INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 17 No. 3 (2025) 49-58
https://publisher.uthm.edu.my/ojs/index.php/ijie

Tensile Strength of Warm Rubberised Asphalt Mixtures Produced Using Dry Method

Rosnawati Buhari[1]*, Muhammad Syahmi Mustafa[2], Syamir Iman Ibrahim[1], Nur Najwa Raisuddin[1]

[1] *Faculty of Civil Engineering and Built Environment,*
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA
[2] *Pamir Development Sdn Bhd, 81200 Johor Bahru, Johor, MALAYSIA*

*Corresponding Author: rosna@uthm.edu.my
DOI: https://doi.org/10.30880/ijie.2025.17.03.006

Article Info

Received: 21 January 2025
Accepted: 24 June 2025
Available online: 29 August 2025

Keywords

Warm mix rubberised asphalt, indirect tensile strength, resilient modulus of asphalt concrete, dry process

Abstract

Recycling crumb rubber in the asphalt industry is an excellent way to reduce the wastage of this byproduct. It has been demonstrated that crumb rubber obtained from used tyres can be used as an addition or replacement material to enhance the characteristics of asphalt mixtures. Considering the importance of expanding a technology for a greener future, producing a crumb rubber warm asphalt mixture (CRWMA) is the aim of this study. This study focuses on investigating the resilient modulus and moisture susceptibility of the asphalt mixtures. The AC14 samples were prepared by replacing 2% to 4% of the net weight of aggregate with crumb rubber, and 3% Sasobit from the total weight of the optimum binder content was used to modify the base binder. The JKR specification and Marshall mix design were used to obtain the optimum binder content of the samples. The effect of crumb rubber proportion in asphalt mixture was determined by observing the mixture's volumetric properties, resilient modulus and moisture susceptibility. The results show that asphalt mixture incorporated with crumb rubber had a greater resilient modulus and indirect tensile strength, even though it was produced at 20°C lower than hot mix asphalt, compared to a conventional asphalt mixture. It indicates that crumb rubber has improved the elasticity of the samples. In conclusion, a combination of 3% crumb rubber and 3.0% Sasobit is the optimum composition for producing a better performance of warm rubberised asphalt mixture compared to a conventional asphalt mixture.

1. Introduction

Long-term asphalt pavement sustainability requires techniques that extend the materials' on-service life and reduce life cycle cost. One of the techniques is the use of waste rubber, which is considered a major environmental pollutant [1]. As an alternative, crumb rubber modified asphalt mixture (CRMA) has been applied in pavement construction for the past 50 years. Besides, the paving industry and the academic research community are paying more attention to crumb rubber (CR) when they realised it helped lessen the environmental impact of discarded tyres [2]. It could be used to enhance road surface condition by improving the skid resistance and hence improving road safety. Aside from that, the CRMA is expected to have a longer lifespan due to the reduced rate of accumulated permanent deformation [3].

Generally, dry and wet processes are both used to add CR into asphalt mixtures. As such, the finer CR is mixed with binder at high temperatures to form a modified binder in the wet process [4], [5]. Crumb rubber and aggregates were mixed before being added to the binder in the dry process. Comparing both methods, the wet process involves a long duration (60 – 180 minutes), is harmful to the environment and expensive due to the high temperature incorporation process of CR in binders [6]. Besides, the dry process that incorporating CR into asphalt is based on the idea of replacing a small portion of the aggregate with rubber to improve the elastic properties of the mixture. Rubber can withstand wheel loads and return to its original shape after loads are released, which can help improve the performance and durability of asphalt mixture [6]; enhance pavement's resistance to rutting, oxidation ageing, fatigue and low-temperature cracking [5], [8], [9]. Moreover, this method does not require special storage and transportation as the wet process, also incorporates 2 to 4 times more than the wet process [3]. Generally, 1% to 5% of rubber by the total weight of aggregate is used for the dry process, while for the wet process, the range is between 10% to 30% of rubber from the total weight of the binder.

Another rationale for using CR as a modification in asphalt is the interplay between the particles of rubber and the asphalt binder. This interaction is the main cause of the enhancement in performance and longevity achieved through the use of CR, both in wet and dry production methods [10]. Although previous studies have revealed that the cost of CRMA mixture is significantly higher than that of conventional asphalt mixture. Some estimates indicate that it can be 20% to 30% more expensive, and there was a study estimating twice as expensive [2]. The cost increase is believed to be due to factors such as the asphalt plant, the modification of the asphalt binder, and the use of higher manufacturing temperatures.

Alternately, many studies have described the combination of Warm mix asphalt (WMA) and CR as sustainable or even necessary [2], [3]. WMA is one of the solutions for achieving sustainable construction that could cut carbon footprint and pollution. In comparison to HMA, WMA provides numerous advantages, including lower costs, improved performance, and a healthier atmosphere [10]. However, as it is produced at low temperature is more prone to adhesion failure at the binder-aggregate interface. This is due to the presence of trapped moisture as a result of insufficient drying of aggregate [2]. Hence, moisture is one of the most important factors influencing the functionality of the WMA.

Therefore, this research focuses on producing the WMA for rubberised asphalt via examining the performance of Crumb Rubber Warm Mix Asphalt's (CRWMA) resilience modulus and moisture damage. The resilient modulus is chosen as it can evaluate the ability of mixtures to bounce back upon releasing the applied stresses. While moisture damage is a common pavement failure that occurs in Malaysia and has always been the most significant factor influencing the use and performance of asphalt pavements [2]. While producing the mixture, a dry process was conducted to get more volume of CR to be recycled, an easier process compared to the wet process, and does not require a modification of base asphalt binder with rubber, which can be a complex and time-consuming process.

2. Materials and Methods

Aggregate, asphalt, and CR are the materials used for HMA and rubberised asphalt mixture samples preparation in compliance with the requirements. The asphalt mixture AC14 was prepared, and Table 1 shows the classification of the aggregates and CR. The crumb rubber size is passing the sieve size 1.18 mm to the pan. Preparation of the specimens was according to the ASTM D 1559 and JKR specification [11].

Table 1 *Gradation of the aggregate and crumb rubber*

Sieve Size (mm)	Aggregate passing, (%) [Standard range]	CR Passing (%)
20	100	
14	95	
10	81	
5	56	
3.35	47	
1.18	26	100
0.425	18	5.3
0.15	10	1.9
0.075	6	0.3
Pan	0	-

The Marshall mix design was used as it can provide a good indication of the performance of the asphalt mixture under a variety of loading and environmental conditions. In addition, it is simple, relatively quick to perform and relatively inexpensive. The asphalt binder grade 60/70 was utilised as the base binder. While preparing CRWMA, CR was sieved and mixed with the aggregates using a dry process. For CRWMA, the modified binder was prepared by incorporating Sasobit in the base binder. The base binder was stirred with 3% Sasobit for 30 minutes at a temperature of 150 °C and a blending speed of 2000 rpm. Then, the modified asphalt binder was characterised using penetration, softening point and viscosity test by referring to the ASTM D5 [12], ASTM D36 [13] and ASTM D4402 [14], respectively. To determine the optimum bitumen content (OBC) based on the JKR specification for HMA, five different asphalt binder contents were prepared. The binder content is 4% to 6% interval of 0.5% for HMA and 6% to 8% interval of 0.5% for CRWMA. During sample preparation, aggregate, filler and asphalt binder were mixed for 2 minutes at a temperature of 165°C for HMA and 145°C for CRWMA. For compaction, the temperature is 155°C and 135°C for HMA and CRWMA, respectively. Fig. 1 shows the material, sample preparation and testing in the laboratory.

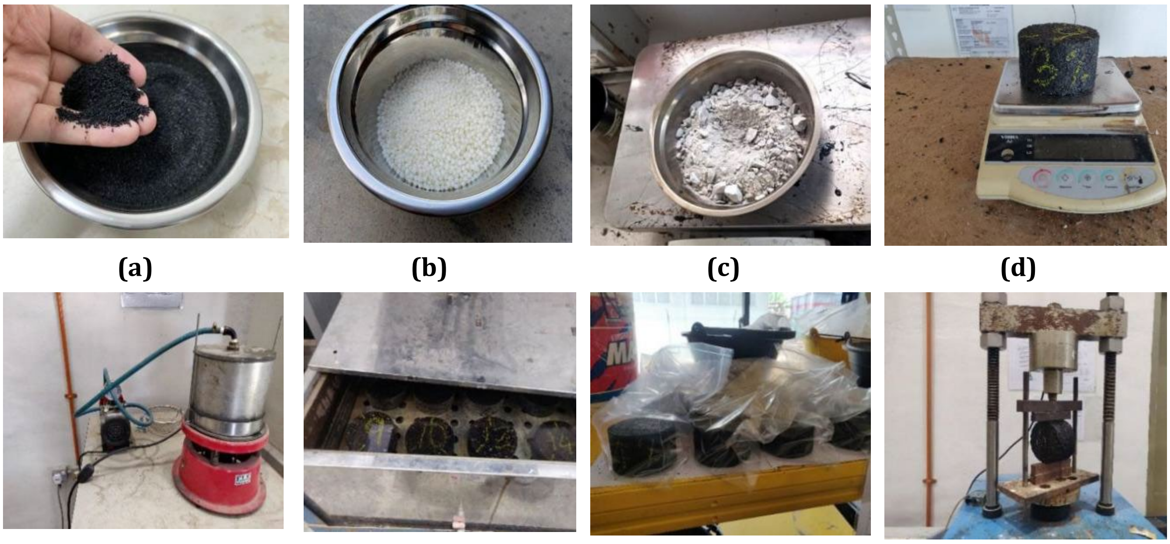
(a) (b) (c) (d)
(e) (f) (g) (h)

Fig. 1 *Materials, sample preparation and testing: (a) Crumb rubber particles; (b) Sasobit additive; (c) AC sample's aggregate; (d) AC sample's weighing procedure; (e) AC sample's water absorption procedure; (f) AC sample's soaking procedure; (g) AC sample's sealing procedure; and (h) Indirect tensile strength test procedure*

2.1 Indirect Tensile Resilient Modulus

The resilient modulus (M_R) of the asphalt mixtures was used to characterise the potential resistance of the mixture to fatigue and rutting damage. To determine the M_R of the mixtures, an Indirect Tensile Resilient Modulus test was conducted [15]. The test was conducted at temperatures of 25°C and 40°C. The sample was cured at a controlled temperature, and the temperature was raised until it reached the test temperature. As a recommendation, the sample should be returned to the temperature-controlled cabinet for an additional 10 minutes following the initial test. The sample is rotated by 90° for another test to be performed.

2.2 Modified Lottman Test

The Indirect Tensile Strength (ITS) of the asphalt mixtures were determined based on the Modified Lottman test (AASHTO T283) [16]. Moisture susceptibility was indicated by the Tensile Strength Ratio (TSR), which is expressed as the average tensile strength of the wet samples divided by the average tensile strength of the dry samples. It shows a reduction in the integrity of a mixture due to moisture damage. In accordance, while preparing samples, aggregate and the asphalt were mixed, after that the loose asphalt mixture was placed in a pan and cooled for 2 ± 0.5 hours at room temperature. Then, it was placed in a 60 ± 3°C oven for 16 ± 1 hour to cure and for a further 2 hours ± 10 minutes at a compaction temperature of ± 3°C before compaction. Most importantly, for this test, 100 mm-diameter asphalt mixture samples containing 7 ± 0.5% air void and each type of asphalt were prepared to allow water immersion into the samples. Two subsets of three asphalt mixture samples were produced for two different testing conditions: dry and wet. Once the above process was completed, the asphalt mixture samples were compiled as dry conditioned samples. As moisture-conditioned asphalt mixture samples must be partially saturated, within 70% to 80%, the asphalt mixture samples were submerged in water and vacuumed for 5 to 10 minutes at 13 to 67 kPa absolute pressures (10 - 26 in.Hg partial pressure). The samples were left submerged and removed after 5 - 10 minutes. Next, the samples are placed in a warm water bath at 60 ± 1°C for 24 ± 1 hour. Prior to testing, both dry and wet condition samples were placed in a heavy-duty plastic bag and soaked in a water bath at a temperature of 25 ± 0.5°C for 2 hours ± 10 minutes. The samples were soaked with their surface below the water level by at least 25 mm. Then, a test was conducted for dry and wet samples to determine the ITS. A minimum TSR of 80% is the failure criterion based on the standard.

3. Results and Discussion

The HMA was produced at a high temperature, while rubberised asphalt mixtures were produced at 20°C lower than that of the HMA. The average value for penetration of the asphalt binder modified with 3% Sasobit is 52 mm, softening point is 76.3 °C, and viscosity is 0.579 Pa.s, as shown in Table 2, which reduced approximately 17.5% for penetration and increased 77% for softening point. It indicates that base binders are stiffening due to incorporating Sasobit and improving high-temperature resistance for asphalt mixtures. Besides, the viscosity of the modified binder is decreasing, which is attributed to a better workability of the asphalt binder. In a part, Table 3 shows the OBC analysis according to the JKR standard. In accordance, the OBC for the asphalt mixtures is 7.8%. This OBC complied with the standard and specification that the alternate trial OBC could be 6% to 8%. The value of OBC is higher than the conventional HMA without crumb rubber, as stated in the JKR standard, such as AC14, for a wearing course that is within the range of 4 - 6% of the total mixture. This may be attributed to the interaction between the binder and rubber, where the CR could absorb the lighter oil components from the binder, causing a reduction in the viscosity and ability of the binder to coat the aggregate particles [17].

Table 2 *Properties of the unmodified and modified binder*

Tests	Unmodified binder	Modified binder
Penetration (mm)	63	52
Softening point (°C)	43	76.3
Viscosity@135°C (Pa.s)	0.772	0.579

Table 3 *Marshall parameters of the sample for optimum binder content*

Marshall Parameter	Specification	Parameter values at the OBC
Stability (kN)	>6000	12600
Flow (mm)	2.0 – 5.0	4.2
Stiffness (N/mm)	>2000	3100
VIM (%)	4.5 – 6.5	6.2
VFB (%)	70 - 80	71

3.1 Resilient Modulus

Theoretically, higher resilient modulus (M_R) of the asphalt mixtures at high temperatures was attributed to the ability of the mixture to resist rutting, while lower resilient modulus values at low rubberised asphalt mixtures were attributed to their ability to resist fatigue damage. Resilient modulus of the control mixture and rubberised asphalt mixtures at 25°C and 40°C are depicted in Fig. 2. As clearly shown in the figure, the resilient modulus of the mixtures is notably influenced by variations in test temperature and proportion of CR in a mixture. In general, when the test temperature increases, the MR of the samples significantly decreases. As expected, M_R of the HMA and rubberised asphalt mixtures are higher at 25°C but lower at 40°C because the material characteristics of the asphalt mixture are sensitive to temperature changes.

In accordance, at the test temperature 25°C, the resilient modulus of the rubberised asphalt mixtures is lower than that of the control asphalt mixture. This decrease is significant for asphalt mixtures with proportions of 2% and 4% CR. Although the asphalt mixtures incorporating 3% crumb rubber also show a decreasing trend, the difference is insignificant compared to the control asphalt mixture. In particular, the asphalt mixture incorporating 2% CR has recorded the lowest value, making it the least effective of all the modifications. The resilient modulus is 3864.67 MPa for asphalt mixtures with a proportion of 3% CR and 3199.67 MPa for asphalt mixtures with a proportion of 2% CR. Although a lower resilient modulus indicates reduced stiffness, it also suggests that incorporating CR can enhance flexibility, improving the mixture's ability to resist cracking and increasing durability under specific conditions [13].

At the test temperature 40°C, M_R of the asphalt mixtures reduced approximately 65% compared to the resilient modulus of the asphalt mixtures measured at a temperature of 25°C. The resilient modulus shows a decreasing trend only for asphalt mixtures with a proportion of 2% CR, while the asphalt mixtures with a proportion of 3% and 4% CR exhibit fluctuating increases. Higher resilient modulus indicates the asphalt mixtures are relatively stiff and rigid, suggesting improved resistance to deformation under traffic loads. The asphalt mixtures with a proportion of 3% crumb rubber had the highest value, which is 1401.38 MPa, that increased by approximately 0.37% compared to the control asphalt mixture. Meanwhile, the resilient modulus of the asphalt mixture with a proportion of 2% CR is the lowest, at 1342.33 MPa. Based on these values, it is important to highlight that mixing and compacting temperatures for preparing rubberised asphalt mixture were reduced by as much as 20°C lower than that for control asphalt mixtures. It could be a response to an improvement in rubber-bitumen interaction and also the elastic contacts within the asphalt mixture [18]. It should be noted that through the dry process, CR particles function as an elastic aggregate. Besides, the elastic contact within the mixture would have a higher ability to absorb energy under the imposed stress and aid to retard the deformation rate.

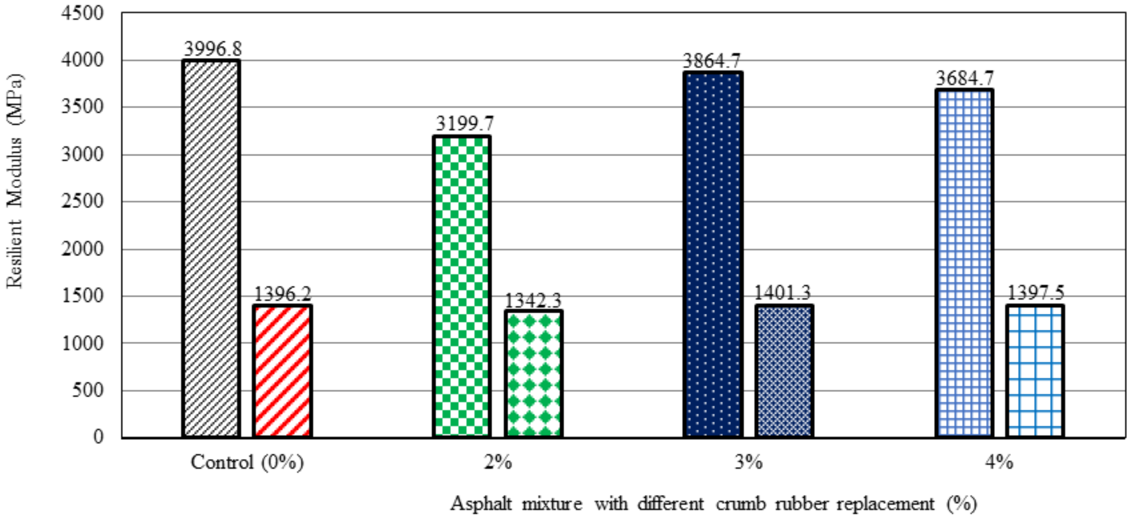

Fig. 2 *Comparison of the control and CRWMA at 25°C (left bar) and 40°C (right bar)*

3.2 Indirect Tensile Strength

The indirect tensile strength (ITS) of the unconditioned and conditioned modified asphalt mixtures was measured. The ITS for dry asphalt mixtures are depicted in Fig. 3. As shown in the figure, the ITS for dry samples displayed an up-and-down pattern. Adding 2% and 3% CR to the asphalt mixtures slightly increased the asphalt mixture's tensile strength compared to the control asphalt mixture. Although adding crumb rubber to higher than 4% in asphalt mixture should be avoided, as it is clearly seen that its ITS was slightly reduced by approximately 4.7%.

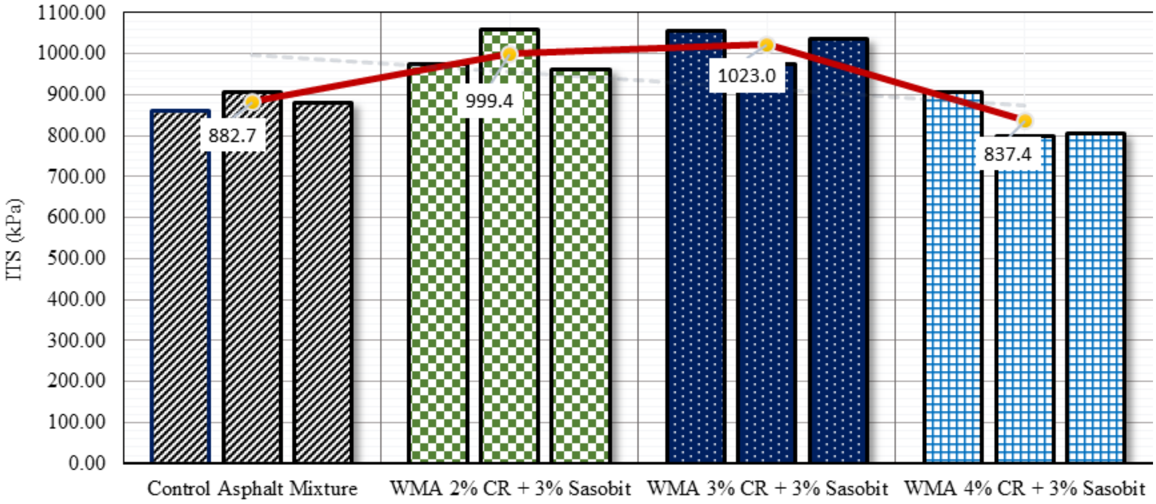

Fig. 3 *The percentage of ITS of the control and CRWMA mixture (dry Sample)*

Fig. 4 shows the ITS of wet asphalt mixtures. It is clearly depicting a fluctuating pattern and is similar to the ITS for dry samples, except that the percentage of ITS increases for asphalt mixtures with a proportion of 3% CR and decreases for asphalt mixtures with a proportion of 4% CR compared to the control asphalt mixture, which is more significant. In accordance, the ITS of the asphalt mixtures with a proportion of 3% CR was measured to be the highest among the samples. The value is approximately 16% higher than the control asphalt mixture, indicating the samples are more resistant to moisture damage. Nevertheless, incorporating 4% CR in the asphalt mixture reduced its ITS value to less than 5.1% compared to the control asphalt mixture, indicating the sample is less resistant to moisture failure. Certainly, incorporating less than 4% in the mixtures would improve the properties of the asphalt mixture toward reducing the moisture susceptibility. It could be an improvement on the adhesion between aggregate and binder, as proven by the other research [3], [18].

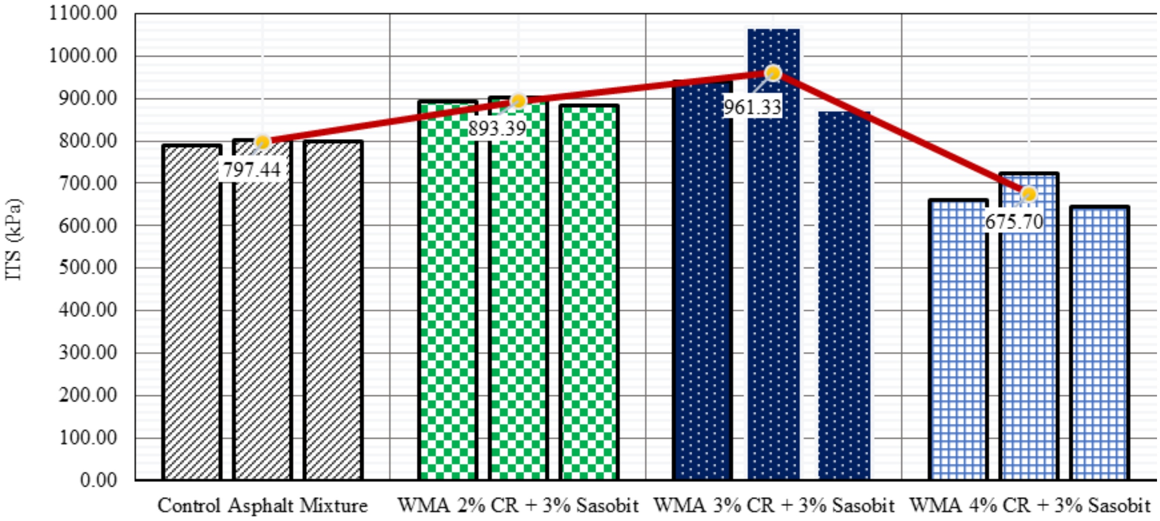

Fig. 4 *The percentage of ITS of the control and CRWMA mixture (wet sample)*

3.3 Indirect Tensile Strength Ratio

Fig. 5 shows the ITSR value for both wet and dry asphalt mixtures. As clearly seen from the figure, every sample exceeds 80%. Higher ITS suggests that rubberised asphalt mixtures can have much greater flexibility and energy absorption capacity [19]. In particular, the ITSR of the asphalt mixtures with a proportion of 2% and 3% CR is much greater than the control asphalt mixture, which is around 12% and 21%; however, the asphalt mixtures with a proportion of 4% CR exhibit a minor drop. The asphalt mixtures with a proportion of 3% CR exhibited the greatest ITSR value, suggesting that the addition of this material improved the samples' resistance to moisture degradation. This improvement means the mixtures are more durable and resilient since they can withstand large loads and stress without breaking down. These results point to positive outcomes for fatigue characteristic prediction. In contrast, the asphalt mixtures with a proportion of 4% CR are more susceptible to water compared to others, which decreases approximately 15% compared to the ITSR of the control samples and in line with the results of the ITS, as expected.

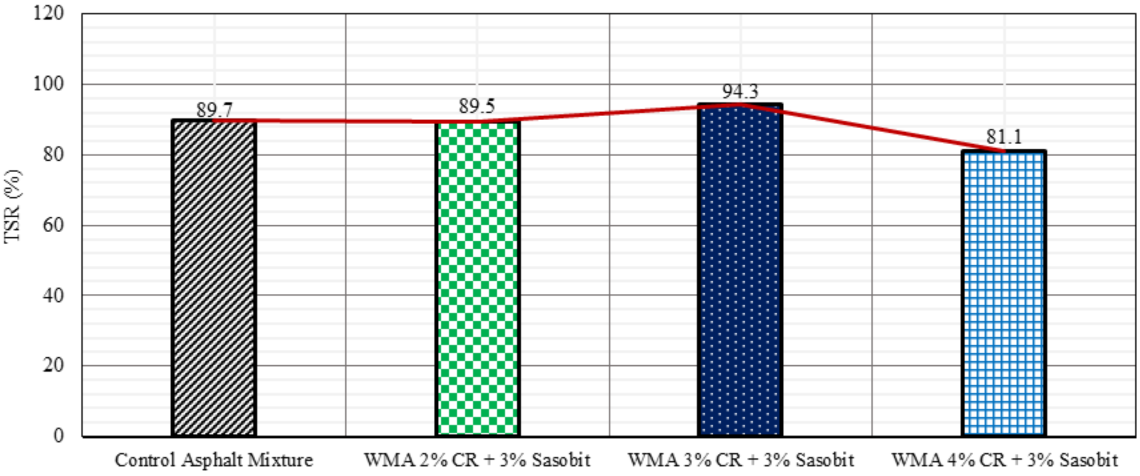

Fig. 5 *The ITSR of the control and CRWMA mixture*

3.4 Statistical Analysis

3.4.1 Analysis Comparison of The Resilient Modulus Between The Rubberised Mixture and The Control

Table 4 shows the statistical analysis of the resilient modulus (M_R) of the asphalt mixtures. It shows the M_R is notably influenced by variations in test temperature and proportion of crumb rubber. It is based on the P-value below 0.05 and the F-value exceeding the critical F-value. The resilient modulus is higher at 25°C but lower at 40°C because the properties of the asphalt mixture change with temperature. However, there is no statistically significant difference between the proportion of crumb rubber, as indicated by the P-value greater than 0.05 and F-value smaller than the critical F-value. In contrast, there is a statistically significant difference between test temperatures, which is at testing temperature 25°C, M_R value is the highest. This indicates that lower test temperatures enhance M_R because the asphalt binder becomes more elastic and stiffer, while higher temperatures cause the binder to soften and become more viscous, reducing stiffness.

In particular, at a temperature of 25°C, the resilient modulus of the sample with crumb rubber is lower than that of the control sample. This decrease is significant for asphalt mixtures with proportions of 2% and 4% CR. Although the asphalt mixtures with a proportion of 3% CR also show a decreasing trend, the difference is insignificant compared to the control. This indicates that asphalt mixtures incorporating 3% CR are the optimum crumb rubber content, as it achieves a resilient modulus comparable to the control while incorporating. This may be due to the fact that rubberised asphalt mixtures can have varying air void content compared to control mixtures, which affects the resilient modulus [17]. Although a lower resilient modulus indicates reduced stiffness, it also suggests that incorporating crumb rubber can enhance flexibility, improving the mixture's ability to resist cracking and increasing durability under specific conditions [19]. At 40°C, the resilient modulus shows a decreasing trend only in asphalt mixtures with a proportion of 2% CR, while the asphalt mixtures with a proportion of 3% and 4% CR samples exhibit fluctuating increases. Although the increase is not significant, the higher resilient modulus in these samples indicates that the asphalt mixture is relatively stiff and rigid, suggesting improved resistance to deformation under traffic loads.

Table 4 *Significant analysis of the resilient modulus between the control asphalt mixture and CRWMA*

Test temperature (°C)	Relation	F	F-crit	P-value	Conclusion
25	control & WMA 2% CR	35.695	7.709	0.004	significant
	control & WMA 3% CR	2.315	7.709	0.203	insignificant
	control & WMA 4% CR	11.757	7.709	0.027	significant
40	control & WMA 2% CR	1.539	7.709	0.283	insignificant
	control & WMA 3% CR	0.031	7.709	0.868	insignificant
	control & WMA 4% CR	0.001	7.709	0.98	insignificant

3.4.2 Analysis Comparison of The Resilient Modulus Within Different Percentages of Incorporated Crumb Rubber

Table 5 shows the ANOVA comparison between test temperatures and the percentage of crumb rubber incorporated. The asphalt mixtures with a proportion of 3% CR performed best with the highest average resilient modulus. However, there is no statistically significant difference between crumb rubber incorporation, as indicated by a P-value greater than 0.05 and an F-value smaller than the critical F-value. In contrast, there is a statistically significant difference between test temperatures, with samples at test temperature 25°C resulting in the highest resilient modulus. This indicates that lower test temperatures enhance resilient modulus because the asphalt binder becomes stiffer and more elastic, while higher temperatures cause the binder to soften and become more viscous, reducing stiffness. Therefore, the sample with 3% CR tested at 25°C demonstrates the best performance in terms of resilient modulus.

Table 5 *ANOVA between test temperatures and percentage of CR incorporating*

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	104736.8	2	52368.41	0.78153	0.561315	19
Columns	7280217	1	7280217	108.6476	0.009079	18.51282
Error	134015.2	2	67007.6			
Total	7518969	5				

3.4.3 Analysis Comparison of The Indirect Tensile Strength Between The Rubberised Mixture and The Control

The results of the unconditioned (dry) and conditioned (wet) for indirect tensile strength (ITS) are displayed in Table 6. The ITS of the asphalt mixtures with a proportion of 2% and 3% CR is significantly greater than the control sample, while the sample with 4% CR exhibits a slight decrease. The energy absorptivity and flexibility of the asphalt mixtures can be considerably increased by rubberised warm mixtures, according to higher ITS [19]. It was identified that the mixtures are more durable and long-lasting since they can withstand large loads and stress without breaking down. These results point to favourable outcomes for fatigue characteristics prediction of rubberised asphalt mixtures with WMA addition.

Table 6 *Significant analysis between the ITS of control and CRWMA samples*

Sample conditioned	Relation	F	F-crit	P-value	Conclusion
Uncondition (dry samples)	control & WMA 2% CR	12.565	7.709	0.023	significant
	control & WMA 3% CR	25.941	7.709	0.007	significant
	control & WMA 4% CR	1.463	7.709	0.293	insignificant
Conditoned (wet samples)	control & WMA 2% CR	17.672	7.709	0.014	significant
	control & WMA 3% CR	9.304	7.709	0.038	significant
	control & WMA 4% CR	5.832	7.709	0.073	insignificant

3.4.4 Analysis Comparison of The Indirect Tensile Strength Within The Different Percentages of Incorporated Crumb Rubber

Table 7 shows the ANOVA comparison between the sample conditioned and the percentage of crumb rubber incorporation. The dry conditioned sample performed best with the highest average resilient modulus. However, there is no statistically significant difference between the samples, as indicated by a P-value greater than 0.05 and an F-value smaller than the critical F-value. In contrast, asphalt mixtures with a proportion of 3% CR show a statistically significant difference in their ITS value compared to others. This indicates that the asphalt mixtures with a proportion of 3% CR optimally enhance the asphalt mixture's performance in terms of flexibility and resistance to tensile stress.

Table 6 *ANOVA between sample conditioned and percentage of CR incorporation*

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	62475.75	2	31237.88	24.90078	0.038609	19
Columns	18112.62	1	18112.62	14.43819	0.062806	18.51282
Error	2508.987	2	1254.494			
Total	83097.36	5				

4. Conclusions

The impact of incorporating crumb rubber on the tensile strength of asphalt concrete mixtures was assessed in this study. The optimum crumb rubber as an aggregate replacement can be determined by observing the results from these performance tests. Based on the results obtained, CRWMA shows good results compared to HMA. Both mixing and compacting temperatures can be reduced, and it did not lower the resilient modulus of the modified samples. Besides, the ITS and ITSR showed that crumb rubber significantly improves the tensile strength of the asphalt mixtures incorporating less than 4% CR. Indirectly, crumb rubber would provide a good effect on the performance of the asphalt mixture in resisting moisture and thus moisture damage. The addition of a WMA additive would reduce the production temperature of the CRMA mixture without a significant reduction of the MR and improve the resistance to moisture damage. It is proven that even though both mixing and compacting temperatures were reduced as much as 20°C, the MR of the CRWMA samples is not significantly different. However, the proportion of crumb rubber should be limited to about 3% when 3% Sasobit is applied to modify the asphalt binder. Other than that, these CRWMA would reduce emissions and energy consumption during production. Further studies can be made to optimise the crumb rubber composition or vary the temperature for mixing and compaction for a better sustainable road construction.

Acknowledgement

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through TIER 1 (Vot Q855)

Conflict of Interest

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

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Rosnawati Buhari, Muhammad Syahmi Mustafa, Syamir Iman Ibrahim;* ***Data collection:*** *Muhammad Syahmi Mustafa, Syamir Iman Ibrahim;* ***Analysis and interpretation of results:*** *Rosnawati Buhari, Muhammad Syahmi Mustafa, Syamir Iman Ibrahim, Nur Najwa Raisuddin;* ***Draft manuscript preparation:*** *Rosnawati Buhari, Muhammad Syahmi Mustafa, Syamir Iman Ibrahim, Nur Najwa Raisuddin. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Hassan, N. A., Almusawi, A. A. A., Mahmud, M. Z. H., Abdullah, N. A. M., Shukry, N. A. M., Mashros, N., ... & Yusoff, N. I. M. (2019). Engineering properties of crumb rubber modified dense-graded asphalt mixtures using dry process. In IOP Conference Series: Earth and Environmental Science, 220, 012009. DOI 10.1088/1755-1315/220/1/012009

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

[3] Tan, E. H., Zahran, E. M., & Tan, S. J. (2022). The optimal use of crumb rubber in hot-mix asphalt by dry process: A laboratory investigation using Marshall mix design. Transportation Engineering, 10, 100145. https://doi.org/10.1016/j.treng.2022.100145

[4] Bakar, S. K. A., Abdullah, M. E., Kamal, M. M., Abd Rahman, R., Buhari, R., Jaya, R. P., ... & Ahmad, K. A. (2018). The effect of crumb rubber on the physical and rheological properties of modified binder. Journal of Physics: Conference Series, 1049, 012099. https://doi.org/10.1088/1742-6596/1049/1/012099

[5] Bakar, S. K. A. (2019). Effect of waste nitrile latex on temperature susceptibility of bitumen. International Journal of Integrated Engineering, 11, 037-044. https://doi.org/10.30880/ ijie.2019.11.09.004

[6] Mohamed, S., Hassan, M., & Hamdy, I. (2019). The Potential use of crumb rubber in hot asphalt mixes in Egypt using dry process. International Journal of Engineering and Advanced Technology, 9, 4356-4360. https://doi.org/10.35940/ijeat.A1952.109119\

[7] Rasidin, N. N., & Buhari, R. (2023). Evaluation of warm mix crumb rubber modified asphalt mixture (WCRMA) on resisting permanent deformation. IOP Conference Series: Earth and Environmental Science, 1205, 012060. https://doi.org/10.1088/1755-1315/1205/1/012060

[8] Bazoobandi, P., Mousavi, S. R., Karimi, F., Karimi, H. R., Ghasri, M., & Aliha, M. R. M. (2024). Cracking resistance of crumb rubber modified green asphalt mixtures, using calcium carbonate nanoparticles and two by-product wax-based warm mix additives. Construction and Building Materials, 424, 135-848. https://doi.org/10.1016/j.conbuildmat.2024.135848

[9] Amirkhanian, S. N. (2001). Utilisation of Crumb Rubber in Asphaltic Concrete Mixtures–South Carolina's Experience. Clemson University. https://www.researchgate.net/publication/237220738.

[10] Ozturk, H. I., & Kamran, F. (2019). Laboratory evaluation of dry process crumb rubber modified mixtures containing warm mix asphalt additives. Construction and Building Materials, 229, 116-940.

[11] JKR 20403 003 7 (2008). Standard Specification for Road Works, Section 4, Flexible Pavement. Jabatan Kerja Raya Malaysia.

[12] ASTM D6 (2009). Standard Test Method for Penetration of Bituminous Materials. American Society for Testing and Materials.

[13] ASTM D36 (2009). Standard Test Method for Softening Point of Bitumen (Ring and Ball Apparatus). American Society for Testing and Materials.

[14] ASTM D4402 (2002). Standard Test, Method for Viscosity Determination of Asphalt at Elevated Temperatures, Using A Rotational Viscometer. American Society for Testing and Materials.

[15] ASTM-D4123-82. (2001), Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures. American Society for Testing and Materials.

[16] AASHTO T283-07. (2008), Resistance of Compacted Hot Mix Asphalt (HMA) to Mixture-Induced Damage. American Association of State Highway and Transportation Officials.

[17] Hassan, N. A., Hainin, M. R., Yaacob, H., Ismail, C. R., & Yunus, N. Z. M. (2013). Evaluation on mix design and rutting resistance of dry mixed rubberised asphalt mixtures. Jurnal Teknologi, 65, 115-120. https://doi.org/10.11113/jt.v65.2156

[18] López-Moro, F. J., Moro, M. C., Hernández-Olivares, F., Witoszek-Schultz, B., & Alonso-Fernández, M. (2013). Microscopic analysis of the interaction between crumb rubber and bitumen in asphalt mixtures using the dry process. Construction and Building Materials, 48, 691-699. https://doi.org/10.1016/j.conbuildmat.2013.07.041

[19] Yazdipanah, F., Ameri, M., Shahri, M., Hasheminejad, N., & Haghshenas, H. F. (2021). Laboratory investigation and statistical analysis of the rutting and fatigue resistance of asphalt mixtures containing crumb-rubber and wax-based warm mix asphalt additive. Construction and Building Materials, 309, 125-165. https://doi.org/10.1016/j.conbuildmat.2021.125165