International Journal of Arts & Sciences,
CD-ROM. ISSN: 1944-6934 :: 6(4):321–335 (2013)

THE EFFECT OF PARTICLE SIZE AND CONCENTRATION OF CRUMB RUBBER ON THE RUTTING AND FATIGUE CRACKING RESISTANCE OF TRINIDAD LAKE ASPHALT AND PETROLEUM BITUMEN

Shandelle Hosein[a], Chris Maharaj[a], Rean Maharaj[b] and Dimple Singh-Ackbarali[b]

[a]*The University of the West Indies, Trinidad and Tobago*
[b] *University of Trinidad and Tobago, Trinidad and Tobago*

Research investigating the interaction of polymeric materials (e.g. crumb rubber (CR) which is recycled tyre rubber) on the fatigue cracking and rutting resistance of asphaltic materials indigenous to Trinidad and Tobago is limited. Especially with regards to CR particle size, literature reveals no previous work done investigating its influence on Trinidad Lake Asphalt (TLA) and Trinidad Petroleum Bitumen (TPB). This paper examines the effect of both concentration and particle size of added CR on the fatigue cracking and rutting resistance of TLA and TPB. The particle sizes ranges under study were ≤250 μm, >250 μm to 355 μm, >355 μm to 500 μm, and >500 μm to 710 μm. These particle sizes were added in concentrations ranging from 1% to 10% by weight CR. It was found that for TLA, the optimal CR particle size range and concentration to maximize rutting resistance were particles ≤250 μm at 5% CR concentration respectively. Pure TLA however showed superior fatigue cracking resistance compared to the CR added blends. For TPB, the optimal particle size and concentration for fatigue cracking and rutting resistance were >500 μm to 710 μm at 2% CR and 5% CR respectively. Adding CR to TLA and TPB can serve to enhance the life of the asphaltic materials. Utilizing CR can also offer great potential as a recycling option for the disposal of used car tyres in Trinidad and Tobago.

Keywords: Crumb Rubber, Asphalt, Bitumen, Fatigue Cracking Resistance, Rutting Resistance.

Introduction

Asphalt is defined by ASTM as a “dark brown to black cementitious materials in which the predominant constituent is bitumen that occur in petroleum processing.” Natural asphalt is found in a 100 acre lake on the island of Trinidad, West Indies. This asphalt comprises a mixture of bitumen (53% to 55%), water, and very fine mineral matter (36% to 37%) (Lake Asphalt of Trinidad and Tobago (1978) Ltd. 2009).

Bitumen has been described as being “A viscous liquid, or a solid, consisting essentially of hydrocarbons and their derivatives, which is soluble in trichloroethylene and is substantially non-volatile and softens gradually when heated. It is black and brown in colour and possesses waterproofing and adhesive properties. It is obtained by refinery processes from petroleum, and is also found as a natural depositor as a component of naturally occurring asphalt, in which it is associated with mineral matter.” (Widyatmoko and Elliot 2008). The primary use of asphalt and bitumen is in road construction as asphalt pavements. Other uses include bituminous waterproofing, the lining of fish hatchery ponds (Schlet 1991) and sealants. It is economically beneficial to enhance the lifespan of asphalt and bitumen. The service life of asphalt pavement has been decreasing due to the increasing number of vehicles on roadways and harsh environmental conditions.

Crumb rubber (CR), which comes from polymer based reclaimed tyre rubber, has been shown to offer beneficial properties to some asphaltic blends. Reclaimed tyre rubber is the second most common polymer used in asphalt modification whereas Styrene-butadiene-Styrene is the first (Becker et al. 2001). The degree of polymer modified asphalt used depends on the type of asphalt (source dependant), cost, availability, construction, and expected performance of pavement. In developing countries the cost of using new polymers is high since they must be imported. The use of CR is low cost and will help reduce landfill waste. During 2003 to 2007, an estimated 1.5 million tyres were imported into Trinidad and Tobago while only 15% were exported. Scrap tyres occupy approximately 4.6% landfill space in Trinidad (SWMCOL 1995). Though a small percentage, it must be noted that 75% of each tyre is void space, further reinforcing the landfill option as a non-sustainable approach of disposing. Additionally, tyres in landfills serve as a breeding ground for harmful vermin and mosquitoes. (Chiu 2008) also affirms the benefit of using recycled tyre rubber as a polymer, while providing a better end of life for scrap tyres, the overall performance of pavements is enhanced.

This paper examines the effect of different particle sizes of CR (≤250 μm to 710μm) at different concentrations of CR (0% to 10% weight added CR) on the fatigue cracking and rutting resistance parameters ($G^*\sin\delta$ and $G^*/\sin\delta$ respectively) of Trinidad Lake Asphalt (TLA) and Trinidad Petroleum Bitumen (TPB).

Literature Review

Rutting and fatigue cracking are known to be the two common distresses that occur in road pavement today (Moghaddam et al. 2011). Heavy traffic in the early life of an asphaltic pavement can lead to permanent deformation of the pavement, referred to as rutting (Mezger 2006). Fatigue cracking comes with age where binders (such as asphalt and bitumen) lose resilience due to volatilization of smaller molecules or oxidation that results in overall brittleness of the pavement (Mezger 2006). Fatigue cracking can also assist rutting. The cracks open up avenues for moisture and oxygen ingress that can accelerate rutting (Navarro et al. 2004). An asphalt pavement is engineered to last 15 years (Boyer 1999), whereas polymer modified asphalt has been shown to increase life of the asphalt pavement by 2 to 10 years (Dwyer and Betts 2011). Processes of asphalt modification involving natural and synthetic polymers were patented as early as 1843 (Yildirim 2007). Using polymer in asphalt adds a three dimensional network to the structure. Cross links are created between each monomer molecule to enhance strength and resistance to softening at high temperature. The three dimensional structure offered helps to increase the amount of strain energy absorbed (Moghaddam et al. 2011). Fatigue cracks grow due to tensile and shear stresses, polymers can offer elasticity to the pavement structure; therefore once a stress is applied the structure can deform and revert to its original shape.

"Rheology describes the study of the deformation and flow of matter" (Barnes et al. 1989). The dynamic shear rheometer is used to measure two important rheological parameters, G^*, the complex shear modulus which represents stiffness and δ, the phase angle, which is the lag between the applied shear stress and the resulting shear strain. δ indicates how elastic the material is i.e. δ=0^o means a completely elastic material while δ=90^o demonstrates a completely viscous material. A study conducted by Technische Universität Darmstadt (Hamed 2010) investigated the rheological properties and fatigue resistance of crumb rubber addition on asphalt mixes. The university found that the 10% CR addition offered the most optimal performance i.e. engineering properties and fatigue resistance. Another study by Clemson University (Putman and Amirkhanian 2006) divided the crumb rubber into particle sizes ranges 850 µm to 1180 µm, 425 µm to 600 µm, and 180 µm to 300µm. These were added in 10% and 15% concentration by weight CR. These mixtures were subjected to rotational viscometer tests. CR binders containing 15% crumb rubber by weight had higher G* values than the 10% CR sample. With respect to particle size, the viscosity increased with decreasing particle size, while the G* increased with particle size.

Previous work by Maharaj (2009) and Russell et al. (2011) on CR added to TLA and TPB found an improvement in rutting, aging, and cracking resistance. It was observed that G* values were highest at 5% crumb rubber addition to both asphalt and bitumen. With regards to CR particle size, literature reveals no previous work done investigating its influence onTLA and TPB.

The Strategic Highway Research Program: Asphalt Research Program made an important correlation between rheology measurements and end of performance data.The pavement is composed of viscoelastic binders and for every traffic load force the pavement experiences, the pavement is being deformed. Some of this work is recovered by rebounding (elastic property) while some is dissipated in the form of permanent deformation and cracking. Therefore to minimize this deformation, the work dissipated per load cycle (W_c) must also be minimized. W_c at a constant stress (W_{c1}) can be expressed as shown in Equation 1 (Kennedy et al. 1994).

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

Where σ is the stress applied during the load cycle. Therefore in order to minimize rutting deformation, G*/sinδ should be increased.

W_{c2} is the work dissipated per load cycle at a constant strain and can be expressed as shown in Equation 2 (Kennedy et al. 1994).

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

Where ε_o is the strain during load cycle.Therefore in order to minimize fatigue cracking, G*sinδ should be minimized.

G*sinδ and G*/sinδ can be directly related to the fatigue cracking and rutting resistance respectively. In order to maximize the rutting resistance parameter, high values of G* and low values of δ are required. Superpave specification (Canadian Strategic Highway Research Program 1995) promotes stiff but elastic structure to reduce rutting. To reduce the fatigue parameter, low values of G* and δ are required. The Superpave specification requires the use of elastic but compliant binders (Canadian Strategic Highway Research Program 1995). Rutting and fatigue cracking resistance may depend on the chemical composition and source of asphalt/bitumen used, the particle size of crumb rubber as well its concentration and texture (FHWA and EPA., 1993 and Bahia and Davies 1994).

Method

A scrap tyre was obtained, the steel was removed, and the rubber shredded using a buffing tool at a tyre retreading facility. The resulting CR of various particle sizes was then dried and passed through different sieve sizes. The particle size ranges used are documented in Table 1.

Table 1. Particle size ranges used in study.

Particle size range	Label
≤250 μm	*A*
>250 μm to 355 μm	*B*
>355 μm to 500 μm	*C*
>500 μm to 710 μm	*D*

These particles sizes were then mixed into TLA (Lake Asphalt of Trinidad and Tobago (1978) Ltd. 2009) and a 60/70 penetration refinery bitumen, TPB (Petroleum Company of Trinidad and Tobago Limited) in concentrations of 1%, 2%, 3%, 4%, 5% and 10% CR by weight. A control sample of 0% was prepared for both asphalt and bitumen. 50 cans were filled with the 25 g samples of asphalt and bitumen blends and put in a thermoelectric heater where the temperature was raised to 200 °C. A high shear mixer was then immersed in the can and set to 3000 rpm.

The samples were then transferred to an oven at 200 °C, under static conditions and in an oxygen-free environment. After 24 hours of curing, the cans were taken out and the molten mixtures were then cast into a ring stamp for subsequent rheological testing. Before testing, the samples were cooled to room temperature and subsequently stored in a freezer at −20 °C.

The rheological characterization of the various asphalt blends were studied using an oscillatory dynamic shear rheometer operated within the linear domain under strain control. The test geometries were plate–plate (diameters 25 mm and 1 mm gap). Viscosity measurements were conducted at a temperature of 70 °C and frequency of 1.59 Hz. This frequency corresponds to vehicles travelling at 80 km/hr separated by a recommended safety practice of 3 car lengths between each vehicle. The maximum temperature of the pavements in actual service ranged from 55 °C to 65 °C. The maximum strain was kept within the limit of the linear viscoelastic region.

Results

The experimental results obtained for the 24 different crumb-rubber-TLA blends and the unmodified TLA (0% crumb rubber) with respect to G*sinδ and G*/sinδ are illustrated in Figures 1 to 3.

Figure 1 shows how G*sinδ or the fatigue cracking parameter is affected by different particle sizes of crumb rubber for concentrations of crumb rubber in asphalt. In order to increase the fatigue cracking resistance, both G* and sinδ should be low (Canadian Strategic Highway Research Program 1995) since the pavement needs to be more elastic than stiff i.e. able to resist external force by rebounding and not cracking. It is observed that different particle sizes have an effect on the fatigue cracking parameter. The lowest value of G*sinδ is produced by Pure TLA or 0% CR concentration. In its pure state, TLA demonstrates low stiffness accompanied with adequate elasticity (phase angle of 51.8 degrees) to prevent cracking from penetrating further into pavement surface. The *B* particle size range added in a 4% by weight concentration offered the lowest value of G*sinδ with CR added TLA. However, it yielded a G*sinδ value that was still approximately 600 times larger than Pure TLA.

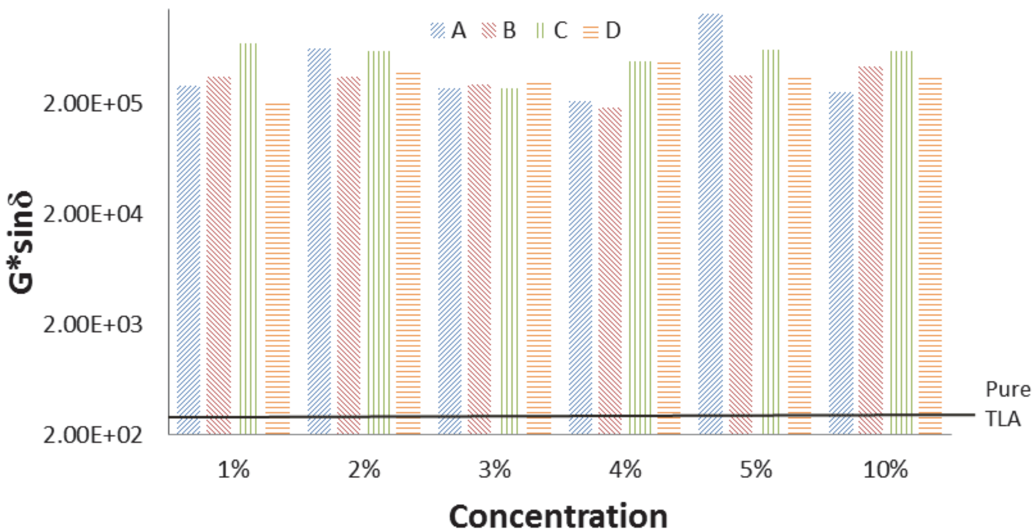

Figure 1. The relationship between the Fatigue Cracking parameter with Particle Size and concentration of CR in TLA.

Figure 2 shows the relationship between the rutting parameter with particle size and concentration of CR in TLA. In order to maximize rutting resistance, G* should be high and sinδ should be small since the pavement needs to be more stiff than elastic i.e. deformation should not be easily transmitted through the pavement. The maximum value of G*/sinδ, which indicates optimal resistance to rutting, was found at 5% CR of particle size range *A*.

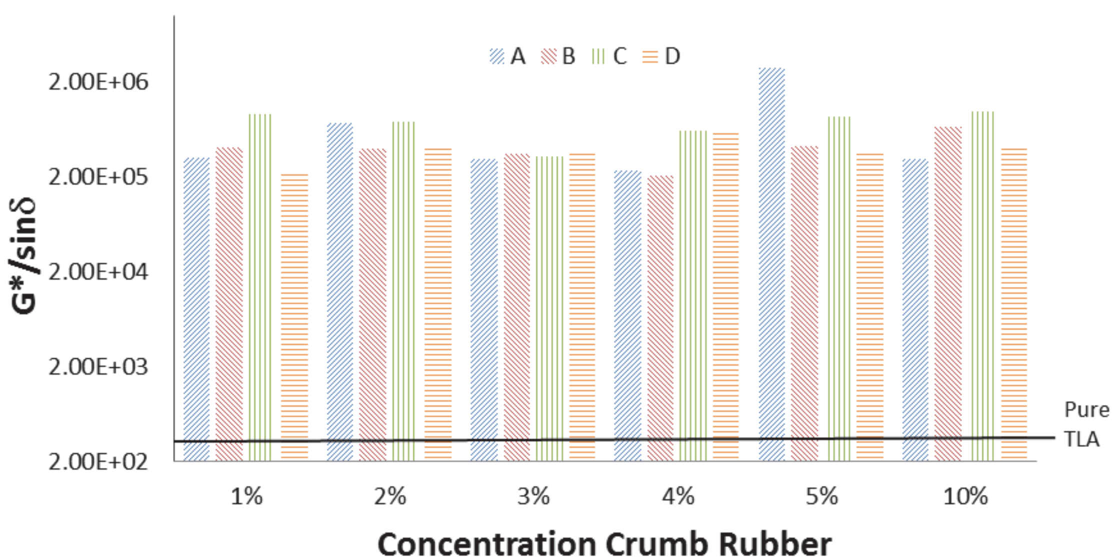

Figure 2. The relationship between the Rutting Parameter with Particle Size and concentration of CR in TLA.

Figure 3 examines the rutting parameter with the 5% concentration of each particle size range.

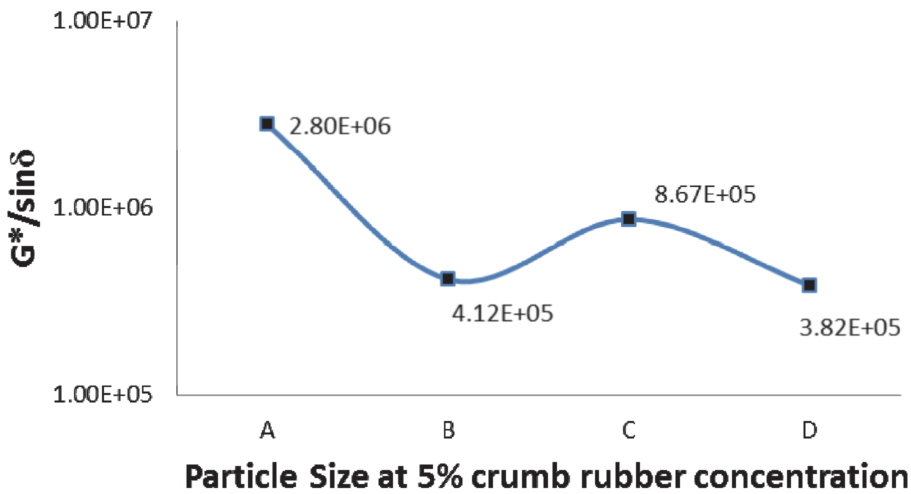

Figure 3. The relationship between the Rutting parameter and Particle Size Range at the 5% concentration of CR in TLA.

The experimental results obtained for the 24 different crumb-rubber-TPB blends and the unmodified TPB (0% crumb rubber) with respect to G*sinδ and G*/sinδ are illustrated in Figures 4 to 7.

When crumb rubber was mixed with refinery bitumen, the smallest value that provided optimal fatigue cracking resistance was found at the 2% concentration at a *D* particle size range as shown in Figure 4.

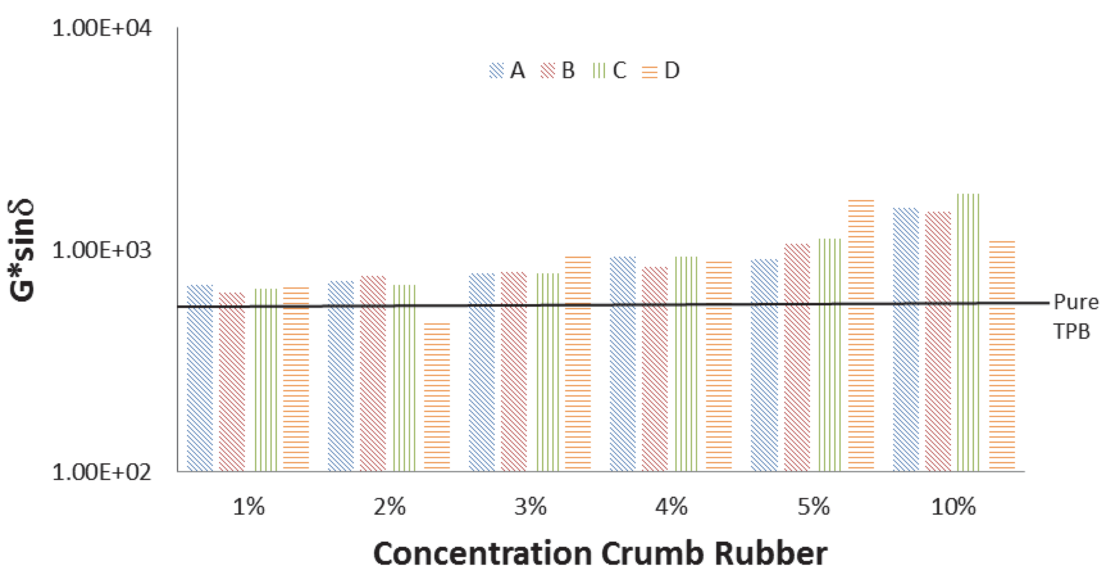

Figure 4. The relationship between the Fatigue Cracking parameter with Particle Size and concentration of CR in TPB.

Figure 5 demonstrates the varying effect of different particle size ranges at the 2% concentration of CR.

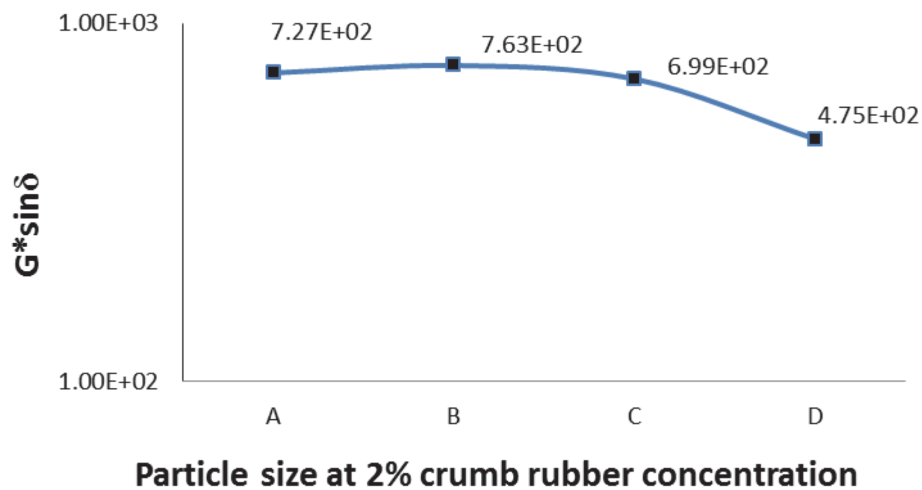

Figure 5. The relationship between the Fatigue Cracking parameter with Particle Size Range at 2% concentration CR in TPB.

The optimum particle size and concentration for rutting resistance in TPB blends can be seen in Figure 6 where particle size range *D* at 5% concentration shows highest value for G*/sinδ. This provides the best rutting resistance.

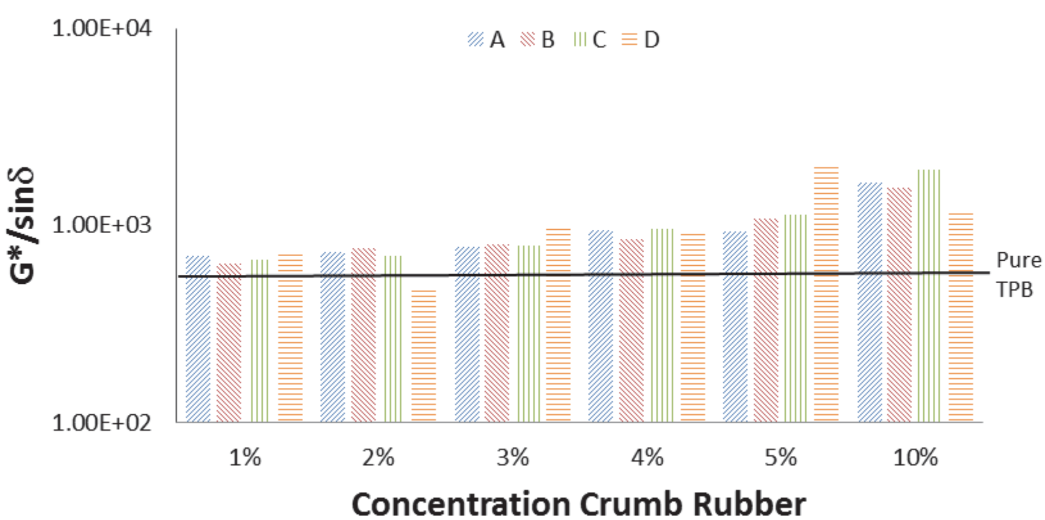

Figure 6. The relationship between the Rutting parameter with Particle Size and concentration of CR in TPB.

Figure 7 gives a closer look at comparison between the rutting parameter and particle size ranges at the 5% concentration of CR.

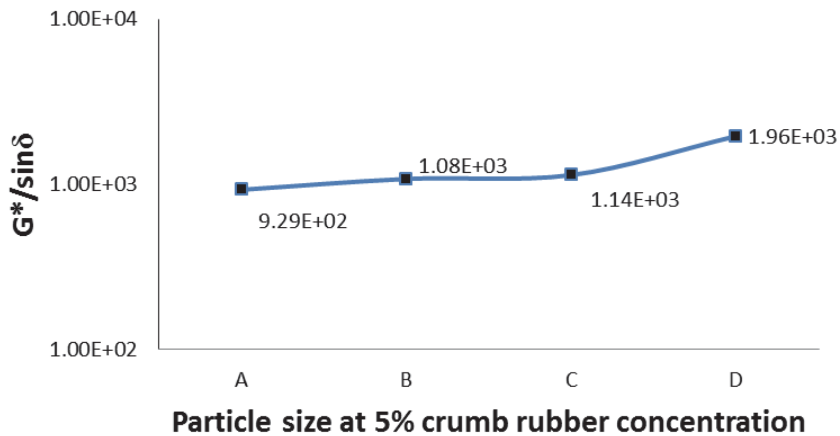

Figure 7. The relationship between the Rutting parameter with Particle Size Range at 5% concentration CR in TPB.

Table 2, Table 3, Table 4, and Table 5 show the most favorable particle size and its associated concentration that provide the most fatigue cracking resistance and rutting in TLA and TPB respectively. Values in bold font in the Tables represent the most desirable concentration. In observing Table 2 there appears to be no distinct relation between particle size range, concentration, and optimum values of fatigue cracking resistance with TLA.

Table 3 reveals that particle size range *C* most often contained the optimum rutting resistance for each TLA CR concentration. With the exception of the 2% CR addition, Table 4 shows that fatigue cracking resistance decreases with increasing concentration of CR in TPB. Table 5 shows that rutting resistance generally increases with increasing concentration of CR added to TPB and also generally occurs with larger particle size ranges.

Table 2. Optimum Fatigue cracking resistance for TLA.

CR Concentration (%)	Minimum G*sinδ value	Particle Size Range (µm)
0	**293**	
1	214,000	*D*
2	347,000	*B*
3	271,000	*C*
4	182,000	*B*
5	338,000	*D*
10	250,000	*A*

Table 3. Optimum Rutting resistance for TLA.

CR Concentration (%)	Maximum G*/sinδ value	Particle Size Range (µm)
0	293	
1	898,000	*C*
2	755,000	*C*
3	350,000	*D*
4	605,000	*C*
5	**2,800,000**	***A***
10	982,000	*C*

Table 4. Optimum Fatigue cracking resistance for TPB.

Concentration (%)	Minimum G*sinδ value	Particle Size Range (μm)
0	556	
1	640	*B*
2	**475**	***D***
3	787	*A*
4	844	*B*
5	915	*A*
10	1,130	*D*

Table 5. Optimum Rutting resistance for TPB.

Concentration (%)	Maximum G*/sinδ value	Particle Size Range (μm)
0	556	
1	716	*D*
2	767	*B*
3	974	*D*
4	953	*C*
5	**1,960**	***D***
10	1,920	*C*

Discussion

The CR is dispersed in the matrix of the binder developing a structure with improved mechanical strength. The oily fractions of the binder are absorbed by the crumb rubber and the rubber particles are swollen, it is this property allows reinforcement of the overall binder matrix and increases the viscosity of the residual binder. As the rubber swells, it now occupies more space in the original matrix and there is a higher resistance to flow, hence an increase in viscosity (Putman and Amirkhanian 2006).

Figure 8 shows how the crumb rubber interacts with the TPB, it is evident that there are detailed crinkles on the surface of the sample. This can be explained using the interaction effect (Putman and Amirkhanian 2006) where the crumb rubber absorbs the oily fractions of the TPB. On absorbing these fractions it creates a suction that leaves this crinkle-like effect.

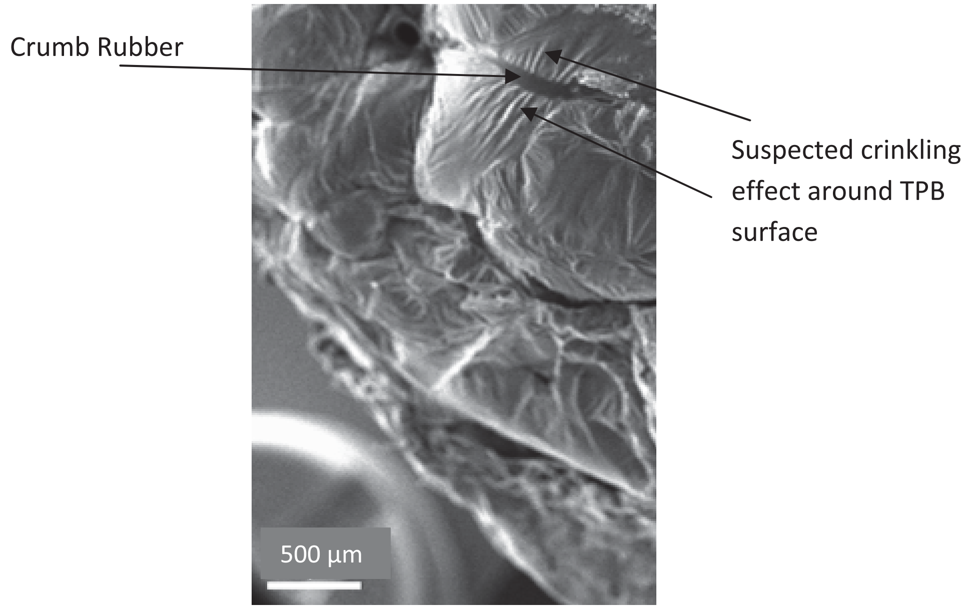

Figure 8. SEM (30 kV with secondary electrons) image of TPB 2% crumb rubber for particle size range *D*.

Some trends between CR particle size and the rheological properties of the modified binder were observed. As discussed in the Literature Review section, a binder that resists fatigue cracking should have properties of being more elastic (G*sinδ must be small), this is so that any energy absorbed can be rebounded and not held in the structure creating stress that will induce cracking.

Rutting resistance can be achieved if the stiffness of the binder is increased. The structure should not be able to deform when a load is experienced, therefore it should be stiff and G*/sinδ should be large. The graphs for TPB were similar for G*sinδ and G*/sinδ versus concentration (Figures 4 and 6) since the sinδ values were closer to unity.

For Figure 1, values of CR added to TLA were not superior for fatigue cracking resistance compared to the 0% CR value. Pure TLA showed its fatigue cracking resistance superiority. However Figure 2 reveals that all values of CR added to TLA provided better rutting resistance because here we are looking for the highest G*/sinδ values in order to minimize the work dissipated per loading cycle as seen in Equation 1.

Beyond the 5% CR concentration (with the exception of particle size range *A*) in Figures 9 and 10, there was not much variation in values as compared to below 5% CR for TLA. This shows that adding any more crumb rubber has minimal effect on changing the fatigue cracking and rutting resistance. Studies by Becker et al. (2001) explain that above a 7% polymer concentration added to asphalt binder, the polymer phase appears to become the matrix of the system. In other words, the polymer is said to be the continuous phase while the asphalt becomes dispersed. It appears that this effect occurs with TLA as well, starting at concentrations above 5% CR where there is no added benefit to the blends. Particle size range *A* followed a different pattern, it did not taper off at the 5% crumb rubber concentration, but rather show a decrease in G*sinδ after peaking. Particle size range *A* consists of particles ≤ 250 µm in size, this represents the largest surface area to volume ratio of all particle sizes. It is suspected that it takes an increased concentration of crumb rubber in order for the crumb rubber polymer to reach the continuous phase as described.

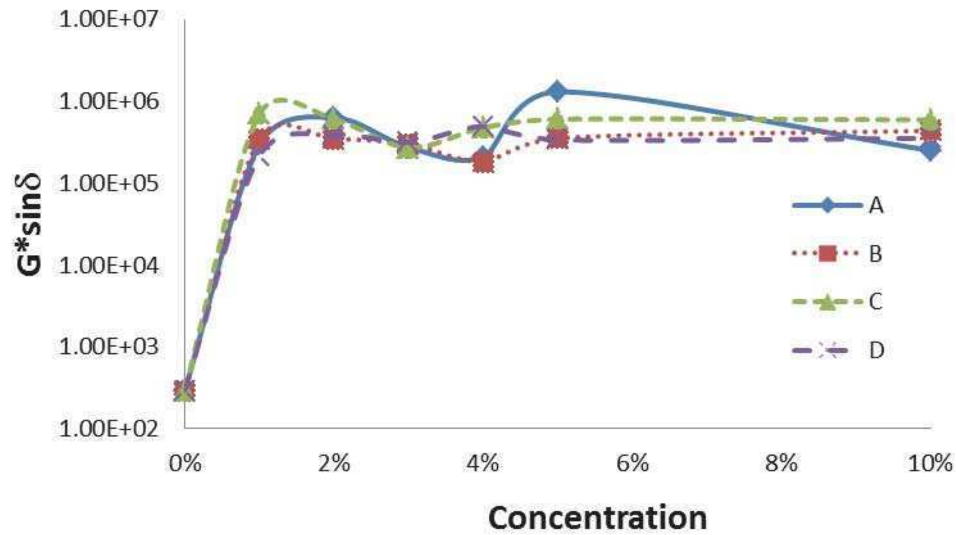

Figure 9. The relationship between the Fatigue Cracking parameter with Particle Size and concentration of CR in TLA.

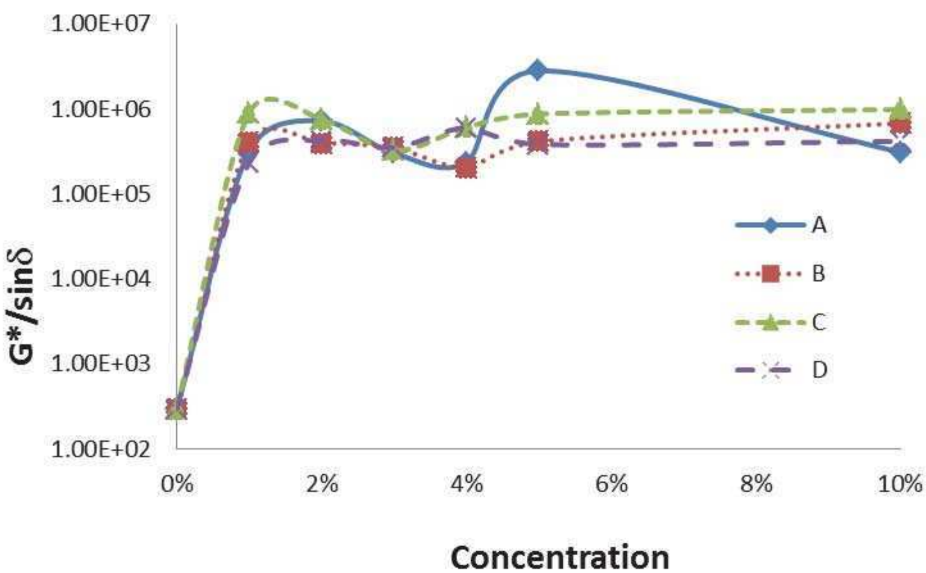

Figure 10. The relationship between the Rutting parameter with Particle Size and concentration of CR in TLA.

Figure 3 revealed that the rutting resistance at the 5% concentration for the TLA generally tended to decrease with increasing particle size range. Conversely, Figure 7 revealed the opposite with the rutting resistance at the 5% concentration generally increasing with increasing particle size range for TPB.

Figure 4 showed that only the *D* particle size range at the 2% concentration provided superior fatigue cracking resistance compared to the 0% CR for TPB. For Figure 6, all values were superior for rutting resistance compared to the 0% CR value with the exception of the *D* particle size range at the 2% concentration for TPB.

For the modified TPB blends shown in Figures 4 and 6, the *D* particle size range produced both the lowest G*sinδ (at 2% CR) and the highest G*/sinδ (at 5% CR) values offering both fatigue cracking and rutting resistance respectively.

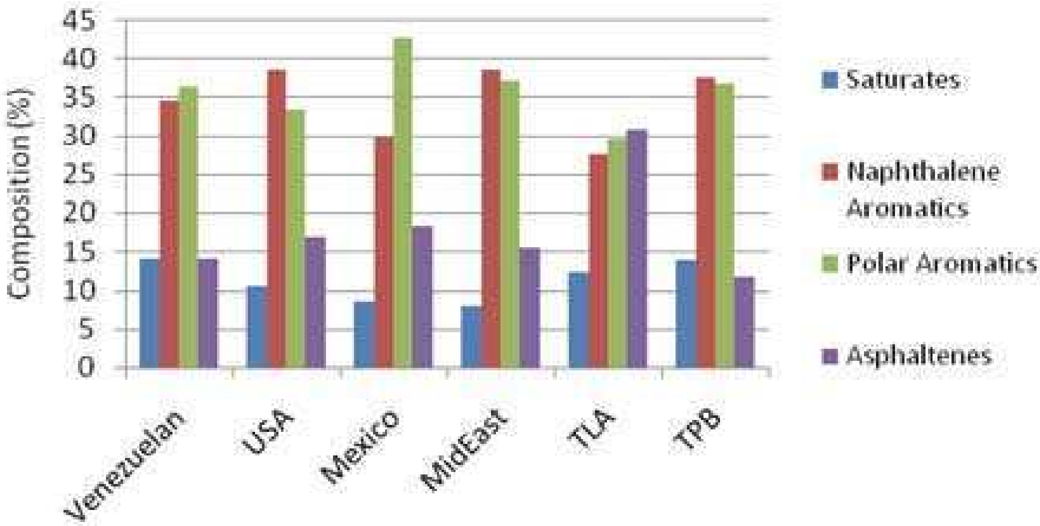

Figure 11. Compositions of different binder sources (Corbet 1970 and Maharaj 2009).

Figure 11 documents the composition fractions of different sources of bitumen found by Corbett (1970) and Maharaj (2009). Focusing on Trinidad Lake Asphalt and Trinidad Petroleum Bitumen, it is clear that the asphaltene composition for TLA more than doubles that of TPB. Asphalt is considered to be a polymer solution in which the oils as the liquid part are the solvent and the asphaltenes suspended in them. The most important structure forming element of asphalts is the asphaltenes, whose quantity and nature of interaction with the other fractions largely determine the rheological properties (Oyekunle 2007). Bull and Vonk (1984) surmised that rubber absorbs the liquid fractions of the asphalt while leaving the high molecular weight asphaltenes in the residual binder. It can be inferred that when the blends were heated, the CR particles absorbs fractions of the binder that become liquid first upon heating. One such fraction is the polar aromatics that are already semi-solid at room temperature.

In Figure 11, it is also noted the difference in compositions between TPB and the compositions of bitumen from other countries. This difference in composition would have most likely led to variations from other studies such as the one conducted by Hamed (2010), where the CR of particle size range 0μm to 600μm provided the greatest fatigue resistance at a 10% concentration.The source of the binder therefore affects the performance of CR blends since the reaction that occurs with CR added binders is dependent on the absorption of the aromatic oils in the asphalt binder (Putman and Amirkhanian 2006).

In Figure 12, it is seen that there is a large variation in complex modulus between pure TLA and the 5% CR added particle size range *D* blend, and this occurs through different testing frequencies. The variation can be attributed to the compositions of the parent TLA and TPB materials and by extension how the differences in composition affects polymer-bitumen compatibility (Lesueur 2009).

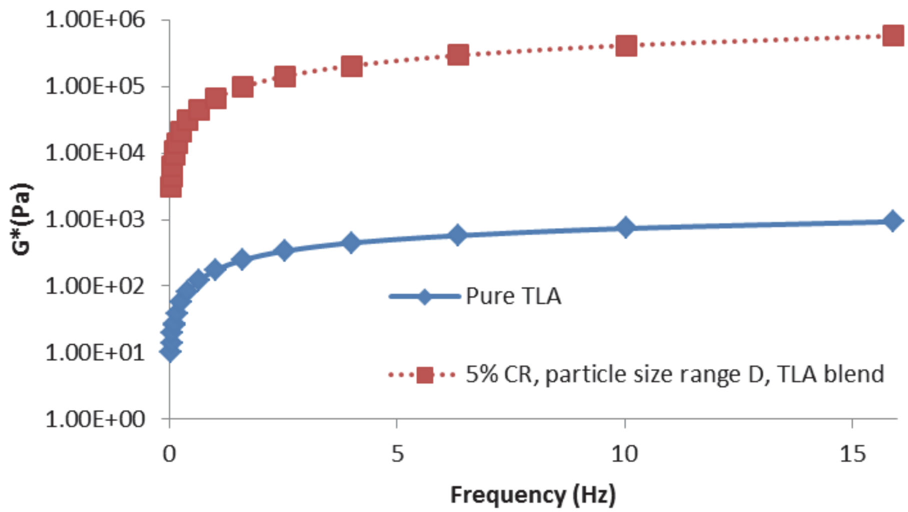

Figure 12. The relationship between complex modulus at different frequencies for pure TLA and the 5% CR added particle size range *D* blend.

The optimum CR particle size range added to TLA for rutting resistance was found to be the smallest particle size range *A*. This particle size range offers the largest surface area to volume ratio. Since more than 30% of TLA is asphaltene, the structure requires particle sizes that will maximize absorption of the remaining fractions i.e. all fractions except the insoluble asphaltene. Whereas, for TPB blends the optimum particle size range for rutting resistance was *D*, the largest particle size range. This particle size range offers the smallest surface area to volume ratio. TPB only contains around 12% asphaltene, almost less than half that contained in TLA. A smaller surface area to volume ratio of CR in this case will suffice, since the components that can be absorbed by the CR are in higher compositions. If too much asphaltene is left without the liquid fractions to form a solution, gelation will occur and the structure will become extremely stiff, rendering it very susceptible to fatigue cracking.

Conclusion

It was found that for TLA, the optimal CR particle size range and concentration to minimize rutting resistance was *A* at 5% respectively. Pure TLA however showed superior fatigue cracking resistance compared to the CR added blends. For TPB, the optimal particle size range and concentration for fatigue cracking and rutting resistance were *D* at 2% CR and 5% CR respectively. Adding CR to TLA and TPB can serve to enhance the life of the asphaltic materials. Utilizing CR can also offer great potential as a recycling option for the disposal of used car tyres in Trinidad and Tobago.

Further investigations should include the effect of CR particle size range and concentrations on ratios of TLA and TPB mixtures. Mixtures of TLA and TPB are commonly used in road pavements with the TPB component occurring in higher concentrations. Accelerated weathering tests can subsequently be done to correlate aging simulation with rheological results.

References

1. Bahia, H., and Davies, R., 1994, "Effect of crumb rubber modifiers (CRM) on performance-related properties of asphalt binders," *Journal of the Association Asphalt Paving Technology* 63: 414-449.
2. Barnes, Howard A., John Fletcher Hutton, and Kenneth Walters. 1989. *An introduction to rheology*. Vol. 3. Elsevier.
3. Becker, Yvonne, Maryro P. Mendez, and Yarjaira Rodriguez. 2001 "Polymer modified asphalt." *Vision Tecnologica* 9, (1): 39-50
4. Boyer, Bob. 1999. "Life Cycle Performance." Asphalt Magazine. Accessed November 12, 2012. http://www.asphaltmagazine.com/archives/1999/Summer/Life_Cycle_Performance.pdf.
5. Bull, A. L., and W. C. Vonk. 1984 "Thermoplastic rubber/bitumen blends for roof and road." *Shell Chemicals Technical Manual TR 8:15*
6. Canadian Strategic Highway Research Program (C-SHRP). 1995. Specification for SuperPave Binders. Canada
7. Chiu, Chui-Te. 2008 "Use of ground tire rubber in asphalt pavements: Field trial and evaluation in Taiwan." *Resources, Conservation and Recycling* 52 (3): 522-532
8. Corbett, L.W. 1970 "Relationship between Composition and Physical Properties of Asphalt." *Proc.,Association of Asphalt Paving Technologists* 39: 481-491.
9. Dwyer, James, and Matt Betts. 2011 "Polymer-modified asphalt: Improving our nation's infrastructure" Accessed June 16, 2013. http://www.pitt.edu/~meb137/paper.html
10. FHWA and EPA., 1993, A study of the use of recycled paving materials – report to Congress. June 1993. Report FHWA-RD-93-147, EPA/600/R-93/095, Transportation Research Board, Washington, DC.
11. Kennedy, Thomas William., Huber, Gerald A., Harrigan, Edward T., Cominsky, Ronald J., Hughes, Charles S., Quintus, Harold Von., and James S. Moulthrop. 1994. Superior performing asphalt pavements (Superpave): The product of the SHRP asphalt research program. No. SHRP-A-410. Strategic Highway Research Program, National Academy of Sciences.
12. Hamed, Farag KM. 2010 "Evaluation of Fatigue Resistance for Modified Asphalt Concrete Mixtures Based on Dissipated Energy Concept." PhD diss., TU Darmstadt.
13. Lake Asphalt of Trinidad and Tobago (1978) Ltd. 2009, TLA Material Safety Data Sheet.
14. Lesueur, D. 2009. "The colloidal structure of bitumen: consequences on the rheology and on the mechanisms of bitumen modification," *Advances in Colloid and Interface Science* 145 (1-2): 42-82.
15. Maharaj, Rean. 2009 "A Comparison of the Composition and Rheology of Trinidad Lake Asphalt and Trinidad Petroleum Bitumen." *International Journal of Applied Chemistry* 5 (2009): 169-179
16. Mezger, Thomas G. 2006. *The rheology handbook*: For users of rotational and oscillatory rheometers, Vincentz. 2nd edition.
17. Moghaddam, Taher Baghaee, Mohamed Rehan Karim, and Mahrez Abdelaziz. 2011 "A review on fatigue and rutting performance of asphalt mixes." *Scientific Research and Essays* 6 (4): 670-682.
18. Navarro, F.J., Partal, P., Martinez-Boza, F., and C. Gallegos, 2004, "Thermorheological behavior of ground-tire rubber-modified bitumens," *Fuels*, 83 (14-15), 2041-2049.
19. Oyekunle, L.O., 2007, "Influence of chemical composition on the physical characteristics of paving asphalts." *Petroleum Science and Technology* 25 (11): 1401-1414.
20. Putman, Bradley J., and Serji N. Amirkhanian. 2006. "Crumb rubber modification of binders: interaction and particle effects." In *Proceedings of the Asphalt Rubber 2006 Conference* vol. 3: 655-677.
21. Russell, S.,Maharaj, R., and A. St George. 2011. "End of Life Management of Scrap Tyres using Crumb Rubber Modified TLA." *International Journal of Applied Environmental Sciences* 6 (1): 91-102.
22. Schlet, Ed D. 1991. "Oregon and Washington Fish Hatcheries Lined with Asphalt." Accessed Nov 5th, 2012. http://www.asphaltinstitute.org/dotAsset/94d66c68-6f28-49a5-83c3-ab38173d9c45.pdf

23. SWMCOL (Solid Waste Management Company (1995) Ltd). 1995. "Report on Waste Qualification Exercise-Guanapo Landfill Site, Beetham Landfill Site, and Forres Park Landfill Site." Trinidad and Tobago.
24. Widyatmoko, I. and R. Elliott. 2008. "Characteristics of elastomeric and plastomeric binders in contact with natural asphalts." *Construction and Building Materials* 22: 239–249.
25. Yildirim, Yetkin. 2007. "Polymer modified asphalt binders." *Construction and Building Materials* 21(1): 66-72.