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Research Article
Mechanistic Enhancement of Asphaltic Materials Using Fly Ash

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Abstract

Background and Objective: The influence of the waste fly ash on the rheological properties of asphalt is unique and varies from material to material due to differences in the chemical composition of the binders. Previous studies show that the optimal fly ash dosages required for mechanical enhancement can range from 2-10% added fly ash. The lack of studies involving Trinidad Lake Asphalt (TLA) and Trinidad Petroleum Bitumen (TPB) has limited the use of fly ash as not only a possible performance enhance but an environmentally sustainable disposal method for the waste fly ash. **Materials and Methods:** Dynamic shear rheology was used to measure the rheological properties of complex modulus (G*) and phase angle (δ) of prepared blends and the fatigue cracking resistance and rutting resistance parameters (G*sinδ and G*/sinδ, respectively) were calculated. **Results:** The differences in rheological responses due to the addition of fly ash to the TLA and TPB are linked to the composition differences between the two materials. The fatigue cracking resistance of the TLA and TPB parent binders were superior compared with their fly ash modified blends. The TLA blends containing between 1-2% added fly ash exhibited particularly low cracking resistance as seen from the G*sinδ maxima. The rutting resistances of the TLA and TPB blends generally increased with incremental fly ash additions with the 1% TLA fly ash blend exhibiting the highest rutting resistance. Previous studies using other base asphaltic materials obtained higher optimal dosages between 2-10%. **Conclusion:** Fly ash additions to TLA and TPB generally improved rutting resistance while decreasing the fatigue cracking resistance at optimal dosages of fly ash below 2%. The study demonstrates the possibility to create customized Trinidad asphalt-fly ash blends to suit special applications and offers an environmentally attractive option for the reuse of waste fly ash.

Key words: Rutting resistance, fatigue cracking resistance, fly ash, modified asphalt, TLA, TPB

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The treatment of the combustion product fly ash has become a major issue in countries that employ the combustion of coal in industrial processes such as electricity generation. Fly ash generally contains significant quantities of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and calcium oxide (CaO), small amounts (ppm levels) of metals including cadmium, lead and mercury as well as low levels of dioxins and PAH compounds[1]. Some of these elements are considered toxic with negative human health and ecological consequences[2,3]. It has been shown in a study conducted by the U.S. Geological Survey (USGS)[4], that fly ash contained up to 30 ppm of radioactive uranium. Worldwide, more than 65% of all fly ash produced is disposed of in landfills and ash ponds which incur significant costs and demand for land to accommodate such facilities. The Environmental Protection Authority USEPA[5], estimates that if the approximately 42 million tons of unused fly ash disposed in such a manner was recycled, there would have been no need for approximately 34 million meter cube of landfill space. The critical factor for the possible reuse of fly ash has grown in importance due to the demand for landfill space and associated costs for this type of disposal, human health and ecological consequences and an increase in global interest in sustainable development. The United States alone produces approximately 131 million tons of fly ash annually according to the Johnson[6]. However, based on information acquired in the American Coal Ash Association Web site, in the year 2008 only 43% of this ash was re-used, most being used in the cement industry[7].

The use of fly ash as a modifier in the asphalt road paving industry to mitigate the decrease in performance of the binder material due to exposure to traffic loads and climatic and environmental changes has generally produced favourable results consistent to those achieved by waste polymer modified asphaltic binders[8]. Recent study demonstrated that incorporating fly ash resulted in improved rheological and performance characteristics while reducing cost and unfavourable environmental impacts[9]. Fly ash was also shown to improve the elastic properties of 40-50 penetration grade asphalt[10]. It was further concluded that fly ash modified asphalt concrete mixtures containing 10% fly ash by weight of asphalt cement (60-70 penetration value), exhibited a relatively higher resistance to permanent deformation as compared with the control mixture[11]. Its effect on the mechanical properties of asphalt mixtures was studied using multiple specimen types containing varying fly ash contents[12]. It was concluded that when fly ash is used as mineral filler, it resulted in higher strength and stripping resistance of the modified blend. The addition of 2% fly ash improved the resilient modulus of the resultant blend at different temperatures. Studies showed improvement in the fatigue life and stiffness by up to 111 and 155%, respectively compared to the unmodified blend[13]. At a marginally higher temperature (30°C), the fatigue life and stiffness both increased by 78%.

The two key rheological and performance indicators employed in asphalt technology to describe the mechanistic characteristics of asphaltic blends are rutting and fatigue cracking[14]. Rutting can be described as the permanent deformation of asphaltic based pavements whereas fatigue cracking occurs when the pavement becomes brittle after losing resilience as a result of small molecule volatilization and/or oxidation of organic functional moieties[15]. Fatigue cracking usually occurs in the early life of an asphaltic pavement and thus can promote rutting as the cracks that develop renders the exposed areas susceptible to the elements thus accelerating the rutting process[16]. Asphaltic binders are considered viscoelastic; they behave partly like an elastic solid (recoverable deformation after loading) and partly like a viscous liquid (non-recoverable deformation after loading). The dynamic (oscillatory) shear rheology (DSR) testing technique is capable of quantifying both elastic and viscous properties and in particular, the measured rheological values of complex modulus (G*) and phase angle (δ) and has been recommended for the characterization of the viscoelastic properties of asphaltic material[17]. Mathematical correlations between rheological parameters (G* and δ) and pavement performance attributes such as rutting and fatigue cracking, have been described by the strategic highway study program: asphalt study program[18]. They suggested that in order to minimize deformation (rutting) and fatigue cracking, the study dissipated per load cycle (W_c) must be minimized. The W_c at a constant stress (W_{c1}) are related according to Eq. 1:

$$W_{c1} = \pi\sigma_0^2 \frac{1}{G^*/\sin\delta} \tag{1}$$

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

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

$$W_{c2} = \pi\varepsilon_0^2 (G^*\sin\delta) \tag{2}$$

where, ϵ_o is the strain during load cycle. The relationship shows that the value of G*sinδ must be minimized in order to minimize fatigue cracking. The asphalt study program superpave specification has also adapted this principle and has recommended 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[19].

Despite the existence of studies using the DSR technique 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[20-23], a review of the literature has produced limited information involving the use of fly ash on the mechanistic properties of the Trinidad asphaltic materials TLA and TPB. The existing studies highlighted the fact that the influence of additives on mechanistic characteristics of the resultant modified blends is dependent on the source and chemical composition of the parent binder: The mechanistic characteristics cannot be generalized as different asphaltic materials may interact with additives differently. The TLA has been internationally well established as a commercial product and a source of superior quality asphalt[24] and unlike TPB, comprises a unique mixture of bitumen, 63% and mineral matter which has been shown to be kaolinitic in nature[25].

This study presents the results of a series of assessments of the mechanistic properties of fatigue cracking resistance and rutting resistance (G*sinδ and G*/sinδ, respectively) of fly ash 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 fly ash waste material as a performance enhancing additive in asphaltic pavements utilizing the Trinidad asphaltic binders TLA and TPB.

MATERIALS AND METHODS

Fly ash was obtained from the combustion of coal at 700°C for 2 h in a box furnace. The material was sieved and the portion passing sieve No. 200 (0.075 μ) was used in this study. 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[26]. Aluminium cans of approximately 500 cm^3 were filled with 250-260 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 fly ash was added (by weight %) gradually while the system was kept at a temperature of 200±1°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

	TLA	TPB
Source	Natural product mined from the pitch lake. Obtained from the lake asphalt of Trinidad and Tobago Limited	By-product of the petroleum fractionation process. 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)	89-99°C	225°C min
Flash point (ASTM D92)	255-260°C	49-56°C

Table 2: Composition of the fly ash-TLA blends

Fly ash required in sample (%)	Actual mass of TLA added (g)	Required mass of fly ash (g)	Actual mass of fly ash added (g)	Actual percentage of fly ash added
0.0	6.0127	0.0000	0	0.00
1.0	6.0113	0.0601	0.0602	1.00
2.0	6.0111	0.1202	0.1204	2.00
4.0	6.0100	0.2404	0.2404	4.00
8.0	6.1071	0.4886	0.4888	8.00

Table 3: Composition of the fly ash-TPB blends

Fly ash required in sample (%)	Actual mass of TPB added (g)	Required mass of fly ash (g)	Actual mass of fly ash added (g)	Actual percentage of fly ash added
0.0	7.0389	0.0000	0	0.00
1.0	6.6608	0.0666	0.0666	1.00
2.0	6.6583	0.1332	0.1336	2.01
4.0	6.3463	0.2539	0.2537	4.00
8.0	6.6430	0.5314	0.5330	8.02
16.0	6.5707	1.0513	1.0516	16.00

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: 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 RheoSystems Dynamic Shear Rheometer (Viscoanalyzer DSR). 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 and 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 mechanistic properties of fatigue cracking resistance and rutting resistance (G*sinδ and G*/sinδ, respectively) were calculated at the different oscillating frequencies and temperatures.

RESULTS AND DISCUSSION

The values of the rheological parameters associated with the mechanistic properties of fatigue cracking resistance and rutting resistance (G*sinδ and G*/sinδ, 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 fly ash as outlined by the strategic highway study program[18].

Figure 1 and 2 show the variation of the fatigue cracking resistance parameter (G*sinδ) with increasing concentration of fly ash in TLA and TPB at oscillating frequencies of 0.1, 1.59 and 15.9 Hz at 60°C.

Figure 1 shows the concentration of fly ash increases, the fatigue cracking resistance parameter increases (G*sinδ value increases) indicating that fly ash modified TLA blends will exhibit lower fatigue cracking resistance compared to pure TLA. Of particular interest were the blends containing

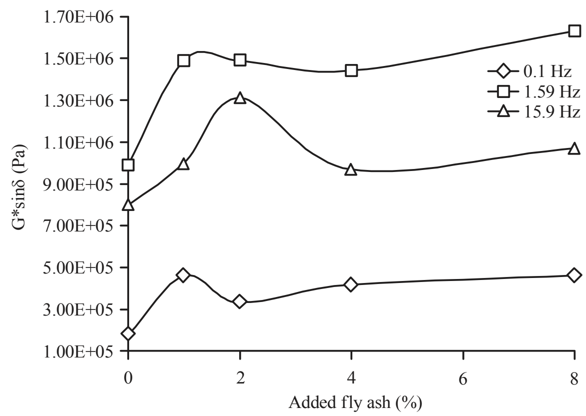

Fig. 1: Variation of the fatigue cracking resistance parameter (G*sinδ) with increasing concentration of fly ash in TLA at various oscillating frequencies at 60°C

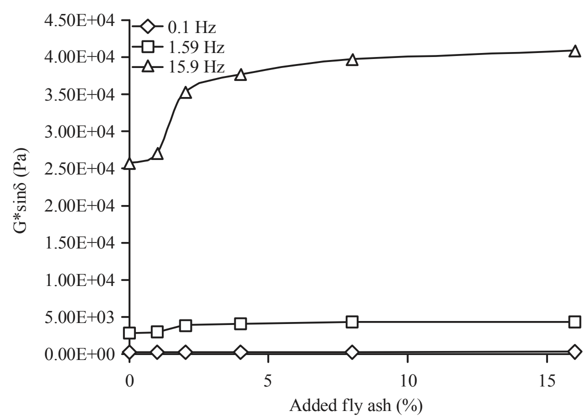

Fig. 2: Variation of the fatigue cracking resistance parameter (G*sinδ) with increasing concentration of fly ash in TPB at various oscillating frequencies at 60°C

between 1-2% added fly ash, which exhibited particularly low cracking resistance as seen from the G*sinδ peak observed at the various measuring frequencies at this concentration range.

Figure 2 shows the behaviour observed with TLA was similar to that observed with the blends formulated using the TPB binder. Blends containing fly ash had higher values of G*sinδ at the measured frequencies indicating that these blends will exhibit the lower fatigue cracking resistance compared to pure TPB. After a relatively significant increase in G*sinδ between 1 and 2%, incremental increases in the percentage added fly ash resulted in minimal increases in G*sinδ. The peak observed for TLA was not observed for TPB. Despite the decreases in fatigue cracking resistance recorded for both TLA and TPB due to fly ash addition, the

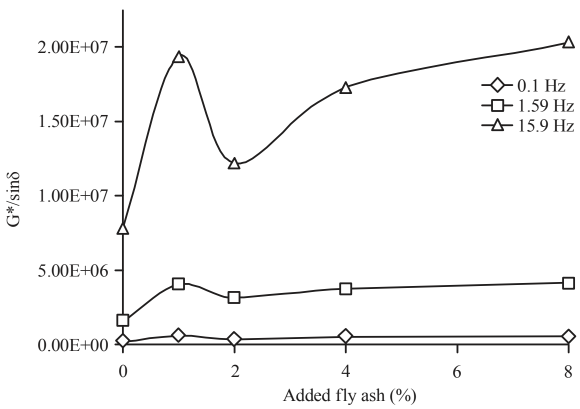

Fig. 3: Variation of the rutting resistance parameter (G*/sinδ) with increasing concentration of fly ash in TLA at various oscillating frequencies at 60°C

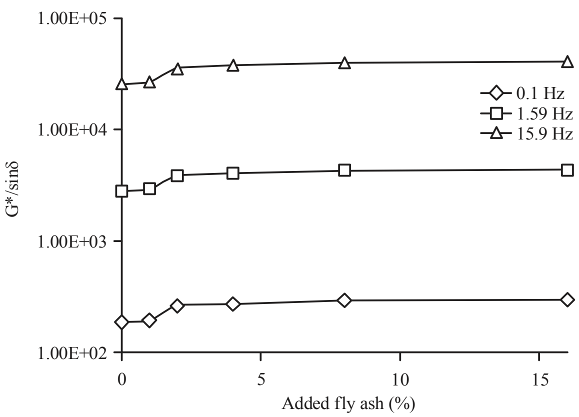

Fig. 4: Variation of the rutting resistance parameter (G*/sinδ) with increasing concentration of fly ash in TPB at various oscillating frequencies at 60

blends were still are within permissible limits as according to the superpave specification the fatigue parameter (G*sinδ) shall be ≤5000 kPa[19].

Figure 3 and 4 show the variation of the rutting resistance parameter (G*/sinδ) with increasing concentration of fly ash in TLA and TPB respectively at oscillating frequencies of 0.1, 1.59 and 15.9 Hz at 60°C.

For both the TLA and TPB parent binders, the results show that the rutting resistance of the fly ash blends generally increases as the concentration of the added fly ash increases as indicated by an increase in the value of G*/sinδ. Figure 3 show, the blends formulated using the TLA binder containing 1% fly ash had maximum values of G*/sinδ at all the measured frequencies indicating that this blend will exhibit the highest rutting resistance of all the blends measured. The variation of G*/sinδ with percentage of fly ash as shown in Fig. 4 was similar to the trend obtained for the variation of

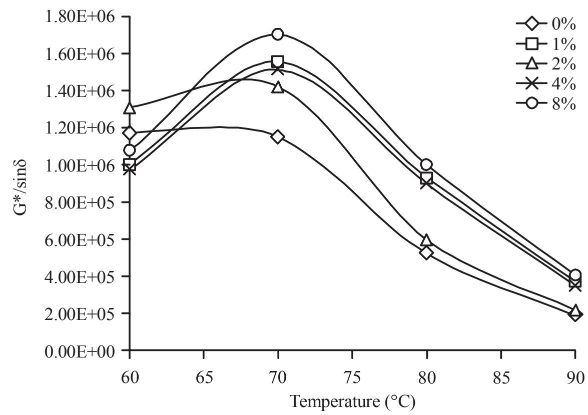

Fig. 5: Variation of the fatigue cracking resistance parameter (G*sinδ) of fly ash modified TLA with increasing temperature at a frequency of 1.59 Hz

fatigue cracking resistance parameter. After a relatively significant increase in G*/sinδ at 1% fly ash, incremental increases in the percentage added fly ash resulted in minimal increases in G*/sinδ.

The difference in the rheological responses due to the addition of fly ash to the TLA and TPB and in particular, its effect on the rutting resistance and fatigue cracking resistance on each of these materials is linked to the composition differences between these two materials and the observations are consistent with those obtained in previous studies incorporating various other polymeric additives in TLA and TPB[20-23]. Studies outlined that the physical and rheological properties of modified asphaltic materials depend on the degree of dispersion of the additive within the system and is influenced by the maltene content (saturates, naphtene-aromatic and polar aromatic contents) of the parent asphalt[27]. Studies employing the ASTM D 4124-86 fractionation procedure found that the maltene content difference between TLA and TPB is significant (TPB having a greater proportion) and can account for the rheological differences between TLA and TPB[25,28,29].

The dependence of the fatigue cracking parameter (G*sinδ) with temperature for the TLA asphaltic base binder and its fly ash modified blends is shown in Fig. 5.

The results demonstrate that the values of G*sinδ for all the TLA blends gradually increased to a maximum (minimum fatigue cracking resistance) at approximately 70°C before gradually decreasing. Generally at temperatures greater than 80°C, all the TLA blends exhibited fatigue cracking resistance characteristics superior to the pure TLA binder. The variation of the fatigue cracking resistance parameter with percentage of added fly ash as shown in Fig. 6 was quite different for the TPB based blends as incremental

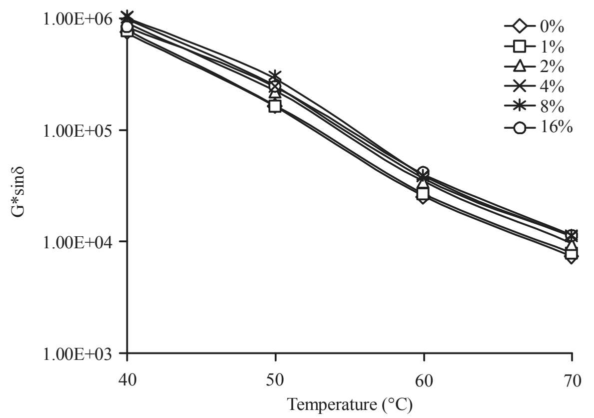

Fig. 6: Variation of the fatigue cracking resistance parameter (G*sinδ) of fly ash modified TPB with increasing temperature at a frequency of 1.59 Hz

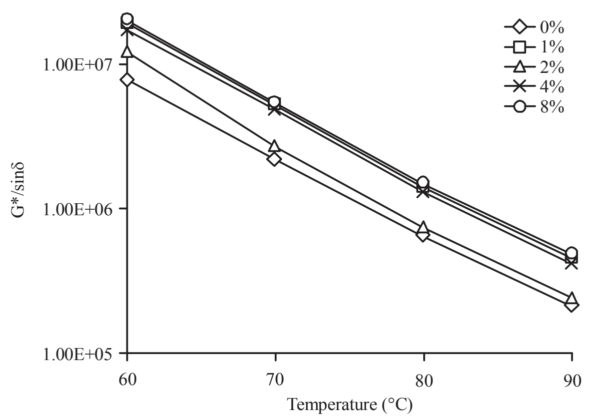

Fig. 7: Variation of the rutting parameter (G*/sinδ) of fly ash modified TLA and TPB with increasing temperature at a frequency of 1.59 Hz

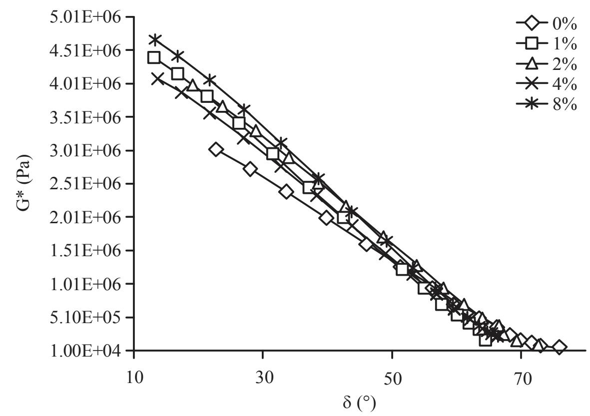

Fig. 8: Black curves for fly ash modified TLA blends measured and 60°C and frequency sweep 0 to 5.9 Hz

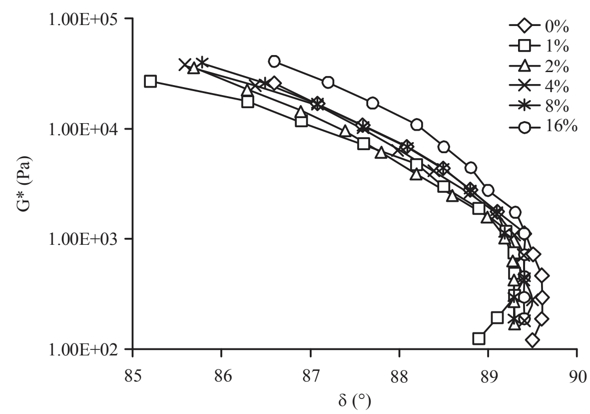

Fig. 9: Black curves for fly ash modified TPB blends measured and 60°C and frequency sweep 0 to 5.9 Hz

increases in added fly ash resulted in gradual improvements in fatigue cracking resistances of the blends.

The dependence of the rutting parameter (G*/sinδ) with the measuring temperature for TLA and TPB fly ash blends are shown in Fig. 7, respectively.

The values of G*/sinδ for all the TLA and TPB blends gradually decreased as the temperature was incrementally increased indicating that the rutting resistance decreases as temperature increases.

An alternative analysis strategy to the strategic highway study program presented above, is the alternative rheology-performance relationship describe by the asphalt study program superpave specification[19]. This approach 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 between G* and δ is referred to as a black curve i.e., "A series of bitumens differing in penetration but not temperature susceptibility (penetration index) will give a single black curve[24,25]. The shifting of the G* vs. δ curves from the curve of the base binder (TLA and TPB) reflects changes in composition or structure caused by the addition of the fly ash additive. The black curves obtained in this study for the TLA and TPB asphaltic binders and its various fly ash modified blends at a frequency of 1.59 Hz at a temperature of 60°C using the asphalt study program superpave specification are depicted in Fig. 8 and 9.

Figure 8 shows the addition of fly ash to TLA, generally resulted in the black curves shifting towards a stiffer (higher G*) and more elastic response (lower δ) compared to the curve of the parent TLA asphalt. This according to the asphalt study program superpave specification[19] should minimize susceptibility to rutting. Figure 9 shows the addition of fly ash 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 study program superpave specification[19] should have a negative effect on fatigue cracking. The analytical findings using the asphalt study program superpave specification and the strategic highway study program produced exact conclusions thus validating the results of this study offered supporting evidence that the two approaches utilized to characterize rutting and fatigue cracking are complementary.

CONCLUSION

This study successfully demonstrated that the influence of fly ash on the mechanical and rheological properties of TLA nad TPB is unique as a difference in the rheological responses was observed between TLA and TPB. The optimal dosage required for TLA and TPB was below 2% unlike previous studies using other base binders which required between 2-10%. This study provided strong rheological evidence for the possibility of utilizing waste fly ash as an asphalt modifier for both TLA and TPB and the potential of creating customized asphalt-fly ash blends to suit special applications.

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