphalt (Widyatmoko and Elliot, 2008), unlike TPB, comprises a unique mixture of bitumen, 63% and mineral matter which has been shown to be kaolinitic in nature (Maharaj, 2009).

In Trinidad and Tobago, the current primary methodology for the final disposal of waste is land filling and there are presently nine (9) disposal sites which receives approximately one thousand tonnes (1000) of waste per day. In small island states like Trinidad and Tobago, the price of real estate is too high to support this practice (GRTT, 2015). Polystyrene (PS) also known as EPS Foam or Styrofoam is a highly popular plastic packaging material and is used to make useful products such as disposable cups, trays, cutlery, cartons, cases etc. Apart from its popularity and usefulness, countries are dealing with the major problem of its disposal. PS is large and bulky and occupies significant space in rubbish bins and landfills. Its lightweight property allows it to be a nuisance as it is easily blown around by air. Alternative disposal methods such as incineration release toxic chemicals into the environment that can be associated with health, safety and environmental concerns (Estrellan and Lino, 2010). It has been reported that in 2010, approximately fourteen millions kilograms of PS was utilized in Trinidad and Tobago representing a 1500% increase over a five year period (840 thousand kilograms in 2005) (Indexmundi, 2003). Mitigation of the negative effects of PS disposal by incorporating it into asphalt fits within the context of the Trinidad and Tobago

National Integrated Waste Management Policy since the policy's main objective is to develop an integrated waste management system that minimizes land-filling, focus on reduction of toxicity and volume of waste, through reuse, recycling and source-separated organic waste management (GRTT, 2015).

Despite the existence of studies on Trinidad Lake Asphalt (TLA) and Trinidad Petroleum Bitumen (TPB) modified with waste polymeric materials such as polyethylene, tyre rubber, used car oil and waste cooking oil, a review of the literature has produced limited research information involving the use of PS on the performance properties of the Trinidad asphaltic materials TLA and TPB. Since the influence of PS is dependent on the composition of the base asphalt and since all asphalts are unique especially TLA, the void of research information presents a major drawback in terms of the potential for reusing the environmentally unfriendly PS as an asphalt modifier in Trinidad and Tobago. In filling the void, this paper will seek to present the results of a series of assessments of the rheological performance properties of fatigue cracking resistance and rutting resistance ($G^* \sin \delta$ and $G^*/\sin \delta$ respectively) of PS modified TLA and a typical refinery bitumen, TPB by measuring the rheological properties of complex modulus (G^*) and phase angle (δ) using small angle dynamic (oscillatory) testing technique. The results will be used to assess the potential for the reuse of PS as a performance enhancing additive in Trinidad and Tobago.

Materials and Method

The waste polystyrene used in the study was spent commercial 8oz styro form cups. The waste cups samples were washed, dried and masticated in range 2-4 mm diameter. The TLA and TPB 60-70 penetration value asphalt binders used in this study were obtained from the Lake Asphalt Company of Trinidad and Tobago and the Petroleum Company of Trinidad and Tobago Limited respectively. Table 1 shows the source and specifications of the TLA and TPB used in this study.

Sample Preparation

The sample blends were prepared using the recommended process (Polacco *et al.*, 2004). Aluminium cans of approximately 500 cm^3 were filled with 250 to 260 g of the asphalt binder and put in a thermoelectric heater Thermo Scientific Precision (Model 6555) where the temperature was raised to 200°C . A digital IKA (Model RW20D) high shear mixer was then immersed in the can and set to 3000 rpm. The PS was added (by weight %) gradually while the system was kept at a temperature of $200 \pm 1^\circ\text{C}$. The composition of the various TLA and TPB blends is shown in Table 2 and 3 respectively.

Table 1. Source and specifications of the TLA and TPB used in this study

Source	TLA	TPB
	Natural product mined from the Pitch Lake. Obtained from the lake asphalt of Trinidad and Tobago limited	By-product of the petroleum fractionation process. Obtained from the petroleum company of Trinidad and Tobago Limited
PACKAGING	Drum	Drum
Penetration at 25°C (ASTM D5)	0-5	60-70
Specific Gravity (ASTM D70)	1.3-1.5 g/cm ³	1.00-1.06 g/cm ³
Softening Point (ASTM D36)	225°C	89-99°C min
Flash Point (ASTM D92)	255-260°C	49-56°C

Table 2. The composition of the PS-TLA blends

% PS required in sample	Mass of TLA added (grams)	Mass of PS added (grams)	Actual % PS added
0.00	6.0025	0.000	0.00
1.00	6.0048	0.061	1.00
3.00	6.0042	0.186	3.00
5.00	6.0053	0.316	5.00
7.00	6.0009	0.452	7.00
10.0	6.0007	0.667	10.0

Table 3. The composition of the PS-TPB blends

% PS required in sample	Mass of TPB added (grams)	Mass of PS added (grams)	Actual % PS added
0.00	6.2505	0.000	0.00
1.00	6.4215	0.065	1.00
3.00	6.3226	0.196	3.00
5.00	6.2227	0.327	5.00
7.00	6.1514	0.463	7.00
10.0	6.3395	0.704	10.00

At the end of mixing, each blend was stored in a desiccator under static conditions and in an oxygen-free environment. After 24 h of curing, the cans were taken out, remixed using the high shear mixer and the molten mixtures were then cast into a ring stamp 25 mm diameter and 1 mm thickness for subsequent rheological testing. Before testing, the samples were cooled at room temperature and stored in a Fisher Isotemp freezer at -20°C.

Sample Characterization

Theory

The Dynamic (oscillatory) Shear Rheology (DSR) technique has been recommended and is currently used for the characterization of the elastic and viscous properties of asphaltic materials and accomplishes this by measuring the rheological values of complex modulus (G^*) and phase angle (δ) (Kim, 2009; Maharaj *et al.*, 2015). The mathematical correlations linking G^* and δ and the key pavement performance attributes-rutting and fatigue cracking, have been articulated by The Strategic Highway Research Program (SHRP) (Kennedy *et al.*, 1994). The SHRP outlines that in order to minimize deformation (rutting) and fatigue cracking, the work dissipated per load cycle (W_c) must be minimized. W_c at a constant stress (W_{c1}) are related according to Equation 1:

$$W_{c1} = \pi \sigma_o^2 \frac{1}{G^* / \sin \delta} \quad (1)$$

where, σ_o is the stress applied during the load cycle. The relationship shows that in order to minimize rutting deformation, $G^*/\sin\delta$ should be increased.

W_{c2} is the work dissipated per load cycle at a constant strain and can be described as shown in Equation 2:

$$W_{c2} = \pi \varepsilon_o^2 (G^* \sin \delta) \quad (2)$$

where ε_o is the strain during load cycle. The relationship shows that the value of $G^*\sin\delta$ must be minimized in order to minimize fatigue cracking. This concept has been accepted by the Asphalt Research Program Superpave who recommends a high G^* (stiffness) but low δ (elastic) structure to reduce rutting and low values of G^* and δ to reduce the occurrence of fatigue cracking (C-SHRP, 1995).

Procedure

The rheological properties of the asphaltic materials and in particular the measurements of rheological properties of complex modulus (G^*) and phase angle (δ) were conducted using the ATS Rheo

Systems Dynamic Shear Rheometer (Viscoanalyzer DSR) as previously outlined (Maharaj *et al.*, 2009a; 2009b; Maharaj and Singh-Ackbarali, 2011; Maharaj *et al.*, 2015). The tests were done under the strain-control mode and the applied strain was kept low enough to ensure that all the analyses were performed within the linear viscoelastic range. The test geometry used was the plate-plate configuration (diameter 25 mm) with a 1 mm gap and the measurements were conducted at the temperatures 40, 50, 60, 70, 80, 90°C for TLA and TPB and its blends and a frequency range of between 0.1-15.9 Hz. The data obtained at different oscillating shear frequencies and temperatures were stored in the computer and the results obtained were analyzed using the Viscoanalyzer software. The value of the rheological parameters associated with the performance properties of fatigue cracking resistance and rutting resistance ($G^* \sin \delta$ and $G^*/\sin \delta$ respectively) were calculated at the different oscillating frequencies and temperatures.

Results

The values of the rheological parameters associated with the performance properties of fatigue cracking resistance and rutting resistance ($G^* \sin \delta$ and $G^*/\sin \delta$ respectively) were calculated at the different oscillating frequencies and temperatures using measurements of the complex moduli (G^*) and phase angles (δ) of TLA and TPB containing varying amounts of PS as outlined by previous studies (Kennedy *et al.*, 1994; Maharaj *et al.*, 2015). Figure 1 and 2 show the changes of the fatigue cracking resistance parameter ($G^* \sin \delta$) with increasing concentration of PS in TLA and TPB respectively at oscillating frequencies of 0.1, 1.59 and 15.9 Hz at 60°C. Figure 3 and 4 show the variation of the rutting resistance parameter ($G^*/\sin \delta$)

with incremental increases in PS in TLA and TPB respectively at oscillating frequencies of 0.1, 1.59 and 15.9 Hz at 60°C. The dependence of the fatigue cracking parameter ($G^* \sin \delta$) with temperature for the TLA and TPB asphaltic base binders and its PS modified blends is shown in Fig. 5 and 6. The dependence of the rutting parameter ($G^*/\sin \delta$) with the measuring temperature for TLA and TPB PS blends are shown in Fig. 7 and 8 respectively. The black curves obtained in this study for the TLA and TPB asphaltic binders due to the addition of PS at a frequency of 1.59 Hz at a temperature of 60°C using the Asphalt Research Program Superpave specification are shown in Fig. 9 and 10.

Discussion

As seen in Fig. 1, as the concentration of added PS in TLA was increased, the fatigue cracking resistance parameter decreased ($G^* \sin \delta$ value decreased) at the three measured frequencies indicating that PS modified TLA blends will exhibit generally higher fatigue cracking resistance compared to pure TLA. As shown in Fig. 2, the blends containing PS had marginally higher values of $G^* \sin \delta$ at the measured frequencies indicating that these blends will exhibit slightly lower fatigue cracking resistance compared to pure TPB. Any increase due to the addition of PS generally occurred after the addition of 1% PS after which incremental increases in the % added PS resulted negligible changes in $G^* \sin \delta$. Despite the slightly lower fatigue cracking resistance values observed for TPB due to the PS addition, the modified blends were still are within permissible limits outlined by the Super pave specification (the fatigue parameter ($G^* \sin \delta$) shall be ≤ 5000 kPa) (C-SHRP, 1995).

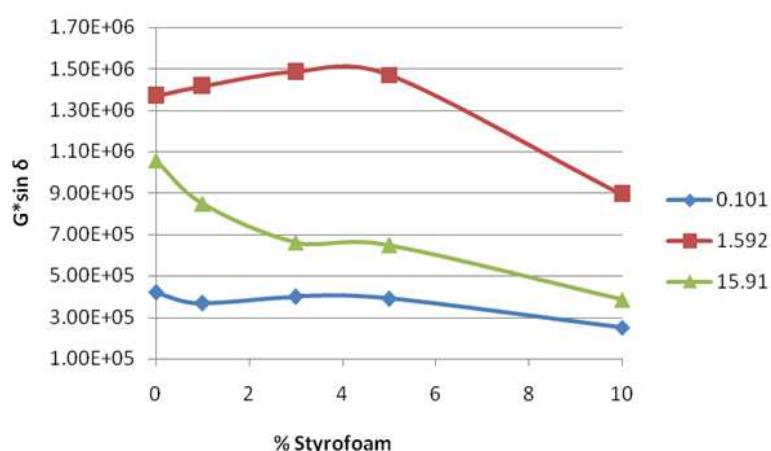


Fig. 1. The variation of the fatigue cracking resistance parameter ($G^* \sin \delta$) with increasing concentration of PS in TLA at various oscillating frequencies at 60°C

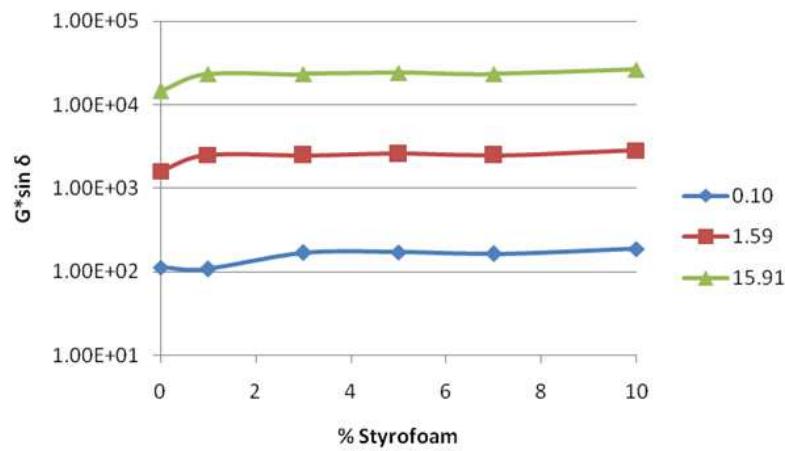


Fig. 2. The variation of the fatigue cracking resistance parameter ($G^* \sin \delta$) with increasing concentration of PS in TPB at various oscillating frequencies at 60°C

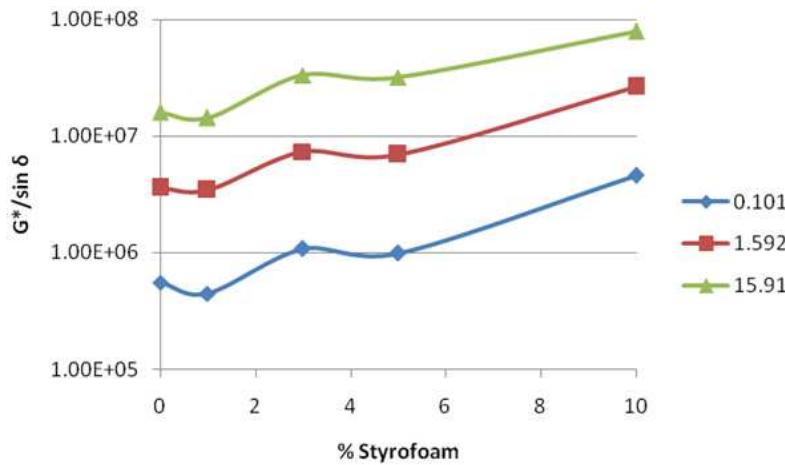


Fig. 3. The variation of the rutting resistance parameter ($G^*/\sin \delta$) with increasing concentration of PS in TLA at various oscillating frequencies at 60°C

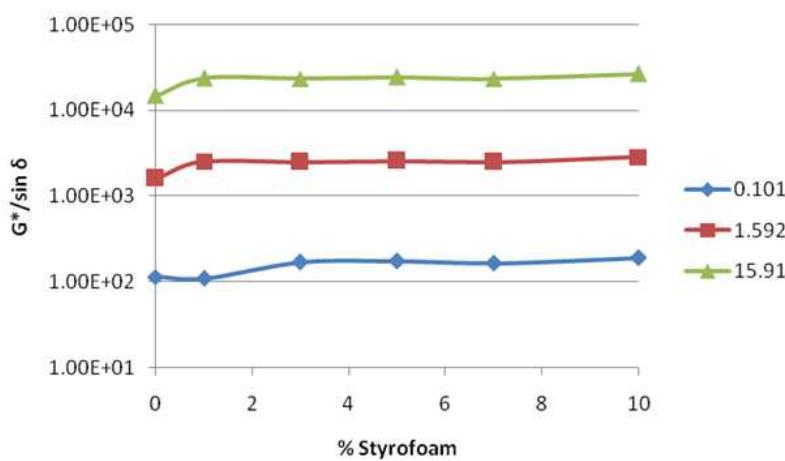


Fig. 4. The variation of the rutting resistance parameter ($G^*/\sin \delta$) with increasing concentration of PS in TPB at various oscillating frequencies at 60°C

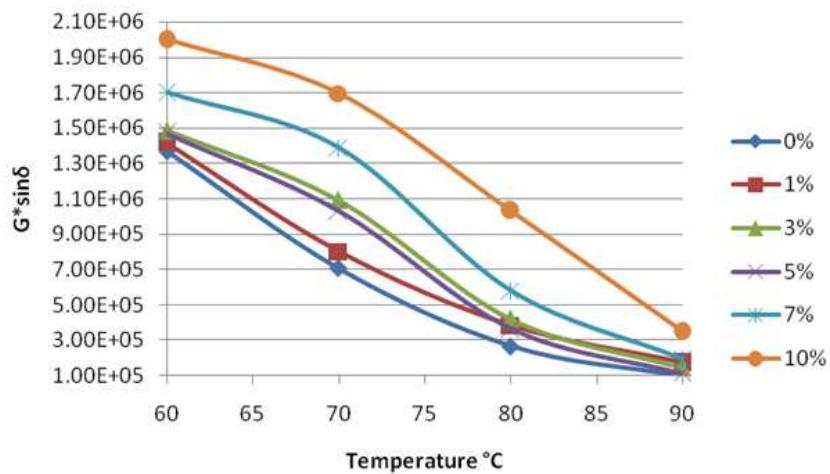


Fig. 5. The variation of the fatigue cracking resistance parameter ($G^*\sin\delta$) of PS modified TLA with increasing temperature at a frequency of 1.59 Hz

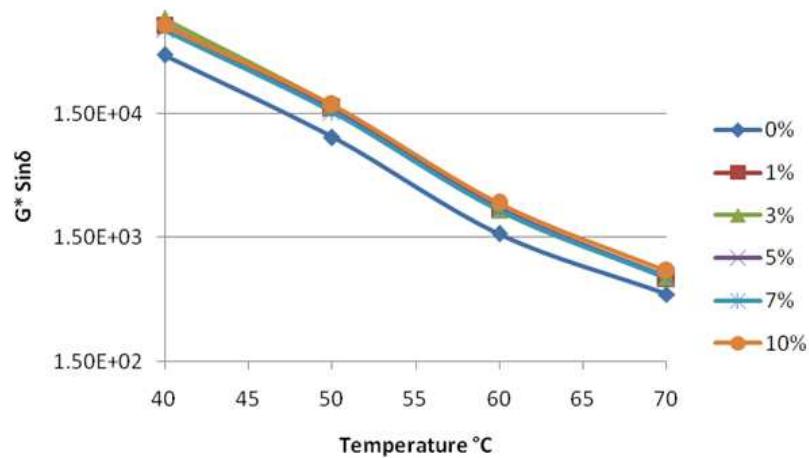


Fig. 6. The variation of the fatigue cracking resistance parameter ($G^*\sin\delta$) of PS modified TPB with increasing temperature at a frequency of 1.59 Hz

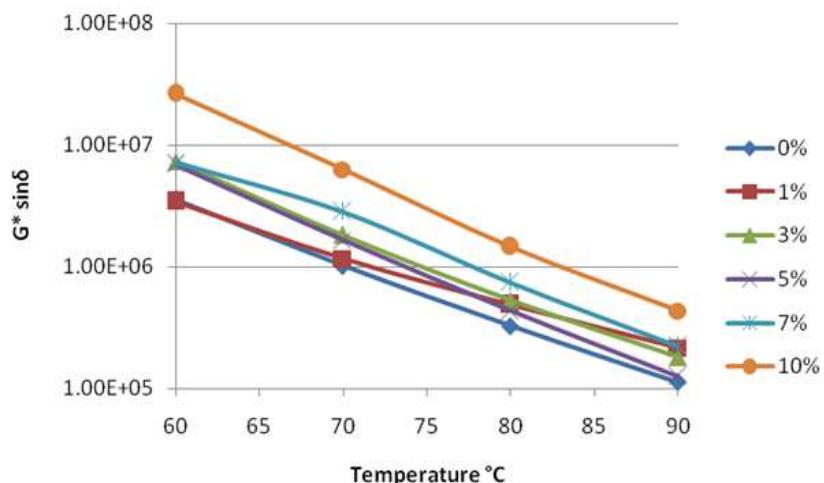


Fig. 7. The variation of the Rutting parameter ($G^*/\sin\delta$) of PS modified TLA with increasing temperature at a frequency of 1.59 Hz

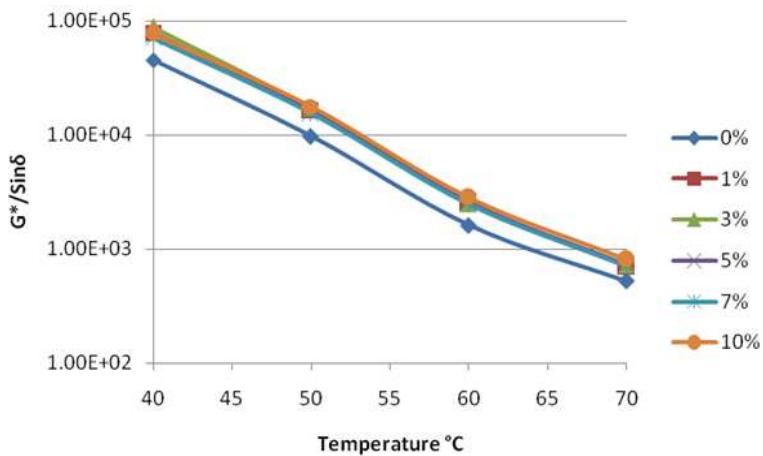


Fig. 8. The variation of the Rutting parameter ($G^*/\sin \delta$) of PS modified TPB with increasing temperature at a frequency of 1.59 Hz

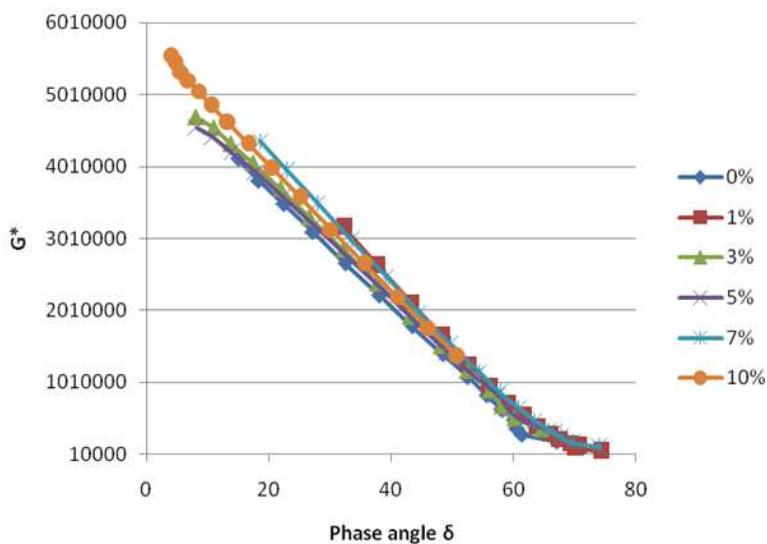


Fig. 9. Black curves for PS modified TLA blends measured and 60°C and frequency sweep 0 to 5.9 Hz

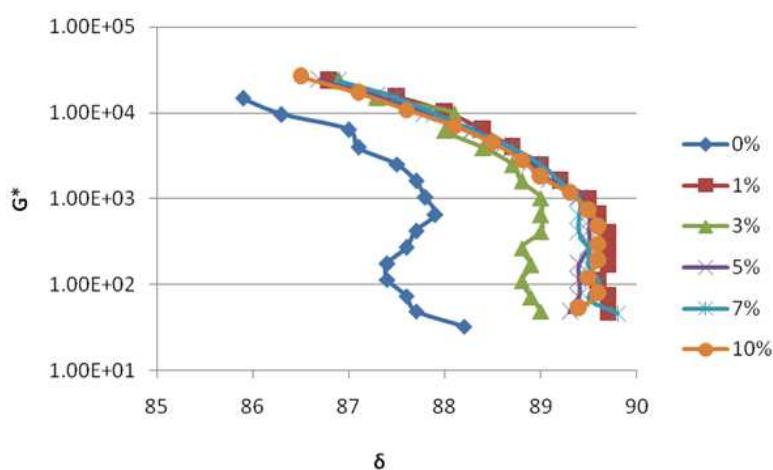


Fig. 10. Black curves for PS modified TPB blends measured and 60°C and frequency sweep 0 to 5.9 Hz

As seen in Fig. 3, for the TLA parent binder, the rutting resistance of the PS modified blends generally increases as the concentration of the added PS increases as indicated by an increase in the value of $G^*/\sin \delta$. Increases in the rutting resistance parameters were notable at added % PS of 1% and above. TLA blends containing 10% TLA had associated rutting resistance parameters of approximately 8 times those of the pure TLA. The variation of $G^*/\sin \delta$ with % PS as shown in Fig. 4 was similar to the trend obtained for the variation of fatigue cracking resistance parameter previously observed in Fig. 2. After an approximately 50% increase in $G^*/\sin \delta$ at 1% PS addition, which indicated an increase in the rutting resistance of the PS modified TLA blend at this level, subsequent incremental increases in the % added PS resulted in minimal increases in $G^*/\sin \delta$ at the measured frequencies.

The dependence of the fatigue cracking parameter ($G^* \sin \delta$) with temperature for the TLA and TPB asphaltic base binders and its PS modified blends as shown in Fig. 5 and 6 demonstrates that the values of $G^* \sin \delta$ for all the TLA and TPB blends gradually decreased as the measuring temperature increased indicating that fatigue cracking resistance characteristics all the blends increased with increasing temperature.

The relationship of the rutting parameter ($G^*/\sin \delta$) with the measuring temperature for TLA and TPB PS blends are shown in Fig. 7 and 8 respectively and shows that the variation of the rutting parameter indicated by the value of $G^*/\sin \delta$ for all the TLA and TPB blends, gradually decreased as the temperature was incrementally increased indicating that the rutting resistance decreases as temperature increases.

The black curves obtained in this study using the Asphalt Research Program Superpave specification are shown in Fig. 9 and 10. The Asphalt Research Program Superpave specification (C-SHRP, 1995) analysis approach strategy recommends a high G^* (stiffness) but low δ (elastic) structure to reduce rutting and low values of G^* and δ to reduce the fatigue cracking. The graphical relationship of G^* vs δ is referred to as a black curve. The shifting of the G^* vs. δ curves from the curve of the base binder (TLA and TPB) due to modification such as the addition of PS reflects changes in composition or structure caused by the addition of the PS additive (Widyatmoko and Elliott, 2008; Maharaj, 2009). As shown in Fig. 9, the addition of PS to TLA, generally resulted in the black curves shifting marginally towards stiffer (higher G^*) blends with similar elastic response (similar δ) compared to the curve of the parent TLA asphalt. This observation according to the Asphalt Research Program Superpave specification (C-SHRP, 1995) should marginally reduce susceptibility to rutting. As shown in Fig. 10, the addition of PS to TPB, generally resulted in the black curves shifting towards a less elastic response (higher δ)

compared to the curve of the parent TPB asphalt. This according to the Asphalt Research Program Superpave specification (C-SHRP, 1995) should have a negative effect on fatigue cracking. The analytical findings using the Asphalt Research Program Superpave specification and the Strategic Highway Research Program resulted in similar conclusions. The consistency of the findings utilizing two varied approaches validates the results of this study and offers supporting evidence that the two approaches utilized to characterize rutting and fatigue cracking is complementary.

The results obtained in this study also offer conclusive supporting evidence validating the concept that the performance characteristics (as indicated by the rheological response of fatigue cracking and rutting in this case) of an asphalt due to the addition of an additive such as PS is dependent on the chemical composition of the asphalt being studied. The results are consistent with previous studies utilizing waste polymeric materials other than PS on TLA and TPB (Maharaj et al., 2009a; 2009b; Maharaj and Singh-Ackbarali, 2011; Maharaj et al., 2015). The performance properties of fatigue cracking resistance and rutting resistance ($G^*\sin \delta$ and $G^*/\sin \delta$ respectively) were significantly higher for parent TLA and PS modified TLA blends compared to the parent TPB and PS modified TPB blends. The unique components of TLA are responsible for its world renowned superior performance characteristics (Widyatmoko and Elliott, 2008). Composition studies indicated that TLA contains 35.3% wt inorganic material which was found to be a kaolinitic in nature. Fractionation of the organic fraction of TLA and TPB employing the ASTM D 4124-86 fractionation procedure showed that while the saturates: Naphtene aromatics: Polar aromatics ratio (three components which constitutes the maltenes) of both materials are similar, TLA contained almost three times more asphaltenes than TPB (30.7% for TLA and 11.7% for TPB) and its ratio of naphtene-aromatic: Polar aromatic: Asphaltene was approximately equal to one. Compared to TPB, TLA was also found to have higher concentrations of heteroatoms, trace metals and organic functional groups compared to TPB implying that TLA should have superior durability and performance characteristics (Maharaj, 2009).

Conclusion

The addition of PS to TLA resulted in an increase in the fatigue cracking resistance as well as the rutting resistance compared to the pure TPB binder. Despite having improvements in rutting resistance due to PS addition, the fatigue cracking resistance of the TPB parent binders were superior compared with the PS modified TPB blends. The incremental increase in temperatures for TPB and TLA based blends resulted in gradual improvements in their fatigue cracking resistances but gradual deterioration in the rutting

resistance of the modified blends. There is strong rheological evidence of the possibility to utilize waste PS as an asphalt performance enhancer for both TLA and TPB thus creating a sustainable strategy for the reuse of waste PS.

Acknowledgement

The authors would like to thank The University of Trinidad and Tobago, Point Lisas Campus for the use of its Instrumentation Laboratory.

Funding Information

There was no external funding in this study.

Author's Contribution

Nazim Mohamed: Provision and sampling of materials. Preparation of final report. Rheology testing and interpretation.

Demitri Ramlochan: Sample collection and rheology testing.

Rean Maharaj: Research idea and project planning. Interpretation of data and preparation of final report.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all other authors have read and approved the manuscript and ethical approval was not required for this study.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

- Bahia, H.U., W. Hislop, H. Zhai and A. Rangel, 1998. The classification of asphalts into simple and complex binders. *J. Assoc. Asphalt Pav. Technol.*, 67: 1-41.
- C-SHRP, 1995. Specification for superpave binders, Canada. Canadian Strategic Highway Res. Program.
- Estrellan, C.R. and F. Lino, 2010. Toxic emissions from open burning. *Chemosphere*, 80: 193-207.
- GRTT, 2015. National waste recycling policy 2015. Government Republic Trinidad Tobago.
- Indexmundi, 2003. Trinidad and Tobago yearly imports in US dollars-polystyrene, expandible, in primary forms.
- Kennedy, T.W., R.J. Cominsky and E.T. Harrigan, 1994. Superior Performing Asphalt Pavements (Superpave): The Product of the SHRP Asphalt Research Program. 1st Edn., Strategic Highway Program, Washington, DC, ISBN-10: 030905821X, pp: 156.
- Kim, Y.R., 2009. Modeling of Asphalt Binder Properties and its Application to Modified Binders. 1st Edn., McGraw-Hill Construction, ASCE Press.
- Maharaj, R. and D. Singh-Ackbarali, 2011. The viscoelastic properties of Trinidad lake asphalt-used engine oil blends. *Int. J. Appl. Chem.*, 7: 1-8.
- Maharaj, R., 2009. Composition and rheological properties of Trinidad lake asphalt and Trinidad petroleum bitumen. *Int. J. Appl. Chem.*, 5: 169-179.
- Maharaj, R., A. Balgobin and D. Singh-Ackbarali, 2009a. The influence of waste polyethylene on the rheological properties of Trinidad lake asphalt and Trinidad petroleum bitumen. *Asian J. Mater. Sci.*, 1: 36-44.
- Maharaj, R., D. Singh-Ackbarali, A. St. George and S. Russel, 2009b. The influence of recycled tyre rubber on the rheological properties of Trinidad lake asphalt and Trinidad petroleum bitumen. *Int. J. Appl. Chem.*, 5: 181-191.
- Maharaj, R., V. Ramjattan-Harry and N. Mohamed, 2015. rutting and fatigue cracking resistance of waste cooking oil modified trinidad asphaltic materials. *Sci. World J.* DOI: 10.1155/2015/385013
- Mezger, T.G., 2006. The Rheology Handbook: For Users of Rotational and Oscillatory Rheometers. 1st Edn., Vincentz Network GmbH and Co KG, ISBN-10: 3878701748, pp: 299.
- Muhammad, A.J., 2016. Effect of polymer modification on rheological properties of asphalt. *J. Civil Eng. Res.*, 6: 55-60. DOI: 10.5923/j.jce.20160603.02
- Navarro, F.J., P. Partal, F.J. Martinez-Boza and C. Gallegos, 2004. Thermorheological behavior and storage stability of ground-tire rubber-modified bitumens. *Fuel*, 83: 2041-2049.
- Polacco, G., J. Stastna, D. Biondi, F. Antonelli and Z. Vlachovicova *et al.*, 2004. Rheology of asphalts modified with glycidylmethacrylate functionalized polymers. *J. Colloid Interface Sci.*, 280: 366-373.
- Rokade, S., 2012. Use of plastic and waste rubber tires in flexible highway pavements, Proceedings of the International Conference on Future Environment and Energy, (ICFE' 12), Singapore.
- Sienkiewicz, M., J.K. Lipka, H. Janik and A. Balas, 2012. Progress in used tyres management in the European union: A review. *Waste Manage.*, 32: 1742-1752. DOI: 10.1016/j.wasman.2012.05.010
- Widyatmoko, I. and R. Elliott, 2008. Characteristics of elastomeric and plastomeric binders in contact with natural asphalts. *Constr. Build. Mater.*, 22: 239-249.
- Yu, J.Y., P.L. Cong and S.P. Wu, 2009. Laboratory investigation of the properties of asphalt modified with epoxy resin. *J. Applied Polym. Sci.*, 113: 3557-3563. DOI: 10.1002/app.30324