Available online at
https://jsst.uitm.edu.my/index.php/jsst

PENERBIT PRESS
UNIVERSITI TEKNOLOGI MARA

e-ISSN: 2785-924X

Journal of Smart Science and Technology 5(1) 2025, 55-63.

Journal of Smart Science and Technology

Volumetric and Performance-based Evaluation of Bituminous Blends

Lee Leon[1], Chris Maharaj[2], Lisa Ramoutar[3], Rean Maharaj[4*]

[1]Department of Civil and Environmental Engineering, The University of the West Indies, St. Augustine Campus, St. Augustine 330912, Trinidad and Tobago
[2]Department of Mechanical and Manufacturing Engineering, The University of West Indies, St. Augustine Campus, St Augustine 330912, Trinidad and Tobago
[3]Industrial Materials Unit-Civil, The Caribbean Industrial Research Institute (CARIRI), The University of the West Indies, St. Augustine Campus, St. Augustine 330912, Trinidad and Tobago
[4]Process Engineering Unit, The University of Trinidad and Tobago, Esperanza Road, Point Lisas 540517, Trinidad and Tobago

Citation:
Leon, L., Maharaj, C., Ramoutar, L., & Maharaj, R. (2025). Volumetric and performance-based evaluation of bituminous blends. *Journal of Smart Science and Technology*, *5*(1), 55-63.

ARTICLE INFO

Article history:
Received 30 June 2024
Revised 11 August 2024
Accepted 13 October 2024
Published 31 March 2025

Keywords:
asphalt
Marshall Stability
paved roads
crumb rubber
aggregate

DOI:
10.24191/jsst.v5i1.83

ABSTRACT

Crumb rubber (CR) and styrene-butadiene-styrene (SBS) from discarded tires and other waste materials were used as additives/replacements in asphalt mixtures. The researchers conducted Marshall and performance-based crumb rubber-modified asphalt (CRMA) testing. The dry process was employed, where CR was added to the aggregate before adding the binder. A control of 0% CR was compared to 1% CR by aggregate weight. Mix design formulations were acceptable for 5.6% and 6.3% binder contents, respectively. Marshall test results were acceptable for both formulations. For performance-based testing, the tensile strength ratio was acceptable for both formulations. However, for permanent deformation strain, the 1% CRMA was slightly higher (5.1%) than the upper acceptable range limit (4.5%), whereas the 0% CRMA control was within the acceptable range. Further investigation into the pre-treatment of CR to facilitate swelling and the phase interlocking to decrease the required binder in the mix design and increase CR addition is warranted. This study demonstrated the potential of reusing CR in road paving applications, providing an innovative, sustainable disposal option.

1 INTRODUCTION

The exponential expansion of contemporary society has propelled the automobile sector towards accelerated development, thereby giving rise to significant environmental concerns. The dispersal of waste tires is a significant concern, with an approximate annual disposal of one billion tires[1]. In addition to depleting land resources, the dispersal of used tires polluted the air and soil[2]. One potentially effective approach to mitigate the issue is the utilization of used tires as an asphalt modifier. Numerous studies have demonstrated that it enhances the flexibility, resistance to ageing, and anti-cracking characteristics of virgin bitumen[3,4]. However, industrial applications of ground tire rubber (GTR) modified asphalt (GTRMA) were not without their limitations. This is due to the unfavourable odour emitted during devulcanization and thermal decomposition of GTR, as well as its poor storage stability and processability[5,6].

In Trinidad and Tobago (TT), policies such as the National Environment Policy[7] and the National Waste Recycling Policy[8] encourage the recovery of waste materials for recycling, reuse or reclamation purposes, and the process of producing energy from waste. Consequentially, there has been renewed scientific interest in the area, as

[4*] Corresponding author. *E-mail address*: rean.maharaj@utt.edu.tt
https://doi.org/10.24191/jsst.v5i1.83

evidenced by numerous studies investigating the reuse of waste materials, especially in asphalt for road paving applications[9–15].

Additionally, TT has ratified the Basel Convention Regional Centre for Training and Technology for the Caribbean Region (BCRC-Caribbean), which views recycling and waste as resources, and the recycling and reuse of waste materials as mitigation options to reduce environmental impacts and stimulate economic development, innovative employment opportunities, and small business entrepreneurs[16].

Crumb rubber (CR) and styrene-butadiene-styrene (SBS) have been used as raw materials for additives or replacements in asphalt mixtures[17]. Both CR and SBS are obtained from discarded tires and other products. CR was found to be beneficial in asphalt where it swells and forms cross-linkages with the molecules in the asphalt binder. It forms a homogeneous system when it is evenly distributed in the binder[18]. Pre-treatment of the CR (using a matrix asphalt in pre-blending process, for example) to facilitate swelling before binder addition is favourable as swelling reinvigorates the elastomeric properties of the CR particles[19] and facilitates a more continuous and interlocked phase[20].

CR can be added to the asphalt formulation via the wet, dry process, and terminal blend process. The wet process involves blending the CR with the binder (with or without the inclusion of additives such as aromatic oils to reduce the viscosity and improve workability) first. The dry process involves adding the CR directly to the heated aggregate first. In the terminal blend process, the CR particles are included in the asphalt binder and blended at the asphalt refinery[21].

A crumb rubber modified asphalt (CRMA) mix was tested for fatigue and permanent deformation characteristics. 80/100 penetration grade asphalt is heated to 160 °C before the CR was added in this wet process. The #30 ASTM International[22] sieved CR containing 10% CR by weight of binder yielded the highest Marshall stability value. Marshall flow values increased marginally with increasing CR content[23].

The dry process can have greater advantages, including more CR usage; there is less desire to use it compared to the wet process because of its poorer performance. Similarly, the sized aggregate of limestone powder was replaced with 20, 40, and 60% CR powder by weight, and the mechanical properties of modified mixes, including moisture susceptibility, stiffness modulus, rutting performance, and fatigue life were evaluated. The results indicated that simultaneously applying the curing process and very fine CR in the asphalt mix considerably enhanced the resistance of asphalt mixes against failures. In addition, the performance of mixes with high contents of CR powder was weakened, which could be improved by a curing process (after the binder was added to the aggregates containing CR powder and mixed at 165 ºC, the mixture was kept in the oven at 165 ºC for up to 2 hours)[24].

The use of these percentages was guided by many previous studies, which indicated that the optimum use of crumb rubber using the dry process fell within ranges of 1.5–2%[25–27].

Previous work by Wulandari[28] using crumb rubber for replacing fine aggregate in cold mixture asphalt found that crumb rubber can be added to the asphaltic material as a replacement material for fine aggregates. The study showed that using crumb rubber replacement, the asphalt-crumb rubber blend had a stability that met the standard specification with finer particular sizes producing blends with higher stability.

A study by Lashari[29] analysed the skid resistance performance of asphaltic surfaces where aggregate was replaced with crumb rubber at various percentages. British pendulum testing was conducted to measure the skid resistance in dry and wet conditions along with compressive strength, tensile strength, and slump testing. The study demonstrated that skid resistance was significantly improved when crumb rubber was added, but the strength performance of the asphaltic blends decreased.

Setyawan[30] used crumb rubber as a fine aggregate substitute in the asphaltic blends using 60/70 penetration grade bitumen. Properties such as volumetric characteristics, Marshall characteristics, resistance to abrasion and impact and permeability were conducted. Replacement of fine aggregate with crumb rubber resulted in lower Marshall Stability, higher flow rate, and a lower Marshall quotient. The blend exhibited a lower density and specific gravity values due to lower porosity and air voids, resulting in the low porosity or air voids.

Replacement of fine aggregate with crumb in asphaltic mixtures has shown promising results as an option for improving the quality of pavement as well as providing a sustainable reuse option for treatment of waste materials such as tires.

The properties and performance of CRMA are highly dependent on the source/nature of binder and aggregates[10,11] and thus optimal concentrations of CR in CRMA will vary from region to region. This study focuses on the Trinidad and Tobago (TT) region. Using a wet process, a 93% aggregate and 7% binder formulation (of which 75% was Trinidad Petroleum Bitumen (TPB) 60/70 penetration and 25% Trinidad Lake Asphalt (TLA)) was investigated with increasing amounts of CR in the binder (up to 5% of the modified binder weight). The optimum CRMA formulation was found to contain 5.0% CR that had higher weathering resistance and compressive strengths than the unmodified sample[31].

https://doi.org/10.24191/jsst.v5i1.83

Following the aforementioned study, TPB is not presently a source of bitumen for asphaltic pavements based on refinery closure. This necessitated an updated study that would contain the revised source of bitumen for analysis. Also, in addition to the volumetric and mechanical evaluation, performance-based testing would also be employed as a means of better representing in-situ performance. The objectives of the study are:

i) Preparation and characterisation (particle size, moisture content, degree of contamination) of CR to be used in the study from end-of-life tires.

ii) The blending of materials for the three (3) mix designs, (CR at 0%, 1%, and 3%), together with crushed limestone and limestone dust aggregates to determine the optimal binder content (OBC).

iii) Measurement of the volumetric characteristics, stability, and flow of all blends produced using the Marshall method and characterisation of rutting, cracking, and moisture susceptibility of the asphalt mixtures.

2 MATERIALS AND METHODS

2.1 Materials

Limestone aggregate was used in this study to produce asphalt mixtures. The physical and mechanical properties of these aggregates are listed in Table 1. The research was guided by local application and specifications for the densely graded mixture used in the research. Locally, the filler material in mix design requirements of bituminous surface dense graded mixes is not mandatory. However, the requirement of filler is in the design of Stone Matrix Asphalt (gap graded) mixtures used locally. The TLA 60/75 binder was obtained from Trinidad Lake Asphalt. The untreated CR obtained in the study was derived from end-of-life tires through granulation and cleaning to a size range from 0.6 mm to 2.5 mm. Moisture content was less than 1% using a KERN DBS 60-3 moisture analyser. Metal, textile, and other contaminants were less than 0.02%, 0.05%, and 0.05%, respectively[31].

Table 1. Characterization of the aggregate and 60-75 TLA binder

Property	19 mm Limestone	12.5 mm Limestone	9.5 mm Limestone	Limestone Dust	Crumb Rubber	Binder
Los Angeles Abrasion (%)	29	32	31	-	-	-
Water absorption (%)	0.737	0.862	1.287	0.261	-	-
Specific gravity (g cm^{-3})	2.685	2.674	2.637	2.642	1.027	1.022
Penetration at 25 °C, dmm	-	-	-	-	-	72
Softening Point, °C	-	-	-	-	-	51

2.2 Mix design and sample preparation

The blending of materials for the three (3) mix designs, incorporated CR at 0%, 1%, and 3%, together with crushed limestone and limestone dust aggregates, as indicated in Fig. 1. The HMA design was carried out using the Marshall Mix design technique to determine the optimal binder content (OBC) for three different HMA mix types with various CR percentages. The different mix types (HMA-CR0, HMA-CR1, HMA-CR3) were distinguished based on the hot mix asphalt concrete (HMA) and the percentage of CR (0, 1, 3). The mix design with 0% CR formulation was applied as the control for the study.

The volumetric characteristics, stability, and flow of all mixtures produced using the Marshall method were assessed using the guidelines outlined in ASTMD 6926 and the Asphalt Institute Manual (MS-2). The mix to be created for performance testing was selected based on the stated volumetric qualities at the optimal binder content. Performance-based testing is more expensive to undertake compared to Marshall testing. The samples for these experiments were created in a gyratory compactor to achieve consistent air void ratio. The performance tests utilised in the investigation to assess rutting, cracking, and moisture susceptibility of the asphalt mixtures were as follows.

i) Indirect Tensile Strength (ITS) – BS EN 12697-23

ii) Repeated Load Axial Cyclic Test (RLAT) – BS EN 12697-25

iii) Indirect Tensile Stiffness Modulus (ITSM) – BS EN 12697-26

https://doi.org/10.24191/jsst.v5i1.83

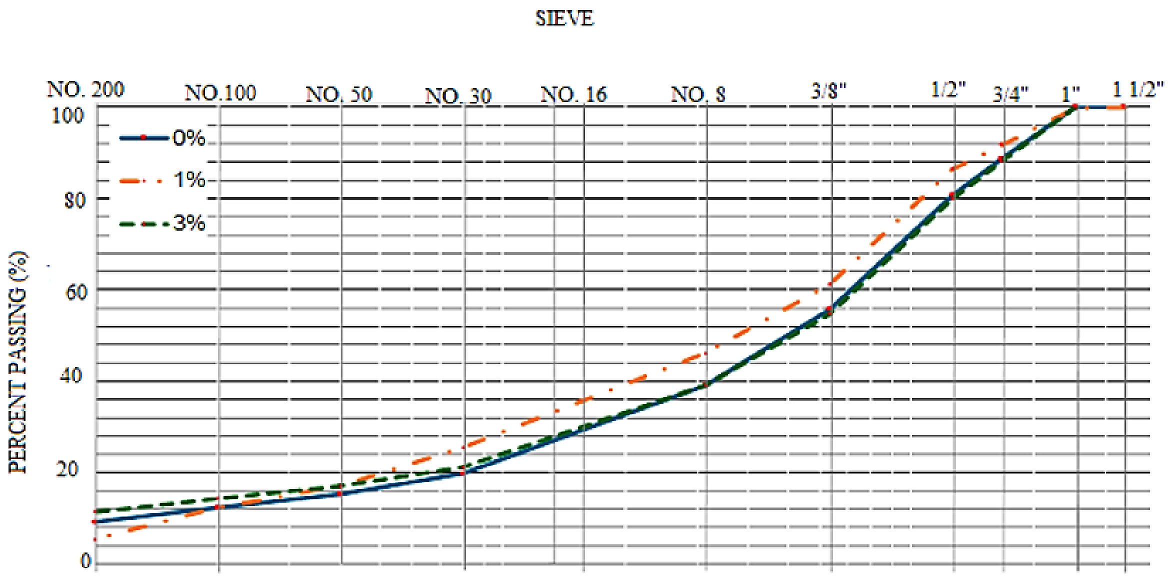

Fig. 1. Wearing course gradation curve for study mixes with varying CR formulation.

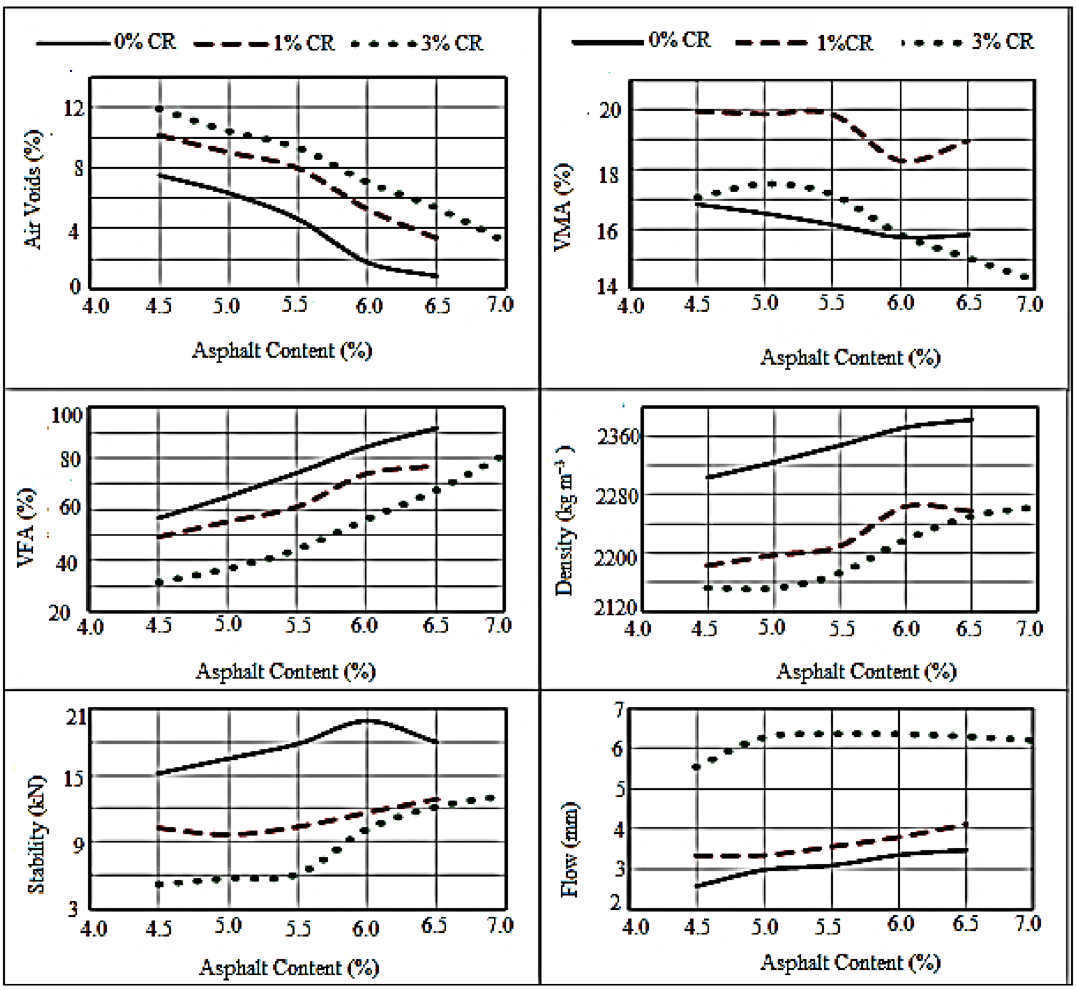

Fig. 2. Marshall Mix design results for various CR content formulation.

https://doi.org/10.24191/jsst.v5i1.83

3 RESULTS AND DISCUSSION

3.1 Volumetric Properties

Fig. 2 illustrates the effect of CR on the density values of HMA. The dense graded asphalt concrete mixtures using 100% virgin aggregates were the densest, with density values ranging between 2,304 and 2,382 kg m^{-3}. The study revealed that as the concentration of CR increased, the density declined linearly due to the lower specific gravity and density of CR compared to natural limestone, as shown in Fig. 3. Test results showed a significant correlation between the increase in CR and the corresponding increase in VMA. HMA specimens containing 1% CR recorded the largest voids in mineral aggregates (VMA) of 18.6% at the air voids content ratio of 4%. However, for the same voids content the 3% CR mixtures had the largest voids filled with asphalt (VFA) of 77%. The VFA readings exhibited an increasing trend. The results also indicated that with the increase in the untreated CR there was a significant increase in the binder content required to obtain an acceptable air voids ratio between 3–5%. This was due to the absorption properties of the CR. A crumb rubber material that was treated should aid in the reduction of the additional increase in binder content.

Fig. 2 and Fig. 3 illustrate the Marshall stability and flow properties of HMA mixtures with different CR concentrations. These parameters are displayed in the illustrations. The flow of the specimens at the optimal binder content (OBC) was lower during the initial point of 0%, and it exceeded the permitted limits when the CR content reached 3%. This occurred as a result of the increased binder content that was necessary in order to accomplish a desired air voids ratio of 4%. Fig. 3 illustrates the rise in the optimal binder content (OBC) of the mix types, which went from 5.6% to 6.8%. The results of the tests indicated that there was a maximum stability of 18.2 kN, and that this stability decreased to 12.9 kN when the CR content was 3%. The selection of the mixes must still be based on satisfying all other volumetric requirements, even though all the mixes exceeded the limit of stability, that is greater than 8 kN. CR may not bind as effectively to the asphalt binder as traditional mineral aggregates do. The weaker bond between the CR and the binder can reduce the overall cohesion of the mixture, leading to issues like premature degradation. CR can increase the oxidation rate in asphalt mixtures, leading to premature ageing of the binder. This accelerated ageing can cause the asphalt to become brittle, thus increasing the risk of cracking and reducing its strength.

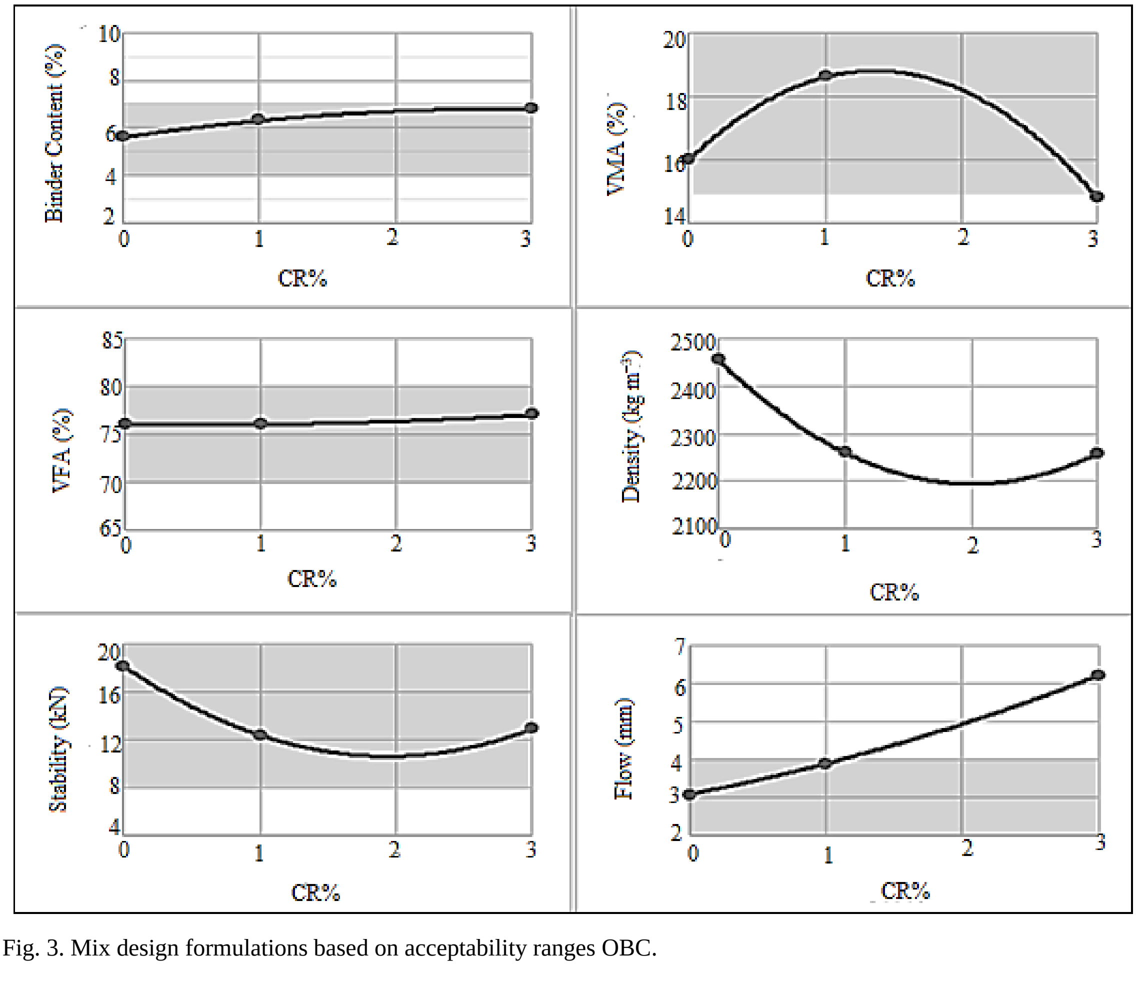

Fig. 3. Mix design formulations based on acceptability ranges OBC.

https://doi.org/10.24191/jsst.v5i1.83

3.2 Performance Properties

Fig. 4 reflects the Indirect Tensile Stiffness Modulus (ITSM) of the HMA mixtures that contain CR. The test was conducted at 25 ºC. A reduction of approximately 40% in the resilient modulus was seen in the mixtures that contained a 3% addition of CR in comparison with the typical mixture. A correlation can be established between the decrease in the modulus and the increase in binder concentration, resulting in a high flow value, which in turn leads to low stability and lower stiffness on the part of the material.

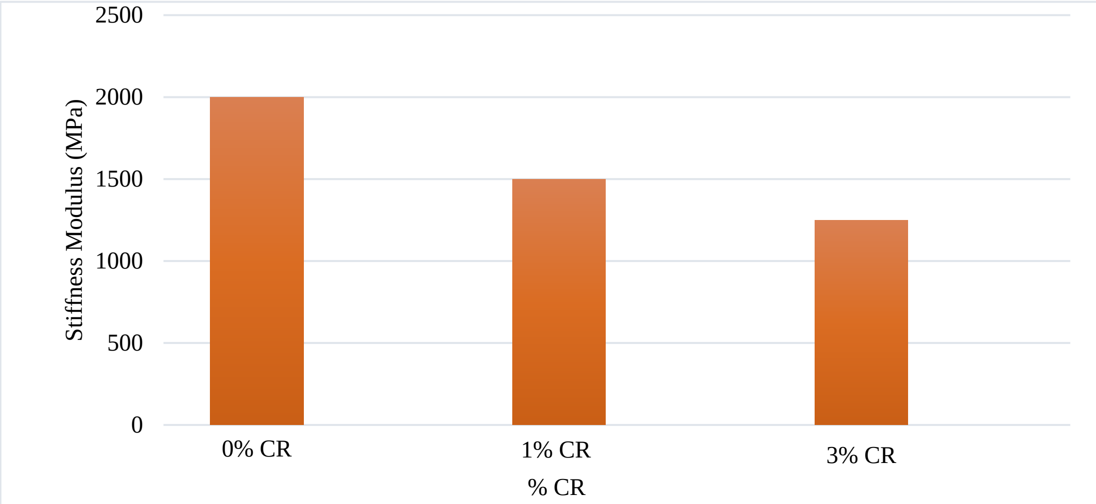

Fig. 4. Stiffness modulus (MPa) at 250 °C.

The indirect tensile strength (ITS) of the sample decreased for the dry values as the amount of untreated CR increased. This observation was made for the dry values. Dry samples reached a maximum strength of 736 kPa, while wet samples reached a maximum strength of 657 kPa. In addition, when the moisture susceptibility of the combination was evaluated by employing the tensile strength ratio (TSR), results that were more than the acceptable local range of 0.7 were observed (see Fig. 5). After being subjected to water, the HMA-CR3 mixtures showed an increase in strength, which is indicative of a high level of resistance to moisture susceptibility.

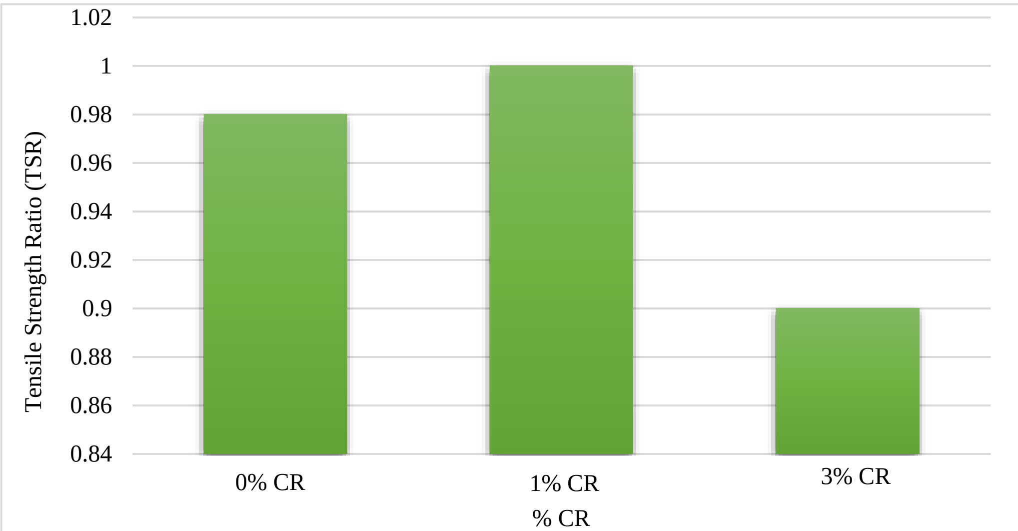

Fig. 5. Tensile strength ratio.

When subjected to repeated loading at 60 °C, RLAT results (Fig. 6) showed that mixes with untreated CR increased the percentage of axial permanent deformation strain. Based on the results, the samples with 0% CR had a strain value of 2.5%, but the samples with 1% and 3% CR revealed strain levels of approximately 5%. The gradual development of ruts results from a combination of densification and shear deformation, which takes place as the number of load applications increases[32]. The findings revealed that incorporating untreated CR blend into the aggregate mix did not improve the strength of the pavement's resistance to rutting. It is possible that the presence of a substantial amount of binder in the mixtures could have caused this behaviour. It would be beneficial to treat the CR before putting it into

https://doi.org/10.24191/jsst.v5i1.83

mixtures because this would help reduce the amount of binder that is present, which could ultimately increase the asphalt mixtures' resistance.

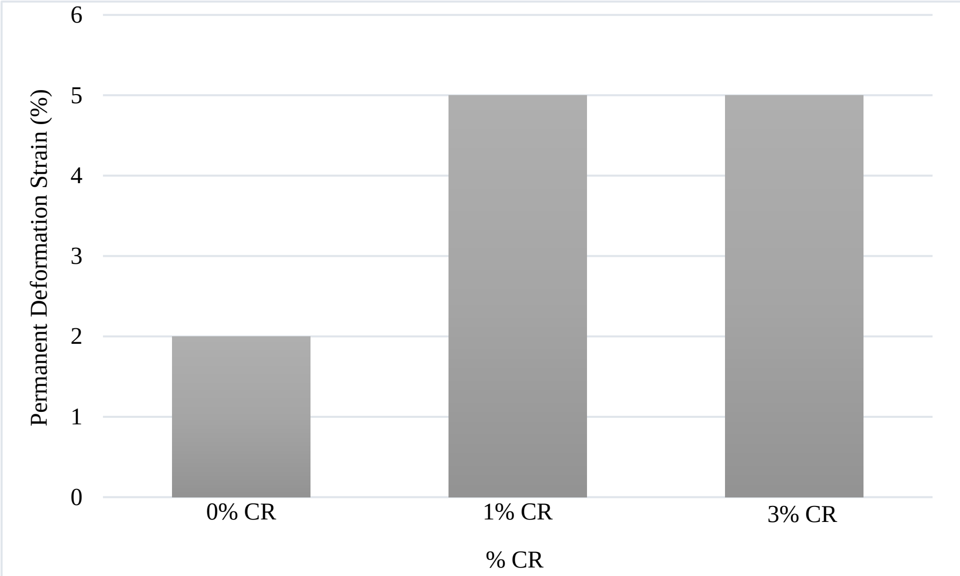

Fig. 6. Permanent deformation strain at 60 °C and 3,600 seconds.

Pre-treatment strategies currently being explored include:

i) Pre-treating the CR with waste oil in a sustainable manner reduces the absorption rate of the binder.

ii) Microwave pre-treatment which has the potential to alter the surface properties of the crumb rubber by increasing surface roughness and promoting chemical bonding. This enhanced interaction between the rubber and the asphalt binder leads to better cohesion within the mixture, reducing issues like ravelling, where the rubber particles might otherwise become dislodged from the binder.

iii) Pre-treating crumb rubber with waste oil softens the rubber particles, preserving and enhancing its elasticity. The waste oil acts as a plasticiser, improving the viscoelastic properties of the mixture. This results in better performance in resisting fatigue cracking and deformation (rutting).

4 CONCLUSIONS

Marshall and performance-based testing of CRMA were conducted using the dry process, where CR was added to the aggregate before the binder. A control of 0% CR was compared to 1% CR by aggregate weight. Mix design formulations were acceptable for 5.6% and 6.3% binder contents, respectively. Marshall test results were acceptable for both formulations. For performance-based testing, the tensile strength ratio was acceptable for both formulations. However, for permanent deformation strain, the 1% CRMA was slightly higher (5.1%) than the upper acceptable range limit (4.5%), whereas the 0% CRMA control was within the acceptable range. The study demonstrated the potential of reusing CR in road paving applications, providing an innovative, sustainable disposal option. Further investigation into the pre-treatment of the CR to facilitate swelling and phase interlocking is warranted.

ACKNOWLEDGEMENTS/ FUNDING

The authors would like to acknowledge the support of The Caribbean Industrial Research Institute (CARIRI) for carrying out this study.

CONFLICT OF INTEREST

The authors declare that there was no conflict of interest.

AUTHORS’ CONTRIBUTIONS

Conceptualisation: L. Ramoutar & L. Leon
Data curation: L. Leon

https://doi.org/10.24191/jsst.v5i1.83

Methodology: L. Ramoutar & L. Leon
Formal analysis: L. Leon, R. Maharaj & C. Maharaj
Visualisation: L. Leon
Software: Not applicable
Writing (original draft): R. Maharaj, L. Leon & C. Maharaj
Writing (review and editing): R. Maharaj
Validation: L. Leon
Supervision: L. Leon
Funding acquisition: Not applicable
Project administration: L. Ramoutar

REFERENCES

1. Thomas, B. S., & Gupta, R. C. (2016). A comprehensive review on the applications of waste tire rubber in cement concrete. *Renewable and Sustainable Energy Reviews*, *54*, 1323–1333. https://doi.org/10.1016/j.rser.2015.10.092

2. Miranda, M., Pinto, F., Gulyurtlu, I., & Cabrita, I. (2013). Pyrolysis of rubber tyre wastes: A kinetic study. *Fuel*, *103*, 542–552. https://doi.org/10.1016/j.fuel.2012.06.114

3. Wang, Q., Li, S., Wu, X., Wang, S., & Ouyang, C. (2016). Weather aging resistance of different rubber modified asphalts. *Construction and Building Materials*, *106*, 443–448. https://doi.org/10.1016/j.conbuildmat.2015.12.138

4. Zhang, H., & Gong, M. (2018). Study on durability of composite-modified asphalt mixture based on inherent and improved performance. *Construction and Building Materials*, *179*, 539–552. https://doi.org/10.1016/j.conbuildmat.2018.05.260

5. Sienkiewicz, M., Borzędowska-Labuda, K., Wojtkiewicz, A., & Janik, H. (2017). Development of methods improving storage stability of bitumen modified with ground tire rubber: A review. *Fuel Processing Technology*, *159*, 272–279. https://doi.org/10.1016/j.fuproc.2017.01.049

6. González, V., Martínez-Boza, F. J., Navarro, F. J., Gallegos, C., Pérez-Lepe, A., & Páez, A. (2010). Thermomechanical properties of bitumen modified with crumb tire rubber and polymeric additives. *Fuel Processing Technology*, *91*(9), 1033–1039. https://doi.org/10.1016/j.fuproc.2010.03.009

7. Government of the Republic of Trinidad and Tobago. (2018). *National environmental policy (NEP) T&T 2018*. https://www.planning.gov.tt/sites/default/files/National%20Environmental%20Policy%20%28NEP%29%20T%26 T%202018.pdf

8. Government of the Republic of Trinidad and Tobago. (2015). *National waste recycling policy*. https://www.planning.gov.tt/sites/default/files/WASTE%20RECYCLING%20POLICY%202015%20Final.pdf

9. Maharaj, R., St. George, A., Russell, S., & Singh, D. (2009). The influence of recycled tyre rubber on the rheological properties of Trinidad Lake asphalt and Trinidad petroleum bitumen. *International Journal of Applied Chemistry*, *5*(3), 181–191. https://www.researchgate.net/publication/256001908_The_Influence_of_Recycled_Tyre_Rubber_on_the_Rheological_Properties_of_Trinidad_Lake_Asphalt_and_Refinery_Bitumen_6070

10. Maharaj, R., Ramjattan-Harry, V., & Mohamed, N. (2015). Rutting and fatigue cracking resistance of waste cooking oil modified Trinidad asphaltic materials. *The Scientific World Journal*, *2015*(1), 385013. https://doi.org/10.1155/2015/385013

11. Mohamed, N., Ramjattan-Harry, V., & Maharaj, R. (2016). Mechanistic enhancement of asphaltic materials using fly ash. *Journal of Applied Sciences*, *16*(11), 526–533. https://doi.org/10.3923/jas.2016.526.533

12. Mohamed, N., Ramlochan, D., & Maharaj, R. (2017). Rutting and fatigue cracking susceptibility of polystyrene modified asphalt. *American Journal of Applied Sciences*, *14*(5), 583–591. https://doi.org/10.3844/ajassp.2017.583.591

13. Singh Ackbarali, D. & Maharaj, R., (2011). The viscoelastic properties of Trinidad Lake asphalt-used engine oil blends. *International Journal of Applied Chemistry*, *7*(1), 1–8. https://www.researchgate.net/publication/256002543

14. Maharaj, R., Balgobin, A., & Singh-Ackbarali, D. (2009). The influence of polyethylene on the rheological properties of Trinidad lake asphalt and Trinidad petroleum bitumen. *Asian Journal of Materials Science*, *1*(2), 36–44. https://doi.org/10.3923/ajmskr.2009.36.44

15. Maharaj, C., White, D., Maharaj, R., & Morin, C. (2017). Re-use of steel slag as an aggregate to asphaltic road pavement surface. *Cogent Engineering*, *4*(1), 1416889. https://doi.org/10.1080/23311916.2017.1416889

16. Rambarran, S., Maharaj, R., Mohammed, S., & Sangster, N. (2022). The utilization of waste toner as a modifier in Trinidad asphalts. *Recycling*, *7*(5), 74. https://doi.org/10.3390/recycling7050074

17. Li, H., Cui, C., Temitope, A. A., Feng, Z., Zhao, G., & Guo, P. (2022). Effect of SBS and crumb rubber on asphalt modification: A review of the properties and practical application. *Journal of Traffic and Transportation Engineering (English Edition)*, *9*(5), 836–863. https://doi.org/10.1016/j.jtte.2022.03.002

18. Zheng, W., Wang, H., Chen, Y., Ji, J., You, Z., & Zhang, Y. (2021). A review on compatibility between crumb rubber and asphalt binder. *Construction and Building Materials*, *297*, 123820. https://doi.org/10.1016/j.conbuildmat.2021.123820

19. Xiang, L., Cheng, J., & Que, G. (2009). Microstructure and performance of crumb rubber modified asphalt. *Construction and Building Materials*, *23*(12), 3586–3590. https://doi.org/10.1016/j.conbuildmat.2009.06.038

20. Cong, P., Xun, P., Xing, M., & Chen, S. (2013). Investigation of asphalt binder containing various crumb rubbers and asphalts. *Construction and Building Materials*, *40*, 632–641. *https://doi.org/10.1016/j.conbuildmat.2012.11.063*

21. Picado-Santos, L. G., Capitão, S. D., & Neves, J. M. C. (2020). Crumb rubber asphalt mixtures: A literature review. *Construction and Building Materials*, *247*, 118577. https://doi.org/10.1016/j.conbuildmat.2020.118577

22. ASTM. (2022). Standard specification for woven wire test sieve cloth and test sieves. E11. https://www.astm.org/e0011-22.html

23. Palit, S. K., Reddy, K. S., & Pandey, B. B. (2004). Laboratory evaluation of crumb rubber modified asphalt mixes. *Journal of Materials in Civil Engineering*, *16*(1), 45–53. https://doi.org/10.1061/(ASCE)0899-1561(2004)16:1(45)

24. Tahami, S. A., Mirhosseini, A. F., Dessouky, S., Mork, H., & Kavussi, A. (2019). The use of high content of fine crumb rubber in asphalt mixes using dry process. *Construction and Building Materials*, *222*, 643–653. https://doi.org/10.1016/j.conbuildmat.2019.06.180

25. Nguyen, H. T. T., & Tran, T. N. (2018). Effects of crumb rubber content and curing time on the properties of asphalt concrete and stone mastic asphalt using dry process. *International Journal of Pavement Research and Technology*, *11*(3), 236–244. https://doi.org/10.1016/j.ijprt.2017.09.014

26. Rodríguez-Fernández, I., Baheri, F. T., Cavalli, M. C., Poulikakos, L. D., & Bueno, M. (2020). Microstructure analysis and mechanical performance of crumb rubber modified asphalt concrete using the dry process. *Construction and Building Materials*, *259*, 119662. https://doi.org/10.1016/j.conbuildmat.2020.119662

27. Wulandari, P. S., & Tjandra, D. (2017). Use of crumb rubber as an additive in asphalt concrete mixture. *Procedia Engineering*, *171*, 1384–1389. https://doi.org/10.1016/j.proeng.2017.01.451

28. Wulandari, P. S., & Tjandra, D. (2019). The use of crumb rubber for replacing fine aggregate in cold mixture asphalt. In *IOP Conference Series: Materials Science and Engineering*, *615*, 012119. https://doi.org/10.1088/1757-899x/615/1/012119

29. Lashari, A. R., Ali, Y., Buller, A. S., & Memon, N. A. (2022). Effects of partial replacement of fine aggregates with crumb rubber on skid resistance and mechanical properties of cement concrete pavements. *International Journal of Pavement Engineering*, *24*(2), 2077940. https://doi.org/10.1080/10298436.2022.2077940

30. Setyawan, A., Nugroho, S. K., Irsyad, A. M., Mutaqo, H. F., Ramadhan, P., Sumarsono, A., & Pramesti, F. P. (2018). The use of crumb rubber as substitute of fine aggregate for hot asphalt mixture using polymer modified bitumen. *IOP Conference Series Materials Science and Engineering*, *333*, 012093. https://doi.org/10.1088/1757-899x/333/1/012093

31. European Committee for Standardization (CEN). (2010). *CEN/TS 14243:2010 Materials produced from end of life tyres - Specification of categories based on their dimension(s) and impurities and methods for determining their dimension(s) and impurities*. https://standards.iteh.ai/catalog/standards/cen/713de38b-eb7a-4a4e-b1b1-fdf10f56a5f8/cen-ts-14243-2010?srsltid=AfmBOorMo43eF9xN2dahE4jea_wXVlFZ6EGph0SW_yR7S24fn2_TjBSF

32. Sousa, J. B., Craus, J., & Monismith, C. L. (1991). *Summary report on permanent deformation in asphalt concrete*. Strategic Highway Research Program. https://onlinepubs.trb.org/onlinepubs/shrp/SHRP-A-318.pdf

https://doi.org/10.24191/jsst.v5i1.83