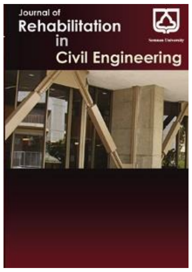

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Influence of Crumb Rubber Incorporated with Different Warm Mix Asphalt Additives on the Mechanical Performance of WMA Mixture

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ABSTRACT

The compacting and mixing processes involving hot mix asphalt during asphalt production can lead to air pollution as a result of a high volatile organic compound. An alternative solution that can reduce greenhouse gas emissions is by using warm mix asphalt (WMA). A proper application of additives to the WMA can improve the asphalt mixture's strength, durability, and workability. In this study, a 60/70 grade asphalt binder was added with 5% of crumb rubber (CR) and three different WMA additives at the recommended dosages, namely Sasobit, Cecabase, and Rediset. The wet method was used to blend the additives with virgin asphalt binders. The mixing and compacting temperatures were set at 135°C and 125°C, respectively, to mix the asphalt mixture. Mechanical performance tests were performed to evaluate the impact of WAM additives with CR on asphalt mixture. Based on the results, all the modified asphalt mixtures showed a better mechanical performance than the virgin asphalt mixture in terms of indirect tensile strength, moisture resistance, permanent deformation, and stiffness. Among all the WMA additives, Sasobit with CR showed the most significant impact on the asphalt mixture's performance.

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1. Introduction

Over the years, the asphalt industry has been exploring ways to reduce fuel consumption to ensure a lower emission rate of greenhouse gases (GHG) that can contribute to poor air quality. Recent technological advancements enabled the more efficient production of conventional hot mix asphalt at lower paving temperatures without compromising its pavement performance. In the asphalt industry, bituminous mixture production involves continuous heating of the aggregate before being coated with bitumen. This process leads to an escalated fuel costs, apart from increased emission of hazardous chemicals and greenhouse gases (GHG). These emissions also exposed the workers to hazardous substances such as fumes and polycyclic aromatic hydrocarbon.

In line with the increased awareness of global warming issues, sustainable development has been gaining increasing attention from industries worldwide [1]. For the asphalt industry, this can be achieved by lowering the asphalt mixing and compaction temperatures using the warm-mix asphalt (WMA) technology. This technology received positive responses from many researchers, road builders, and government road agencies based on various laboratory and field studies. Thus, it is a potential technology to be explored for the improvement of the asphalt industry. In addition, the reduction of binder viscosity during the mixing results also leads to a decrease in the mixing production temperature. Subsequently, the reduction in energy consumption also contributes to lower GHG emission and environmental pollution [1, 2].

According to Hossain et al., [3], WMA technology is one of the latest developed technologies in the asphalt industries that not only lower GHG emission but also reduce energy consumption. The mixing and compaction temperatures are reduced by a range of 15-60°C during the production and paving processes. As a result, the utilisation of this technology enables the asphalt industry to lower its carbon footprint and plant production costs due to lower energy demand. It is also more environmental-friendly with lower production of anthropogenic emissions into the atmosphere [4–6]. However, the reduction of temperatures in the mixing and compaction process is achieved by reducing the binder viscosity to a lower level than those traditionally required in hot asphalt mix production. Such alternation can result in incomplete drying of the aggregate. Consequently, the moisture trapped in the coated aggregate may reduce the aggregate-bitumen bonding and affect the strength of the pavement and shorten its design life.

In the last decade, many studies that evaluated warm asphalt mixtures have been published. Airey et al., [7] assessed the moisture susceptibility of warm mix asphalt prepared with granite and limestone aggregates that were added with crushed granite filler and anti-stripping agent by using the saturated aging tensile stiffness test. The results indicated that the mixture incorporating anti-stripping agents exhibited improved moisture susceptibility with a higher retained stiffness value than those with crushed granite filler. Table 1 shows a summary of laboratory test findings on the effects of WMA additives in asphalt incorporated of crumb rubber.

Table 1. Laboratory researches on the effect of CR incorporating WAM additives in asphalt.

Refs	WMA name	WMA (%)	CR (%)	Results
[8]	Licomont BS 100	4	15 and 20	• Both WAM additives raise the complex modulus value, improved the rutting resistance, and lowering phase angel value. • The addition of crumb rubber enhanced the performance of the low and high temperature.
	Sasobit	4		
[9]	Sasobit	2 and 4	20	• WMA additives decreased the viscosity and low-temperature performance of crumb rubber asphalt binder. • Among all WMA additives, Sasobit has the most significant impact on crumb rubber asphalt binder performance.
	Licomont BS 100			
	Asphaltan A			
[10]	Sasobit	-	15 and 20	• WMA additives with crumb rubber reduce the indirect tensile strength, rutting resistance, and stiffness modulus compared to hot mix asphalt. • Sasobit additive gives better asphalt mixture performance than Aspha-min additive.
	Aspha-min	-		
[11]	Synthetic wax (CB)	3	20	• ITS and TSR values for CR incorporating the WMA additives were within the requirements of test standards. • CR incorporating the WMA additives improved the coating ability for asphalt mixture. • The addition of WMA additives incorporating crumb rubber drove to reduce the viscosity.
	Surfactant agent (IL)	0.5		
	Polyphosphorc acid (IR)	1		
	Foaming liquid (WM)	0.6		
[12]	Sasobit	-	10	• The compaction temperature reduces with the addition of crumb rubber and WMA additives. • The addendum of WMA additives into CR mixtures resulted in the raise of %VFA value and the lowering of %VMA value.
	Aspha-min	-		
[13]	Aspha-min	-	10	• The increment in the mixing and compaction temperatures related to the addendum of CR can be balanced by adding the WMA additives. • The addendum of Sasobit to rubberized asphalt binder significantly minimizes the viscosity of the binders. In contrast, the addendum of Aspha-min did not impact the viscosity of the rubberized asphalt binders.
	Sasobit	-		
[14]	Synthetic microcrystalline wax	-	-	• Both WMA additives enhanced fatigues and high-temperature performance and decreased the performance of the low temperature. • Crumb rubber has a significant effect on fatigues and high-temperature performance.
	Liquid chemical	-		
[15]	Sasobit	2	-	• WMA additives improved the dynamic contact angle. • The Advera additive showed superior performance among all the other WMA additives.
	Advera	6		
	Rediset	2		
[16]	Sasobit	4	15	• Both WMA additives decreased the temperature susceptibility and enhanced the high-temperature performance of CR asphalt binder. • Sasobit with CR has a considerable impact on the asphalt binder's workability, while the CW has a slight effect on the CR asphalt binder workability.
	Commercial Organic Additive (CW)	4		
[17]	Fischer–Tropsch (F-T) wax (A1)	4	20	• The WMA additives incorporation CR asphalt binder can reduce the mixing and compaction temperature by 30°C when compared with virgin asphalt mixture.
	Montan wax (A2)			
	Refined Montan wax (A3)			
	Synthetic fatty acid (A4)			

The majority of the studies focused on the asphalt binder performance rather than the asphalt mixture performance.

Aman et al., [18] conducted a study to assess the moisture damage of asphalt mixtures that contain hydrated lime, quarry dust filler, and pavement modifier as an anti-stripping agent. It aimed to evaluate the adhesion of loose mix in the presence of water and the moisture susceptibility by using the indirect tensile strength test. The result indicated pavement modifier was incorporated in the mix as an anti-stripping agent and the WMA additive showed better resistance to moisture damage and improved aggregate bitumen coating. Apart from that, the use of the warm additives in asphalt mixes and their performances have also been investigated by Kristjánsdottir et al., [19], Prowell et al., [20], and Xiao et al., [21]. All the studies indicated that WMA additives improved the overall performance of asphalt compared to virgin asphalt.

However, Ma et al., [22] reported that despite the benefits of WMA, the reduced asphalt binder viscosity of the warm asphalt mixes could result in incomplete drying of the aggregate interface, subsequently influenced the bond strength between asphalt binder and aggregate when exposed to loading and environmental conditions. Furthermore, the binder viscosity reduction also affects the binder rheology and the homogeneous distribution in the asphalt binder during the mixing process [23–26]. To overcome this, crumb rubber is one of the waste materials that has been introduced to improve the mixture properties, especially the stiffness. Bilema et al., [27] investigated asphalt mixes that were prepared with various CR particle sizes aimed at enhancing the stiffness of asphalt mixtures. The results indicated that an increase in the size of CR particles led to an increased ITS and a decreased moisture resistance. This study set out to bridge the gap by assessing the effects of CR-incorporated WMA additives on the mechanical performance of asphalt mixture. This study aimed to assess the impact of CR-incorporated WMA additives on the moisture damage, strength, and rutting behaviour of asphalt mixture.

2. Materials and methods

The 60/70 asphalt binder penetration grade was used in this study. The aggregate was supplied by Hanson Industries Sdn Bhd, and 9.5 Nominal Maximum Aggregate Size (NMAS) gradation was used. Crushed granite aggregates were washed, dried, and sieved into a selected size range according to research conducted by Bilema et al., [28]. The CR size of 0.15 mm was collected from Miroad Rubber Industries Sdn Bhd. Three warm mix additives were used, including two organic additives (Sasobit and Rediset) and one chemical additive (Cacebase). The dosages of the WMA additives were selected based on the recommendations from previous studies [29–31]. Table 2 displays the composition of the modified and original asphalt binders.

Table 2. Composition of the modified and virgin asphalt binders.

ID	Asphalt binder (%)	Crumb rubber (%)	Warm mix additive (%)
PG 64/22	100	-	-
Sasobit+5%CR	100	5	1.5
Cecabase+5%CR	100	5	0.44
Rediset+5%CR	100	5	1.5

Figure 1 illustrates the mixing process of the asphalt binder incorporating 5% of crumb rubber. Crumb rubber of 0.15 mm sizes was prepared in a homogenous mixture using a high shear mixer for 700 rpm at 177°C in 30 minutes continuously [32]. Each additive was added separately and mixed with the asphalt binder for 1000 rpm at 120°C in 10 minutes. The modified asphalt binders were applied immediately after the blending process to prevent separation from storage. Furthermore, modified bitumen and aggregates were pre-heated for four hours in an oven before mixing them together with the asphalt mixer apparatus. The asphalt mixture was mixed and compacted at a temperature of 135°C and 125°C respectively. The loose mixture was then put back into the bowl and placed in an oven for short-term aging for two hours at the compaction temperature before compacted with the Superpave Gyratory Compactor.

Fig. 1. The mixing process for the modified asphalt.

The optimum asphalt binder content was selected at 6% for the virgin asphalt mixture and 6.25% for the modified asphalt mixture. A total of 60 specimens were prepared for mechanical performance tests (Table 3). The standard air voids for indirect tensile strengths (ITS), resilient modulus, and dynamic creep tests was 4% while the air voids requirement for moisture damage test was 7%. To achieve specimens with 7% ± 0.5 air void, the N_{design} was reduced from 100 to 65 gyrations.

Table 3. Mechanical performance tests methods.

Asphalt mixture tests	Tests Method	Parameters
Indirect tensile strengths	AASHTO T283	- Test temperature at 25°C - 4% air voids
Moisture sensitivity	AASHTO T283	- 7% air voids - Saturated 70% to 80% for wet samples - Water bath for 24 hours at 60°C for wet samples
Resilient modulus	ASTM D4123	- Test temperature at 25°C - 4% air voids - Preconditioning pulse: 5 seconds - Poisson's: 0.35 - Force: 1000N
Dynamic creep (permanent deformation)	NCHRP 9-19	- Test Temperature at 40°C - 4% air voids - No of Cycles: 3600 cycles - Loading wave: Haversine

3. Results and discussion

3.1. Effect of CR-incorporated WMA additives on indirect tensile strength (ITS)

The strength of the asphalt mixture can be measured by the ITS test at room temperature of 25°C based on the ASSTHO T-283. The asphalt mixture with a low ITS value can display cracking issues [33, 34]. Fig. 2 shows the impact of CR and different WMA additives on the ITS. Research outcomes indicated that all asphalt mixtures with WMA additives and CR have a superior ITS result in comparison with the virgin asphalt mixture. The same finding was found by Shu et al., [26]. Another previous study also reported that the addition of CR resulted in an improved ITS value of the asphalt mixture [35]. The asphalt mixture with Sasobit and CR showed the highest ITS with an increase of 22.6% when compared to the virgin asphalt mixture. The increment was only 20.5% with the addition of Rediset and CR. This behavior supports the finding of a study done by Bagi et al., [36]. They concluded that the Rediset leads to an increase in the ITS value compared to the asphalt mixture without the Rediest additive. However, the addition of Cecabase with CR showed the lowest ITS with 798 kPa. In summary, the WMA additives incorporating the CR drove to enhance the bonding between the asphalt binder and aggregate; resulting in increasing the asphalt mixture's strength compared with the virgin asphalt mixture.

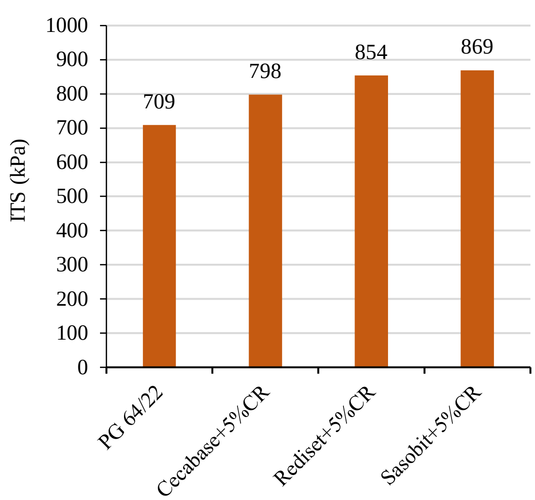

Fig. 2. Indirect tensile strength result of the modified and virgin asphalt mixtures.

3.2. Effect of CR incorporated-WMA additives on moisture resistance

The moisture damage was measured based on ASSTHO T-283. Moisture sensitivity test was used to assess the ability of the asphalt mixture to resist any moisture damage. Strong bonding between the aggregate and asphalt binders can result in high resistance to moisture [28]. Fig. 3 shows the moisture damage results of virgin and modified asphalt mixtures. Furthermore, modified asphalt mixture with WMA additives and CR also demonstrated higher wet and dry ITS values than the virgin asphalt binder. The asphalt mixture with CR and Sasobit exhibited the highest dry and wet ITS with 334 kPa and 282 kPa, respectively. Among the three WMA additives, the asphalt mixture with Sasobit and CR showed a higher tensile strength ratio (TSR) than the other two additives. Therefore, the Sasobit with CR had a higher resistance towards moisture damage. From the result of the TSR for Sasobit with CR, it concluded that the addition of Sasobit with CR led to enhanced adhesion between the aggregate and asphalt binder. This was in line with the finding of a recent study that reported a more superior resistance to the moisture damage by the Sasobit compared to other WMA additives [33]. In this study, all the modified asphalt mixtures produced a lower TSR than the virgin asphalt mixture. A slight decrement in TSR for the modified asphalt mixture can be attributed to the CR addition, as concluded by previous research [28]. The asphalt mixture with Cecabase and CR had a significant TSR result of 84.3%. Among the three WMA additives, the Rediset with CR had the lowest TSR (82.3%). Additionally, the TSR of both virgin and modified asphalt mixtures passed the requirement of the moisture sensitivity test with TSR of higher than 80%.

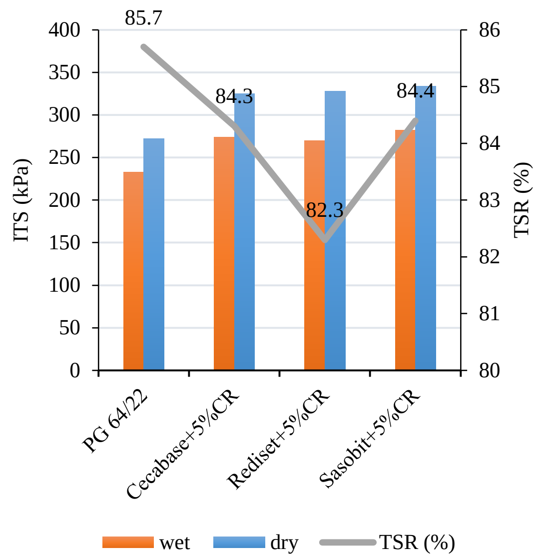

Fig. 3. Effect of the crumb rubber and WMA additives on the resistance of moisture damage.

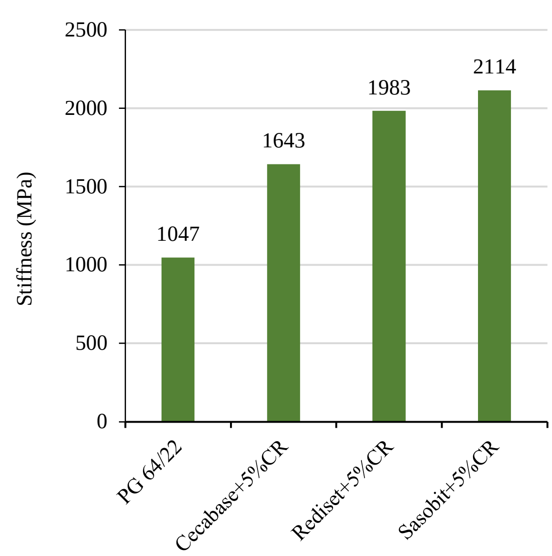

Fig. 4. Stiffness results for the modified and virgin asphalt mixtures.

3.3. Effect of CR-incorporated WMA additives on resilient modulus

The resilient modulus test is used to measure the stiffness level of the asphalt mixture at room temperature of 25°C. In this study, it was conducted according to ASTM D4123 using Universal Testing Machine (UTM). Fig. 4 displays the effect of various WMA additives with CR on the resilient modulus of the asphalt mixtures. From the results, all asphalt mixtures with WMA additives and CR exerted a significant impact on the resilient modulus. The resilient modulus values for the asphalt mixture content of Rediset and Cecabase with CR were 1983 MPa and 1643 MPa, respectively. Furthermore, the asphalt mixture with Sasobit and CR recorded a massive stiffness modulus that was equivalent to twice the value of the virgin asphalt mixture. The huge increment in the stiffness results for the modified asphalt mixture following the addition of the CR was in agreement with previous research [37].

3.4. Effect of CR-incorporated WMA additives on permanent deformation

The permanent deformation of the asphalt mixture was assessed based on the NCHRP 9-19. The permanent deformation test was conducted by using the Universal Testing Machine UTM at 40°C. Fig. 5 shows the effects of different WMA additives with CR on the permanent deformation of the asphalt mixture. The results showed that the asphalt mixtures with WMA additives and CR exhibited lower permanent deformation values as a result of increased resistance to the rutting behaviour compared to the virgin asphalt mixture. This finding was consistent with previous research done by Moreno et al., [35]. In short, lower permanent deformation can lead to higher resistance in the rutting behaviour of the asphalt mixture. Among all the WMA additives, the Sasobit with CR exerted the biggest impact on the permanent deformation of the asphalt mixture. Besides, the asphalt mixtures with CR-incorporated Rediset and Cecabase also showed 18.7% and 36% of decrement in the values of permanent deformation respectively when compared to virgin asphalt mixture. Figures 4 and 5 show the inverse relationship between stiffness and permanent deformation whereby an increase in the stiffness value lowered the permanent deformation value. In other words, increasing the stiffness of the asphalt mixture would lead to an enhanced rutting resistance.

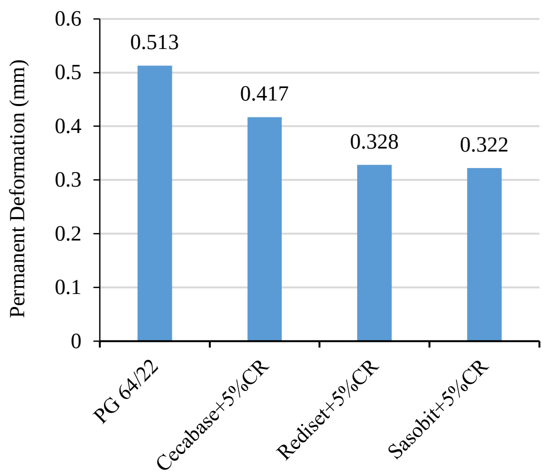

Fig. 5. Impact of various WMA additives with crumb rubber on the permanent deformation of asphalt mixtures.

4. Conclusion

Based on the assessment of the mechanical performances, this study concluded that WMA additives can reduce the mixing and the compacting temperature by 30°C. Thus, a decreased level of energy is needed to mix and compact the asphalt mixture, thus potentially reduce GHG emission. Furthermore, all the asphalt mixtures with WMA additives and CR passed the requirements of moisture sensitivity test with TSR higher than 80%. It was also found that the combination of WMA additives and CR improved the stiffness of the asphalt mixture as they recorded higher indirect tensile strength and resilient modulus values in comparison with the virgin asphalt mixture. Additionally, the addition of WMA additives with CR produced asphalt mixture with high resistance to rutting behaviour. In summary, among all the WMA additives evaluated in this study, the Sasobit with CR recorded the most significant impact on the mechanical performance of the asphalt mixture.

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Conflict of interest

The authors declare no conflict of interest.

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