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Performance Characterization of Rubberized Asphalt Mixtures Incorporating Waste Tire and Solid Natural Rubber

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Abstract

The performance of asphalt mixtures modified with 7% and 10% waste tire and solid natural rubber is assessed in this study, along with the effects of replacing fine aggregate with these materials. According to binder testing, a 10% rubber modification improved viscosity and deformation resistance while raising the softening point to 62.25°C. According to Marshall's findings, modified binders needed a higher optimal asphalt content of 6.05% to 6.25%. While the 7% modification produced the highest stability of 23.0 kN, replacing 50% of the river sand with Solid Natural Rubber decreased stability to 6.29 kN, falling short of requirements due to reduced structural rigidity. The 10% rubber mixture showed notable increases in stiffness modulus, increasing by 88.99% at 25°C and 105.69% at 40°C, according to testing. Additionally, the 10% modification achieved the highest durability, with 3,701 cycles, a 9.4% improvement over the control, according to the Indirect Tensile Fatigue Test results. According to the study's findings, rubber modifications of 7% and 10% greatly increase load-bearing capacity and fatigue resistance; however, in order to preserve the pavement's structural stability and integrity, rubber use as a fine aggregate replacement must be strictly limited.

Keywords: Fatigue, Fine aggregate, Marshall characteristic, Rubberized asphalt mixture, Solid natural rubber, Stiffness modulus, Waste tire.

1. Introduction

Road infrastructure is likely to deteriorate more quickly as a result of the recent increase in traffic volume and the lack of funding for road construction and maintenance. As a result, several actions must be taken, including routine road maintenance to restore and enhance pavement quality and pavement design optimization to better support traffic loads. These initiatives are crucial to preventing accelerated road damage and guaranteeing the durability and security of the transportation system [1]-[3]. Rapid urbanization and the lack of natural aggregates present major challenges for the construction industry, as global aggregate demand approached 55 billion tons in 2020 and is predicted to double by 2030. By reducing reliance on virgin materials, incorporating waste-derived aggregates provides a workable way to promote the circular economy. Using waste as an aggregate source is a promising way to reduce the environmental effects of using up natural resources. Additionally, using aggregates made from waste in pavement construction not only reduces the need for new materials but also supports sustainability by providing an environmentally friendly option that aligns with the principles of a circular economy [4],[5]. There is now a huge demand for new building materials, which has caused a shortage of the resources needed to make them and an increase in construction waste. The construction industry, a significant contributor to global carbon dioxide (CO_2) emissions and the depletion of natural resources, has made environmental concerns and the sustainable use of natural resources its top priorities [6]. Replacing natural aggregates with secondary materials made from waste, such as construction and demolition waste, is a crucial tactic for moving toward a circular economy. Many nations have already embraced this strategy as a successful way to lower waste generation and advance resource management [7], [8].

Waste tires are a type of waste identified for secondary use as components in pavement development. Crumb rubber (CR), a waste component from discarded tires, has been thoroughly examined for its ability to address pavement issues while also aiding in the recycling of large amounts of waste tires that end up in landfills. The use of crumb rubber in asphalt production was initiated in the 1960s to improve the surface properties of asphalt products [9]. Worldwide, various approaches to utilizing crumb rubber in asphalt development to improve its properties have been identified for study. Recent findings indicate that asphalt products that contain crumb rubber have a higher ability to withstand cracks compared to asphalt products without crumb rubber [10]-[12].

The particles of crumb rubber also show an increased specific surface area because of the surface morphology of the material. This helps in the effective absorption of oil and resin from the asphalt binder. However, the porous and disordered structure of the material makes the crumb rubber particles more prone to aging when exposed to heat and oxygen. Crumb rubber particles may swell when mixed with asphalt binder because the pores are filled with asphalt. This makes the material more cohesive and denser in nature [13], [14]. Such a property makes the use of modified asphalt with crumb rubber more suitable for thermal recycling. The application of crumb rubber in asphalt mixtures has attracted considerable research and application in the field of waste tire recycling. The mixture of crumb rubber in asphalt is referred to as Crumb Rubber Modified Asphalt Mix (CRMA). The addition of crumb rubber to asphalt improves pavement efficiency by enhancing the material's resistance to rutting, fatigue cracking, and temperature susceptibility. The addition of crumb rubber to asphalt makes the material stiffer and more durable than the conventional asphalt mixture [15].

Apart from crumb rubber, other types of renewable rubber are liquid natural rubber and solid natural rubber. Natural rubber, as an elastomer, exhibits properties useful for stabilizing asphalt and concrete. It has been announced that Indonesia plans to use natural rubber in asphalt mixtures to increase domestic demand for rubber, support natural rubber prices, and improve the well-being of natural rubber farmers [16]. As part of the development of Indonesian road infrastructure, latex rubber, as an element of asphalt concrete, has been used, as reported by many researchers [17],[18], who showed positive outcomes. By making the most of the components of the asphalt mix, namely natural rubber and crumb rubber, significant advantages are achieved. Even though significant performance advantages are achieved with rubberized asphalt, its large-scale industrial application is often hindered by practical issues, including initial production costs, storage stability issues with the modified bitumen, and workability and compaction challenges. Storage stability is an important issue, as rubber particles tend to separate from the bitumen during static storage, as reported in [14], [16], due to density differences. Furthermore, the increased viscosity of the modified bitumen requires higher mixing and compaction temperatures, which may affect the process. Overcoming these problems, which are both academic and practical, is important for the sustainable application of the process [17],[19].

The purpose of this paper is to investigate the application of solid natural rubber and crumb rubber, both as an asphalt modifier and as partial substitutes for fine aggregate. Although significant studies have been conducted to investigate the effects of the application of rubber as an asphalt modifier [1], [3], [19]-[21], the application of solid natural rubber and crumb rubber as partial substitutes for fine aggregate in Hot Mix Asphalt (HMA) is considered rare. It is important to note that previous studies mainly focused on the application of crumb rubber as an aggregate replacement or natural rubber as an asphalt modifier. Therefore, the novelty of this paper is based on the hybrid application of waste tire rubber and solid natural rubber as partial substitutes for fine aggregate in Asphalt Concrete—Wearing Course (AC-WC) mixtures. Notably, the novelty of this paper is based on the assessment of the mechanical potential of the application of rubber in its solid form as an element of the pavement structure, as opposed to its application as an element of the binder. Additionally, the application of Indonesian local solid natural rubber provides an economic advantage, as it supports the local economy. It is believed that applying this material will enhance the pavement's elasticity. However, applying these materials as partial substitutes for fine aggregate is considered technically challenging due to their sensitivity to temperature. This indicates the significance of applying these materials, as it is important to establish the optimal level of use to ensure compliance with the required technical specifications. As such, the purpose of this paper is to evaluate whether the application of this material is suitable for heavy-traffic road structures or whether it should be considered for application in light-traffic road structures. With this purpose in mind, the paper will investigate the potential of solid natural rubber as an aggregate replacement in AC-WC mixtures. To achieve this, an in-depth assessment will be conducted through Marshall characteristic tests and Stiffness Modulus tests.

2. Materials and Methods

2.1. Materials Preparation

The materials used in this study include asphalt binder with a penetration grade of 60/70, coarse aggregate, fine aggregate, filler, solid natural rubber (SNR), and waste tire powder (CR). Coarse aggregate is made up of crushed stone with a size range of 9.5 mm to 2.36 mm, while the fine aggregate is composed of stone ash and sand. The filler is made up of stone ash that passes through a No. 200 sieve (0.075 mm). The solid natural rubber (SNR) is obtained from Nusantara Plantation Research located in Bogor, Indonesia, while waste tire powder (CR) is obtained from a recycling plant located in Malang, Indonesia. Both SNR and CR are used in the production of rubber asphalt as substitutes for fine aggregate (i.e., sand). Fig. 1 shows the particle size distribution curves for SNR, CR, and river sand. From this figure, it is clear that SNR has the highest passing rate compared to waste tire powder (CR) and river sand. This is because SNR passes through the sieve at a size of 5.0 mm, while waste tire powder (CR) starts to pass through the sieve at a size of 1.0 mm, indicating that waste tire powder (CR) is finer compared to both SNR and river sand, which start to pass through the sieve at a size of 2.3 mm.

Fig. 2 shows the particle-size distribution of the aggregates used. Prior to use, characterization tests were conducted to determine the properties of the aggregates, including specific gravity, water absorption, and abrasion resistance.

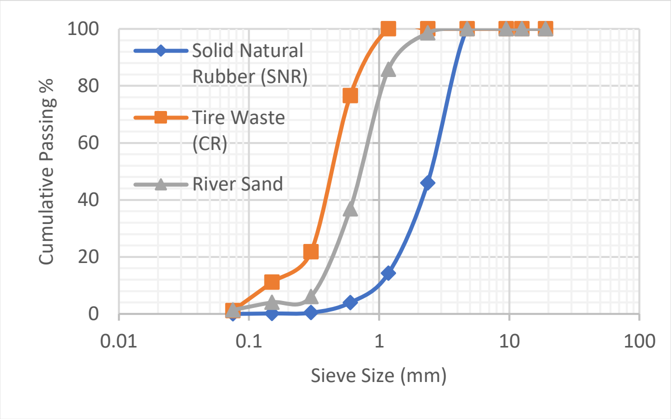

Figure 1. Distribution of SNR, CR, and River Sand Sizes.

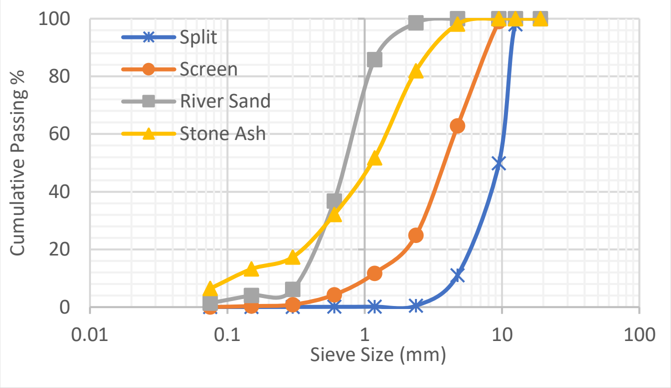

Figure 2. Distribution of aggregate sizes used.

The splitting and sieving tests for the aggregates were conducted in accordance with the SNI 1969:2016 standard, whereas the tests for the River Sand and Stone Ash aggregates were conducted in accordance with the SNI 1970:2008 standard. The abrasion resistance tests for the aggregates were conducted in accordance with SNI 2417:2008, using the Los Angeles Machine method. Additionally, the specific gravity of filler, stone ash, solid natural rubber, and waste tire was measured in accordance with SNI 1964-2008. The results of the aggregate characteristics tests, including specific gravity, are presented in Table 1 and are used to calculate volumetric parameters in the Marshall test.

2.2. Methods

The research methodology involves a series of laboratory experiments conducted in stages (see Fig. 3), including material preparation, rubberized asphalt formulation, and the fabrication and testing of Marshall specimens. Rubber asphalt used as a binder between mixtures is produced by blending a 60/70 penetration base asphalt with solid natural rubber and waste tire powder, as per previous research by [22].

Table 1. Results of aggregate characteristics testing.

Test Result	Test Type				
	Dry Specific Gravity	**SSD Specific Gravity**	**Apparent Specific Gravity**	**Water Absorption [%]**	**Wear [%]**
Split	2.65	2.66	2.75	1.33	13.87
Screen	2.75	2.78	2.82	1.14	12.55
River Sand	2.49	2.55	2.63	2.75	
Stone Ash	2.47	2.57	2.72	3.12	-
Filler Stone Ash	2.73	2.73	2.73	-	-
KA	0.652	0.652	0.652	-	-
CR	0.628	0.628	0.628	-	-

The asphalt binder modification involves incorporating rubber at 7% and 10% by weight of the base asphalt. A specific ratio of SNR to CR was maintained at 35:65. The selection of the 7% and 10% content is based on previous research, which indicates that rubber content should not exceed 12%. °C, a temperature determined from previous studies [23]-[25]. If this limit is exceeded, storage stability will be adversely affected, leading to phase separation of the rubber and bitumen matrix at high temperatures [16]. Furthermore, whereas in a conventional analysis a 50:50 ratio of SNR and CR is usually adopted, in this analysis a 35:65 ratio has been used to optimize SNR and CR. The nomenclature of the specimens of rubberized asphalt mixtures is SNRCR 7 and SNRCR 10 for rubber content of 7 and 10%, respectively. The mixing of the asphalt base and the rubber content is carried out using a stirrer at 800 rpm for 30 minutes. The mixing temperature of the asphalt base and the rubber content is set at 175°C, as established in earlier studies [22]-[25].

2.3. Hot Asphalt Mix Design

The asphalt mixture in question is AC-WC (Asphalt Concrete – Wearing Course), in accordance with Indonesian government regulations, specifically the Bina Marga Specification Revision 2 of 2018. The first step in the design of the asphalt mixture is determining the asphalt content, as represented by the Design Mix Formula (DMF). The DMF is determined by an approach that is in accordance with the Asphalt Institute's MS-2, 7th Edition, and is represented by the following factors: the percent aggregate retained on the No. 8 CA, the percent passing the No. 8 and retained on the No. 200 FA, and the percent passing the No. 200 sieve. Based on these factors, the asphalt content range for the AC-WC mixture is determined to be 5%-7% with an interval of 0.5%. This step is followed by determining the Optimum Asphalt Content (OAC) based on the asphalt content obtained in the previous step. The second step in the design of the asphalt mixture is the determination of the aggregate mixture composition by the mathematical analysis approach, resulting in the following composition: Split 32.24%, Screen 26.62%, River Sand 10.37%, Stone Ash 25.56%, and Stone Ash Filler 5.21%. The third step in the design of the asphalt mixture is to validate the aggregate composition obtained in the previous step using the gradation curve shown in Fig. 4, ensuring that the AC-WC mixture falls within the limits set by the Bina Marga Specification Revision 2 of 2018. Apart from the asphalt modification function, the solid natural rubber and waste tire powder serve as a substitute for fine aggregate, replacing river sand in the asphalt mixture. The ratio of substitution between the two materials, namely solid natural rubber and river sand, evaluated in the study, ranges from 0% to 50%. Studies have shown that a substitution rate exceeding 50% results in degradation of the asphalt mixture's strength, as reported by [10], [20], [21].

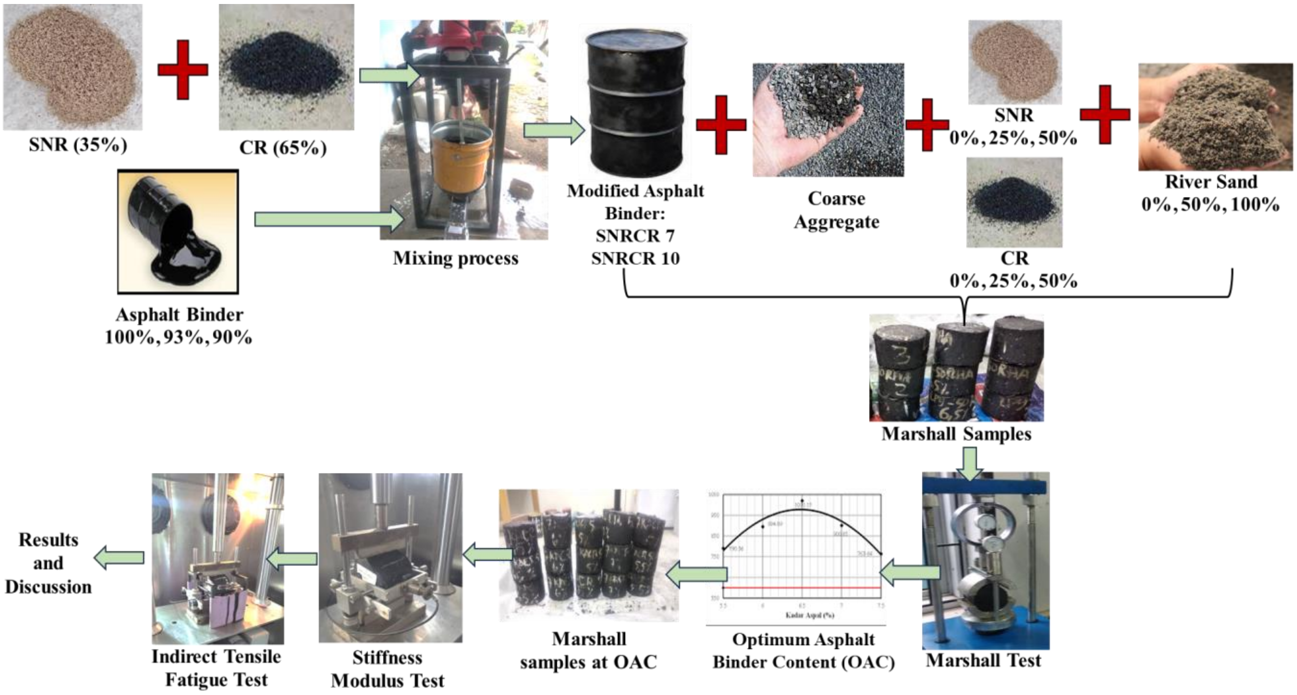

Figure 3. Research Stage Flow

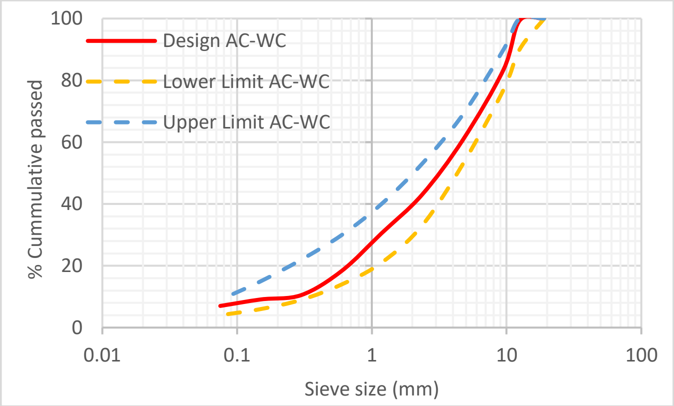

Figure 4. AC-WC mixture

2.4. Laboratory Testing

To assess the performance of the asphalt mixtures, a series of tests was carried out. These tests included the determination of the viscosity of the asphalt binder, as well as the mechanical properties of the hot mix asphalt. These tests included Marshall tests as well as stiffness modulus tests. As per ASTM D4402, the viscosity test was carried out to identify the precise temperature ranges for mixing as well as compaction.

2.4.1. Marshall testing and mixture composition

The Marshall procedure was used in accordance with the American Association of State Highway and Transportation Officials (AASHTO) T245 standard for the preparation of the Marshall specimens and the asphalt mixing processes. The aggregate used had a maximum size of 25 mm. Mixes with different percentages of bitumen content were prepared at a mixing temperature of 165°C and a compaction temperature of 155°C. The Marshall procedure involved the preparation of the Marshall specimens with 75 blows on each face in a 10 cm diameter mold. The entire Marshall procedure was conducted in two stages: the first was for the determination of the Optimum Asphalt Binder Content (OAC), and the second was for the evaluation of the characteristics of the mixes at the OAC. The different percentages of the mixes are presented in Table 2. In total, 135 Marshall specimens were prepared. These included different percentages of asphalt binders, such as unmodified asphalt and modified asphalt with 7% and 10% SNCR content. These mixes also included different percentages of SNCR content instead of river sand in the aggregate mixture. These percentages included 0%, 25%, and 50%. Five increments of asphalt content were used in the mixes. These increments included asphalt percentages ranging from 5% to 7%. The increments had a difference of 0.5%. The OAC was determined in accordance with the Indonesian Rubber Asphalt Specification (PD-08-2019-B). The mixes were then evaluated on the basis of different parameters such as VMA (Voids in Mineral Aggregate), VIM (Voids in Mix), VFA (Voids Filled with Asphalt), Marshall Stability, and flow. Further Marshall specimens were prepared for the determination of the characteristics of the mixes at the OAC. These Marshall specimens are presented in Table 3. In total, six Marshall specimens were prepared for each OAC variation. Therefore, the total number of Marshall specimens was 54. These Marshall specimens were used in the characterization of the mixes for the determination of the stability of the mixes in the Marshall procedure.

Table 2. Number of Marshall test samples to obtain optimum asphalt binder content (OAC).

No.	**Sample**	**Asphalt Binder Used**	**Sand Substitute Material [%]**			**Planned asphalt binder content [%]**					**Total**
			River Sand	**SNR**	**CR**	**5**	**5.5**	**6**	**6.5**	**7**	
1	Aspen	Asphalt base 60/70	100	0	0	3	3	3	3	3	15
2	SNRCR 7	SNRCR 7	100	0	0	3	3	3	3	3	15
3	SNRCR 7-50CR	SNRCR 7	50	0	50	3	3	3	3	3	15
4	SNRCR 7 – 50SNR	SNRCR 7	50	50	0	3	3	3	3	3	15
5	SNRCR 7 – 25CRSNR	SNRCR 7	50	25	25	3	3	3	3	3	15
6	SNRCR 10	SNRCR 10	100	0	0	3	3	3	3	3	15
7	SNRCR 10-50CR	SNRCR 10	50	0	50	3	3	3	3	3	15
8	SNRCR 10 – 50KA	SNRCR 10	50	50	0	3	3	3	3	3	15
9	SNRCR 10 – 25CRSNR	SNRCR 10	50	25	25	3	3	3	3	3	15

Table 3. Number of Marshall test samples on OAC.

No.	**Sample**	**Asphalt Binder Used**	**Sand Substitute Material**			**Total**
			% River Sand	**% SNR**	**% CR**	
1	Aspen	Asphalt base 60/70	100	0	0	6
2	SNRCR 7	SNRCR 7	100	0	0	6
3	SNRCR 7-50CR	SNRCR 7	50	0	50	6
4	SNRCR 7 – 50SNR	SNRCR 7	50	50	0	6
5	SNRCR 7 – 25CRSNR	SNRCR 7	50	25	25	6
6	SNRCR 10	SNRCR 10	100	0	0	6
7	SNRCR 10-50CR	SNRCR 10	50	0	50	6
8	SNRCR 10 – 50KA	SNRCR 10	50	50	0	6
9	SNRCR 10 – 25CRSNR	SNRCR 10	50	25	25	6

2.4.2. Stiffness modulus testing

Stiffness modulus tests were conducted to determine the mechanical performance of the asphalt mixtures at different temperatures. The tests were carried out using a Universal Testing Machine (UTM-30) in accordance with the procedure outlined in BS DD 213-1993. The pulse width for loading was set at 250 ms, and the pulse repetition period was set at 3,000 ms [26]. The specimens, prepared via the Marshall method, featured standard dimensions of 100 mm in diameter and 63 mm in height. As a nondestructive test, each specimen was tested in two stages: following the initial measurement, the specimen was conditioned in a temperature-controlled chamber, then rotated 90 degrees about its longitudinal axis before the subsequent test was conducted. Table 4 displays the number of samples for the stiffness modulus test, totaling 28 units. For each proposed mixture, there are 4 samples: 2 tested at 25°C and 2 tested at 40°C.

Table 4. Number of samples for stiffness modulus and fatigue testing.

No.	**Sample**	**Asphalt Binder Used**	**Sand Substitute Material [%]**			**Stiffness Modulus Testing**		**Fatigue Testing**	**Total**
			River Sand	**SNR**	**CR**	**25°C**	**40°C**	**20°C**	
1	Mod-Aspen	Asphalt base 60/70	100	0	0	2	2	1	5
2	Mod- SNRCR 7	SNRCR 7	100	0	0	2	2	1	5
3	Mod- SNRCR 7-50CR	SNRCR 7	50	0	50	2	2	1	5
4	Mod- SNRCR 7 – 25CRSNR	SNRCR 7	50	25	25	2	2	1	5
5	Mod- SNRCR 10	SNRCR 10	100	0	0	2	2	1	5
6	Mod- SNRCR 10-50CR	SNRCR 10	50	0	50	2	2	1	5
7	Mod- SNRCR 10 – 25CRSNR	SNRCR 10	50	25	25	2	2	1	5

2.4.3. Fatigue testing

The fatigue resistance of the asphalt mixtures was assessed using the Indirect Tensile Fatigue Test (ITFT) on a Universal Testing Machine (UTM), in accordance with BS EN 12697-26:2004. Testing was conducted under constant stress control at a stabilized temperature of 20°C. The loading protocol involved a 100 ms pulse width followed by a 500 ms rest period, assuming a Poisson's ratio of 0.35. The procedure concluded upon reaching one of three criteria: specimen fracture, an axial displacement of 9.0 mm, or completion of 1,000,000 cycles.

3. Result and Discussion

3.1. Test Results of Modified Asphalt Binder Characteristics

As can be seen in Table 5, where the comparison of the characteristics of the modified asphalt is shown when three materials are used, namely Aspen, SNRCR 7, and SNRCR 10, it is evident that each material has its own set of characteristics. In the penetration test, Aspen records the highest value at 60.4, with a standard deviation of 1.3, while SNRCR 7 and SNRCR 10 record lower values at 35.6 and 40, respectively, with relatively small deviations. At the softening point, Aspen has the highest temperature at 54°C, followed by SNRCR 7 at 58.5°C and SNRCR 10 at 62.25°C, indicating that the more SNRCR is used, the higher the asphalt's softening point will be. Specific gravity increases from 1.038 for Aspen to 1.085 for SNRCR 10. In the viscosity test, the temperatures that the asphalt is expected to encounter in the mixing process and compaction process for the Marshall method are used, where the viscosity is 0.2 Pa·s at the mixing process and 0.4 Pa·s at the compaction process, indicating that the asphalt has to undergo a higher mixing and compaction temperature than the standard asphalt, according to references [25],[27]. Collectively, these results demonstrate that increasing the amount of SNRCR increases its softening point, specific gravity, and viscosity while decreasing its penetration relative to Aspen.

Table 5. Results of Modified Asphalt Binder Characteristics Testing.

Properties of the binders	Modified asphalt binder		
	Aspen	SNRCR 7	SNRCR 10
Penetration testing [0.1 mm]	60.4	35.6	40
Softening point test R&B [°C]	54	58.5	62.25
Specific gravity	1.038	1.039	1.085
Viscosity at 0.2 Pa·s for mixing temperature [°C]	151	164	173
Viscosity at 0.4 Pa·s or compaction temperature [°C]	137	156	164

Interestingly, penetration increases with increasing amounts of SNRCR from 7 (35.6) through 10 (40.0). This can be understood as a saturation effect arising from the interaction between the rubber and the binder. More rubber particles are present at 10% rubber content, leading to a greater number of maltene fractions becoming trapped. The binder becomes more rigid due to its increased softening point, but also more elastic/softer as it has greater difficulty penetrating during the 25°C needle penetration test. The viscosity measurements reported in Table 5 are directly related to workability and compaction issues. The increased mixing temperature for SNRCR 7 and 10 (164°C-173°C) is a direct result of the increased stiffness imparted by the binder. The hybrid system of SNRCR aims to balance sufficient binder stiffness for stability with sufficient workability with conventional paving equipment to realize the benefits of the rubber modification.

3.2. Results of Marshall Characteristic Testing of Asphalt Mixtures

Based on the asphalt characteristic tests, it was found that SNRCR 7 and SNRCR 10 exhibit better properties compared to Pen Asphalt (Aspen). Therefore, subsequent testing was conducted on hot mix asphalt using Marshall tests. A total of 15 Marshall samples were prepared for each variation of SNRCR 7 and SNRCR 10 to determine the optimal asphalt binder content (KAO). Table 6 shows the Marshall test results within the asphalt content range of 5% to 7%. The test results indicate that the bulk density of the SNRCR 7 samples is nearly the same as that of the Aspen samples, while the SNRCR 10 samples show a decrease in bulk density. This is influenced by the specific gravity of the modified asphalt used in the mix. Previous studies [28] also suggest that higher rubber content in asphalt mixtures tends to decrease the density. For the effective asphalt content, the trend of the results shows a similar pattern across all samples. According to Table 6, the parameters that do not meet the specified limits are VIM (Void in Mineral), VFA (Voids Filled with Asphalt), and ductility. VIM indicates the amount of air voids in the mixture, which is heavily influenced by the amount of asphalt binder and filler filling these voids, thus affecting the VFA value. A smaller VIM generally indicates higher stability; however, in this test, the SNRCR 7 sample shows the highest stability value compared to Aspen and SNRCR 10, suggesting that this mixture has the most optimal characteristics. Based on the results from Table 6, the KAO for the SNRCR 7 sample is determined to be 6.05%, and for the SNRCR 10 sample, it is 6.25%. Comparing these with the KAO of the base asphalt (Aspen), it can be seen that the SNRCR 7 and SNRCR 10 samples require higher asphalt binder contents to meet the specifications. This is due to the solid rubber content in the modified asphalt binder, which can absorb more asphalt to bond with the aggregate [29], [30]. Table 7 presents the Marshall test results for samples of Aspen, SNRCR 7, and SNRCR 10 using the Optimum Asphalt Content (OAC). OAC is the ideal asphalt content for asphalt-based mixtures, providing the best properties, such as strength, resistance to deformation, and stability. Determining the OAC is essential to ensure the asphalt mixture performs optimally—neither too hard nor too soft—and meets established quality standards. The purpose of preparing Marshall samples with the OAC is to verify the range of asphalt contents obtained, thereby improving the accuracy of the results. Based on the results in Table 7, asphalt modified with SNRCR shows more difficulty in coating the internal voids within the mixture, especially in the SNRCR 7 sample, which exhibits a low VFA (Voids Filled with Asphalt Binder) and high VIM (Void in Mixture). This condition tends to influence the stability value. The test results indicate that the Aspen sample has the highest stability among the SNRCR 7 and SNRCR 10 samples.

Table 6. Marshall test results for Aspen, SNRCR 7, and SNRCR 10 samples for the planned asphalt binder content of 5 – 7%.

Parameter	Spec.	Samples		
		Aspen	**SNRCR 7**	**SNRCR 10**
Density [gr/mL]	-	2.29 – 2.38	2.29 – 2.38	2.28 – 2.35
Effective asphalt binder content (pbe) [%]	-	4.09 – 6.11	4.09 – 6.11	4.05 – 6.07
The ratio of passing particles no. 200 to Pbe	0.6 – 1.4	0.9 – 1.3	0.8 – 1.2	0.8 – 1.2
VMA [%]	min. 15	15 – 17	14 – 17	15 – 18
VIM [%]	3 – 5	2 – 8	2 – 7	3 – 8
VFA [%]	min. 65	53 – 88	56 – 85	54 – 80
Stability [kN]	min. 8.83	10.10 – 12.70	9.40 – 23.0	9.40 – 16.70
Flow [mm]	2 – 5	4 – 6	4 – 6	3 – 7
Marshall quotient (MQ)[kN·mm^{-1}]	-	2.41 – 3.54	2.24 – 8.22	2.06 – 6.46

Table 7. Marshall test results for OAC samples (Aspen, SNRCR 7, and SNRCR 10).

Parameter	Spec.	Samples		
		Aspen	SNRCR 7	SNRCR 10
Type of asphalt binder used	-	Aspen	SNRCR 7	SNRCR 10
OAC [%]	-	6.0	6.05	6.25
Density [gr/mL]	-	2.34	2.33	2.34
Effective asphalt binder content (pbe) [%]	-	5.10	5.15	5.31
The ratio of passing particles no. 200 to Pbe	0.6 – 1.4	1.1	0.97	0.94
VMA [%]	min. 15	16	16	16
VIM [%]	3 – 5	4	5	5
VFA [%]	Min. 65	73	71	72
Stability, 30-minute immersion [kN]	Min. 8.83	11.68	11.14	11.24
Stability, 24-hour immersion [kN]	Min. 8.83	11.09	10.39	10.59
Flow [mm]	2 – 5	4	5	4
Marshall quotient (MQ) [kN·mm^{-1}]	-	2.72	2.37	2.76
Residual Marshall stability after 24-hour immersion [%]	Min. 90	95	93	94

Among the modified samples, the best stability is achieved with SNRCR 10. Deformation resistance is also better in SNRCR 10%, as it has a lower ductility than Aspen. The Marshall stability after 24 hours of soaking shows that the Aspen sample is more resistant to changes than SNRCR 10, and the residual stability value still meets the specifications.

In addition to using Aspen, this subsection explains the Marshall test characteristics for mixtures with SNRCR 7 modification and the substitution of river sand with KA and CR materials. Table 8 shows the Marshall test results for asphalt content between 5% and 7%, where some parameters do not meet the specifications. The bulk density of samples using the substitution of river sand with KA and CR is lower compared to the SNRCR 7 samples without sand substitution. For the parameters of effective asphalt content (pbe) and the No. 200 particle passing ratio, the results are the same for samples SNRCR7-50CR, SNRCR7-50SNR, and SNRCR7-25CRSNR. However, the SNRCR 7 sample differs, with the mixture's specific gravity influencing it: the SNRCR 7 sample without river sand substitution has a higher specific gravity. The VMA (Voids in Mineral Aggregate) test results indicate that several samples do not meet the VMA limit at certain asphalt contents. The use of SNR and CR as sand substitutes tends to decrease the VMA value, except in the 25CRSNR mixture. This substitution effect is also visible in the VIM, which increases with SNR in the samples. The higher air-void content causes this to form when using SNR, compared to river sand or CR. The magnitude of VIM influences the VFA and mixture stability. The VFA values obtained with CR and SNR substitutes tend to be lower than those obtained with river sand. Furthermore, stability testing shows a decrease in stability values at certain asphalt contents when CR and SNR materials are used as substitutes. This is due to the elastic properties of CR and SNR particles, which reduce their capacity to withstand loads effectively.

Table 9 presents the Marshall test results for the KAO sample, which uses SNRCR 7% asphalt as the binder. The test results indicate that the bulk density of samples using CR and SNR as replacements for river sand decreases. For the effective asphalt binder content (pbe), the values tend to increase with higher OAC levels. This increase in effective asphalt content is attributed to the capacity of coarse aggregate, river sand, and CR and SNR to absorb large amounts of asphalt binder. In the VMA test, all samples still meet the minimum limit of 15%. However, in the VIM parameter, one sample fails to meet the specifications, namely SNRCR 7-50SNR, with a VIM value of 6%. This occurrence is due to SNR's higher asphalt absorption capacity, which reduces the amount of asphalt available to fill air voids, resulting in a more porous mixture. Consequently, the stability value decreases and does not meet the standard. Visually, the SNRCR 7-50SNR sample feels softer compared to the SNRCR 7-50CR sample, indicating that the SNRCR 7-50SNR is less resistant to deformation.

Table 8. Marshall test results for SNRCR 7, SNRCR 7-50CR, SNRCR 7 – 50SNR and SNRCR 7-25CRSNR samples for the planned asphalt binder content of 5 – 7%.

Parameter	Spec.	SNRCR 7	SNRCR 7 – 50CR	SNRCR 7 – 50 SNR	SNRCR 7 – 25CRSNR
Type of asphalt binder used	-	SNRCR 7	SNRCR 7	SNRCR 7	SNRCR 7
Sand substitute material	-	100% river sand	50% river sand + 50% CR	50% river sand + 50% SNR	50% river sand + 25% CR + 25% SNR
Density [gr/mL]	-	2.29 – 2.38	2.01 – 2.05	1.99 – 2.04	1.95 – 2.06
Effective asphalt binder content (pbe) [%]	-	4.09 – 6.11	4.15 – 6.17	4.15 – 6.17	4.15 – 6.17
The ratio of passing particles no. 200 to Pbe	0.6 – 1.4	0.8 – 1.2	0.8 – 1.2	0.8 – 1.2	0.8 – 1.2
VMA [%]	min. 15	14 - 17	13 – 17	15 – 17	14 – 20
VIM [%]	3 – 5	2 – 7	4 – 7	4 – 8	4 – 8
VFA [%]	Min. 65	56 – 85	60 - 73	52 - 73	51 – 69
Stability [kN]	Min. 8.83	9.4 – 23.0	5.9 – 9.4	6.6 – 9.4	5.2 – 11.3
Flow [mm]	2 – 5	4 – 6	1 - 4	4 - 5	3 – 6
Marshall quotient (MQ) [$kN \cdot mm^{-1}$]	-	2.24 – 8.22	2.38 – 5.57	1.17 – 1.89	0.82 – 2.78

Table 9. Marshall test results for KAO samples (SNRCR 7, SNRCR 7-50CR, SNRCR 7 – 50SNR and SNRCR 7-25CRSNR).

Parameter	Spec.	SNRCR 7	SNRCR 7 – 50CR	SNRCR 7 – 50 SNR	SNRCR 7 – 25CRSNR
Type of asphalt binder used	-	SNRCR 7	SNRCR 7	SNRCR 7	SNRCR 7
Sand substitute material	-	100% river sand	50% river sand + 50% CR	50% river sand + 50% SNR	50% river sand + 25% CR + 25% SNR
KAO [%]	-	6.05	6.50	6.75	6.00
Density [gr/mL]	-	2.33	2.03	2.01	2.04
Effective asphalt binder content (pbe) [%]	-	5.15	5.67	5.92	5.16
The ratio of passing particles no. 200 to Pbe	0.6 – 1.4	0.97	0.88	0.84	0.97
VMA [%]	min. 15	16	15	17	15
VIM [%]	3 – 5	5	4	6	5
VFA [%]	Min. 65	71	72	67	68
Stability, 30-minute immersion [kN]	Min. 8.83	11.14	10.74	6.29	9.31
Stability, 24-hour immersion [kN]	Min. 8.83	10.39	10.05	5.00	8.81
Flow [mm]	2 – 5	5	4	5	3
Marshall quotient (MQ) [$kN \cdot mm^{-1}$]	-	2.37	2.88	1.27	3.28
Residual Marshall stability after 24-hour immersion [%]	Min. 90	93	94	80	95

This is also reflected in the higher flow value observed in this sample. For the residual Marshall stability test, the SNRCR 7-50SNR sample has a residual value of 80%, which exceeds the specified limit and indicates that using SNR as a 50% replacement for river sand is less effective in improving Marshall characteristics. In comparison, the use of Aspen and SNRCR 7 enhances the Marshall properties of samples containing 50% CR and 25% CR + 25% SNR, as evidenced by increased stability and residual stability values. This phenomenon is also affected by the bond between the binder and the aggregate, which is compromised by water, thereby significantly impacting the interfacial behavior and reducing the adhesion between the mixture components [30], [31]. Visually, samples containing SNR appear rougher and softer compared to the others. This is important as it indicates a texture difference that could influence the mix's performance. In summary, it appears that changing 50% of river sand with SNR does not significantly improve Marshall values; thus, its use should be considered in relation to the needs of the project as well as the standards applicable to it. There is a significant difference in performance between CR and SNR. In addition, it should be noted that the SNRCR 7-50SNR mix did not satisfy the stability criteria (6.29 kN) when compared to its corresponding mix with CR. This is attributed to a difference in morphology; SNR particles are less rigid and absorb more, thus less binder is available for coating the aggregate particles. This results in a drier mix (6% VIM as seen in Table 9), which affects stability when soaked, as it reduces bonding between the interface.

Apart from the discussion on the behavior of SNRCR 7% when river sand is substituted in the above sections, we also discuss the behavior when the mixture is made with the modified asphalt SNRCR 10. As shown in Table 10, the Marshall test values are presented for asphalt content ranging from 5% to 7%. The substitution of river sand with CR and SNR in the mixture is likely to result in a reduced bulk density. If we consider the effective asphalt content in the mixture (pbe), the values are higher than those obtained in the SNRCR 10% mixture. The VMA values generally exceed 15%, but some asphalt contents do not meet the standards, specifically at SNRCR 10-50CR and SNRCR 10-50SNR. The VMA values tend to be lower than those of the SNRCR 10% samples because CR and SNR particles more easily fill the voids between coarse aggregate, resulting in fewer air voids within the mixture. Some of the planned asphalt binder content for VIM is still within the specifications. This is because CR and SNR initially absorb the asphalt binder content. This means that the content of VFA will be low compared to the SNRCR 10%. This means that the VIM values are already high. This causes the stability of the mixture to be low compared to the expected standard. This occurs because of the elastic and non-rigid nature of the CR and SNR aggregates. This contrasts with the hard and stiff texture of river sand [32].

Table 11 presents the results of the Marshall test for the OAC samples, and it is evident that some of them do not meet some of the requirements, specifically VIM, VFA, stability value, and residual stability. However, the SNRCR 10-50SNR sample exceeds the maximum limit of some of its parameters compared to other samples. This is because, unlike other samples, it uses SNR instead of river sand. Since the specific gravity of SNR is lower than that of river sand, more of it is mixed with other aggregates. As a result, more asphalt is absorbed by SNR to bind the coarse aggregates, leaving less asphalt to bind air voids. This is evidenced by the high VIM value and the lowest VFA. Regarding stability, only the SNRCR 10-50CR sample meets the standards when compared to other samples. However, after 24-hour immersion testing, its stability value decreases to approximately 90%. The SNRCR 10-50SNR sample has a residual Marshall stability value of 85%, which does not meet the standard limit. These results indicate that the use of SNRCR 10 with sand substitution using CR and SNR tends to be less satisfactory compared to SNRCR 7. This is because SNRCR 10 contains more rubber than SNRCR 7, significantly affecting performance during Marshall testing, especially during water immersion for 30 minutes and 24 hours.

3.3. Results of Stiffness Modulus Testing of the Mixture

The purpose of the Stiffness Modulus (Smix) testing is to measure the stiffness and durability of the asphalt mixture against traffic loads. This testing helps evaluate the mixture's ability to resist deformation and maintain stability under load, thereby ensuring the quality and longevity of the proposed mixture [33]. For the proposed mixture types to be tested through stiffness modulus measurements, there are seven mixtures. However, this testing was not conducted on the Marshall samples containing 50% SNR, as they did not meet the established Marshall specifications.

Table 10. Marshall test results for SNRCR 10, SNRCR 10-50CR, SNRCR 10 – 50SNR and SNRCR 10-25CRSNR samples for planned asphalt binder content of 5 – 7%.

Parameter	Spec.	SNRCR 10	SNRCR 10 – 50CR	SNRCR 10 – 50 SNR	SNRCR 10 – 25CRSNR
Type of asphalt binder used	-	SNRCR 10	SNRCR 10	SNRCR 10	SNRCR 10
Sand substitute material	-	100% river sand	50% river sand + 50% CR	50% river sand + 50% SNR	50% river sand + 25% CR + 25% SNR
Density [gr/mL]	-	2.28 – 2.35	2.02 – 2.09	2.03 – 2.05	1.98 – 2.04
Effective asphalt binder content (pbe) [%]	-	4.05 – 6.07	4.11 – 6.13	4.11 – 6.13	4.11 – 6.13
The ratio of passing particles no. 200 to Pbe	0.6 – 1.4	0.82 – 1.23	0.81 – 1.21	0.81 – 1.21	0.81 – 1.21
VMA [%]	min. 15	15 – 18	11 – 17	14 – 16	15 – 17
VIM [%]	3 – 5	3 – 8	3 – 5	4 – 7	4 – 9
VFA [%]	Min. 65	53 – 80	67 – 75	55 – 71	44 – 71
Stability [kN]	Min. 8.83	9.4 – 16.7	8.4 – 10.1	8.6 – 9.5	6.6 – 8.8
Flow [mm]	2 – 5	3 – 7	3 – 9	1 – 4	2 – 4
Marshall quotient (MQ) [kN·mm^{-1}]	-	2.06 – 6.46	1.17 – 3.16	2.07 – 5.76	1.75 – 3.11

Table 11. Marshall test results of OAC samples (SNRCR 10, SNRCR 10-50CR, SNRCR 10 –50SNR and SNRCR 10-25CRSNR).

Parameter	**Spec.**	**SNRCR 10**	**SNRCR 10 – 50CR**	**SNRCR 10 – 50 SNR**	**SNRCR 10 – 25CRSNR**
Type of asphalt binder used	-	SNRCR 10	SNRCR 10	SNRCR 10	SNRCR 10
Sand substitute material	-	100% river sand	50% river sand + 50% CR	50% river sand + 50% SNR	50% river sand + 25% CR + 25% SNR
OAC [%]	-	6.25	6.5	6.8	6.8
Density [gr/mL]	-	2.34	2.04	2.01	2.04
Effective asphalt binder content (pbe) [%]	-	5.31	5.63	5.93	5.93
The ratio of passing particles no. 200 to Pbe	0.6 – 1.4	0.94	0.89	0.84	0.84
VMA [%]	min. 15	16	15	17	16
VIM [%]	3 – 5	5	5	6	5
VFA [%]	Min. 65	72	70	63	70
Stability, 30-minute immersion [kN]	Min. 8.83	11.24	9.31	6.73	7.42
Stability, 24-hour immersion [kN]	Min. 8.83	10.59	8.86	5.69	6.73
Flow [mm]	2 – 5	4	4	4	4
Marshall quotient (MQ) [kN·mm^{-1}]	-	2.76	2.33	1.55	1.84
Residual Marshall stability after 24-hour immersion [%]	Min. 90	94	90	85	91

The stiffness modulus testing of the mixture was conducted on samples of Mod-Aspen, Mod-SNRCR 7, and Mod-SNRCR 10, with two samples tested for each test temperature, namely 25°C and 40°C. The average test results are presented in Fig. 5. Fig. 5 shows that the Smix values for mixtures using SNRCR are higher compared to the control sample, which is Mod-Aspen. For samples using SNRCR 7, there was an increase in Smix of 32.30% at 25°C and 67.14% at 40°C. Meanwhile, for Mod-SNRCR 10, the increase in Smix was 88.99% at 25°C and 105.69% at 40°C. Fig. 5 also indicates that samples using SNRCR are more sensitive to temperature changes. The use of SNRCR as a binding agent demonstrates better temperature sensitivity compared to Aspen asphalt, as evidenced by the SNRCR graph positioned above the Aspen graph. This means that the Smix values of mixtures with SNRCR increase more significantly with rising temperature.

Additionally, the Mod-SNRCR 7 and Mod-SNRCR 10 curves exhibit a steeper gradient compared to the Mod-Aspen curve. This indicates that while the incorporation of SNRCR significantly enhances the stiffness modulus, it also increases the mixture's sensitivity to temperature variations. However, it is important to note that even with higher sensitivity, the absolute Smix values for SNRCR mixtures remain substantially higher than those of the control sample at both 25°C and 40°C, indicating superior load-bearing capacity. In addition to using SNRCR as an asphalt modifier, the resulting Smix values are also higher compared to the control sample (Aspen). This subsection discusses the influence of SNR and uses CR as a replacement for river sand in samples modified with SNRCR 7.

Fig. 6 shows the results of Smix testing for the mixtures: Mod-SNRCR 7, Mod-SNRCR 7 with 25% CR and SNR (25CRSNR), and Mod-SNRCR 7 with 50% CR (50CR). The sample without sand replacement, namely Mod-SNRCR 7, has the highest Smix value, reaching 1946 MPa at 25°C and 1090 MPa at 40°C. Meanwhile, the sample using 25% CR and SNR (25CRSNR) exhibits higher Smix values than the sample with 50% CR, indicating that the combination of CR and SNR in SNRCR 7 has a positive effect.

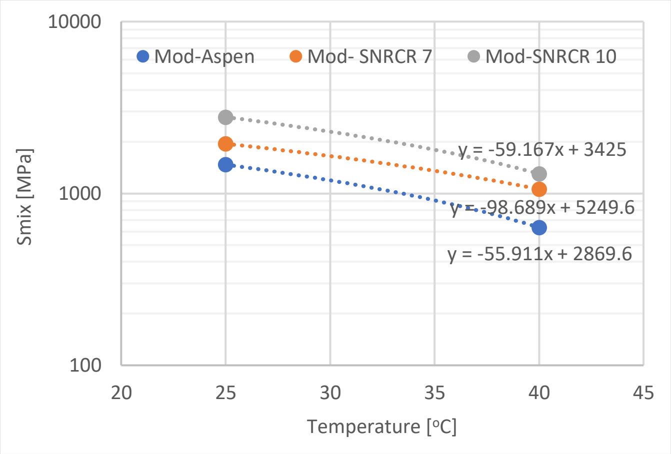

Figure 5. Comparison of Smix values (Aspen, SNRCR 7, and SNRCR 10).

A decrease in Smix values occurs in the 25CRSNR sample, with reductions of 51.90% at 25°C and 76.30% at 40°C compared to the control sample. For the 50CR sample, the decrease in Smix is 61.55% at 25°C and 52.45% at 40°C. These results suggest that using 50% CR can reduce sensitivity to temperature changes. The effect of incorporating SNR and CR as replacements for river sand in hot mix asphalt can be observed from the relationship between Smix and temperature, as shown in Fig. 6. The graph line with the steepest gradient indicates a high sensitivity to temperature changes. Based on Fig. 6, the Mod-SNRCR 7 sample has a larger gradient compared to other samples, even though its Smix value is also higher. The sample using 50% CR as a fine aggregate replacement shows lower sensitivity to temperature changes, evidenced by its smaller gradient value. Conversely, the sample using SNR as a fine aggregate replacement (Mod-SNRCR 7-25CRSNR) tends to be more sensitive to temperature changes, as indicated by its larger gradient value compared to the 50CR sample. From these results, it can be concluded that incorporating SNRCR as an asphalt modifier can enhance the Smix value, although it also increases sensitivity to temperature changes compared to the control sample.

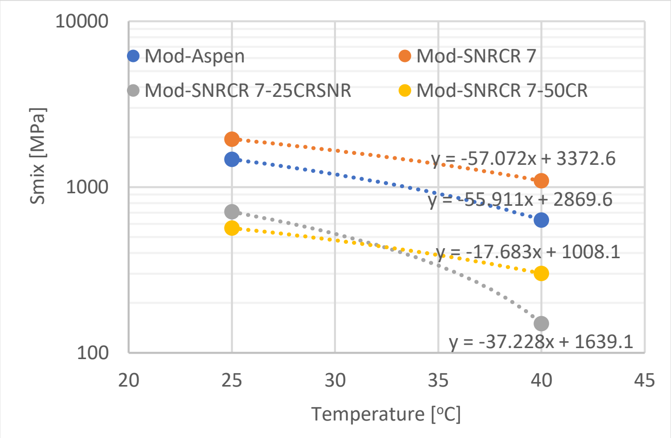

Figure 6. Comparison of Smix values (Mod-Aspen, Mod-SNRCR 7, Mod-SNRCR 7-25CRSNR, and Mod-SNRCR 7-50CR).

In this subsection, the influence of using SNRCR 10 on samples incorporating SNR and CR as replacements for river sand is also discussed. Fig. 7 presents the sample without SNR and CR replacements, namely Mod-SNRCR 10, which has the highest Smix value of 2782 MPa at 25°C and 1302 MPa at 40°C. The decrease in Smix observed in the sample with 25% SNR and 25% CR (Mod-SNRCR 10-25CRSNR) is 78.64% at 25°C and 82.46% at 40°C, compared to the control sample. Meanwhile, the sample using 50% CR (Mod-SNRCR 10-50CR) shows a reduction in Smix of 74.46% at 25°C and 62.14% at 40°C. This trend indicates that using 50% CR yields better results than the combination of SNR and CR, as the reduction in Smix is smaller. Fig. 7 summarizes the comparison of Smix values for all samples utilizing SNRCR 10. It also depicts the relationship between Smix and test temperature, from which a linear equation was derived to determine the gradient (slope). The 50% CR sample, Mod-SNRCR 10-50CR, has a gentler gradient, which implies that it has a lower response to temperature change. The control sample using SNRCR 10 without any replacements has a steep gradient, implying that it has a high response to temperature change. In conclusion, using SNRCR 10 improves Smix compared to the control. The reduction in Smix for samples using CR and SNR substitution is due to the fact that the rubber particles are more elastic and less rigid than river sand. The internal structure becomes less rigid when half of the river sand is replaced with CR. Interestingly, the smaller gradient observed in the 50% CR substitution samples suggests that while these mixtures are less stiff, they are more stable (less sensitive) across temperature changes. This is likely due to the elastic damping effect of the crumb rubber, which mitigates the softening effect of the bitumen at higher temperatures. For future development, it is recommended to conduct more in-depth testing on the effects of other replacement material proportions and additional mechanical properties, to ensure that the resulting mixture not only possesses structural strength but also exhibits improved resistance to temperature variations.

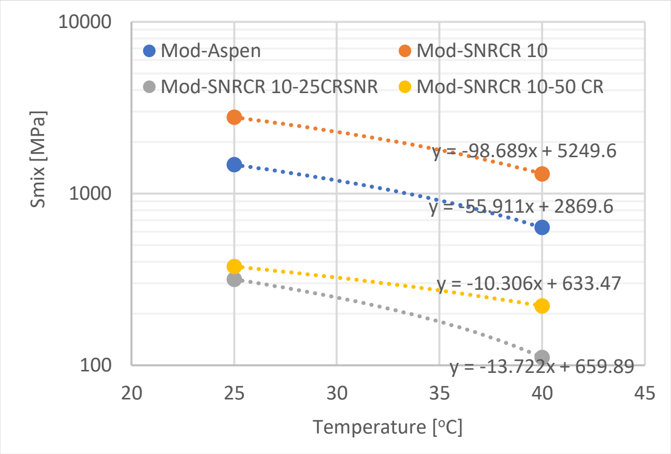

Figure 7. Comparison of Smix values (Mod-Aspen, Mod-SNRCR 10, Mod-SNRCR 10-25CRSNR, and Mod-SNRCR 10-50CR).

3.4. Results of Fatigue Testing

Fatigue is an important failure criterion in pavement systems and affects the progressive wear of bound layers. In this study, the fatigue life of the pavement during ITFT was established using the peak product of stiffness and loading cycles as a failure criterion. Table 12 demonstrates a clear contrast between binder modification and fine aggregate substitution. The F-SNRCR 10 mixture exhibited the best fatigue performance and was able to resist 3,701 cycles, a 9.4% improvement over the control asphalt. This proves that a 10% content of rubber increases the binder's elastic recovery. Conversely, the F-SNRCR 7 mixture was able to resist only 1,601 cycles, which proves that a 7% content of rubber cannot tolerate a stress level of 500 kPa. However, replacing mineral sand with CR and SNR aggregates proved to be even more detrimental. Although tested at lower stress levels of 300-400 kPa, which is lower than that of mineral sand, the samples failed badly. The F-SNRCR 10-25CRSNR samples lasted for only 101 cycles. The very high initial strain values indicate that replacing stiff aggregates with elastic rubber particles weakened the skeleton of the mix. From a mechanical perspective, although SNRCR enhances the quality of binders, replacing aggregates with it destabilizes structural stability. Although microscopic examination of samples was not conducted, the macroscopic failure mechanisms proved useful in understanding the inner mechanisms of failure. It is evident that F-SNRCR 10 samples failed with more ductility than the base asphalt, which indicates that rubber particles are effective crack arrestors in bitumen matrices. Such mechanisms are commonly observed under micro-scale investigations, which have proved useful in understanding why samples lasted longer. The suggested improved interfacial bonding is consistent with micro-structural observations made by [34]-[37], which indicated that improved surface roughness of binders is achieved with rubber modification. Such improved surface roughness enhances mechanical interlocking with aggregates.

Table 12. Fatigue testing results.

Test Result	Unit	F-Aspen	F-SNRCR 7	F-SNRCR 10	F-SNRCR 7-50CR	F-SNRCR 7 - 25CRSNR	F-SNRCR 10-50CR	F-SNRCR 10 – 25CRSNR
Cyclic load	N	5202	5076	5029	4563	4622	3743	3702
Tensile Stress	kPa	500	500	500	400	400	300	300
Tensile Strain	με	1175	1186	1185	1154	1186	1164	1151
Initial Strain	με	94	164	108	154	175	491	1151
Load Repetition	Cycle	3381	1601	3701	1011	531	241	101

3.5. Practical Implications and Challenges

Laboratory tests indicate that using shredded natural rubber and crumb rubber as recycled products in asphalt mixtures is technically possible. However, moving from the laboratory setting to full-scale practical use faces a number of issues. The issue of consistency arises because different types of recycled rubbers have different particle sizes and purity. This could lead to changes in Marshall stability. The temperatures for processing the recycled materials, which reach as high as 173°C, as shown in Table 5, are of concern in terms of energy consumption and possible aging of the binder during production. Even though this study did not undertake a full Life Cycle Assessment of the product, it suggests that the environmental benefits of waste reduction have to be balanced against the energy costs of production. The economic benefits of using recycled rubbers will require an analysis of the costs of handling the recycled rubbers in order to ensure that they are cost-competitive. The construction benefits of the use of SNRCR mixtures could be in the possible difficulties in workability and handling in tight spaces because of the higher viscosity of the SNR and CR binders. This could require specialized equipment for paving. Suggestions for future studies could involve the use of warm mix technology in production in order to lower the production temperatures. A cost-benefit analysis of the process and product could be undertaken in order to ensure that the product and process are cost-competitive.

4. Conclusions

The paper examines the use of solid natural rubber (SNR) and waste tire powder (CR) as an alternative to fine aggregates, i.e., river sand, in the composition of rubber asphalt blends. By processing the SNR and CR into a granular form with particles similar in size to those of fine aggregates, the materials may be used as a replacement for sand in the asphalt blend. Various proposed mixes and combinations of SNR and CR were tested, and the following conclusions were reached:

1) From the Marshall tests, SNRCR 7 and SNRCR 10 are seen to be performing better than the control asphalt, Aspen. However, the optimum asphalt content (OAC) of these two, SNRCR 7 and SNRCR 10, is seen to be higher than that of the control asphalt, Aspen, because of the capacity of the rubber content to absorb more asphalt. Consider the VIM and VFA. These indicate that the addition of SNRCR-modified asphalt changes the inner structure of the mix, resulting in some of the tests being below the standard. SNRCR 10, however, has the highest stability but drops after 24-hour immersion. Replacing river sand with SNR and CR tends to reduce the bulk density of the mix and Marshall stability, but increase the VIM. These, however, depend on the amount of replacement material used. Excessive CR and SNR may be detrimental to quality, but moderate amounts may enhance the stiffness of the mix.
2) Tests for stiffness modulus show that mixtures with SNRCR-modified asphalt, i.e., SNRCR 7 and SNRCR 10, have higher values than those of the Aspen control mix, along with increased sensitivity to temperature changes. When river sand is replaced by SNR and CR, it reduces modulus and strength values but increases sensitivity to temperature changes. Thus, it is very important that the proportioning of materials is done properly to achieve strength along with desired quality standards.
3) From the fatigue test, it is evident that when 10% of SNRCR is added to the binder, it enhances its durability by increasing repetitions of loads by 9.4% (3,701 cycles) compared to the control asphalt. On the other hand, when 7% of SNRCR is used, it is evident that it is inadequate to sustain flexibility under high stress. It is evident that although SNRCR is effective when used to modify the binder, its use to replace other aggregates (CR and SNR) reduces fatigue life by thinning the structural frame. It is apparent that when used effectively, rubber is best utilized when it is used to modify binders.

On the economic side, the initial cost of SNRCR-modified asphalt will be higher than that of normal asphalt because we use waste materials and require more energy. Nevertheless, this cost will be offset by the longer life of the pavement. The use of waste tires in the form of powder (CR) and natural rubber in the form of solid material (SNR) contributes to a sustainable economy. This can lead to a reduction in maintenance and mitigation costs in the long term. These are crucial in the sustainable management of pavements. In the future, studies could be directed towards optimizing the content of substitutes for river sand, such as SNR and CR. This could be done in order to improve their performance more efficiently, especially in terms of stability, stiffness, and resistance to deformation and extreme temperatures. In addition, more studies could be directed towards the physical properties of substitutes in order to determine their effect on the mechanical properties and long life of the mix. In order to achieve a deeper understanding of the inner microstructure of the mix, it is recommended that microstructural investigations be carried out by employing Scanning Electron Microscopy (SEM) to examine the bonding mechanism of the mix at the interface of the binder and aggregate. Moreover, it is crucial that testing of the mix be performed with respect to its fatigue resistance, durability during weathering, and environmental effects. A separate study of Life Cycle Assessment (LCA) should be performed to evaluate the environmental trade-offs and energy savings of using these waste materials compared to conventional mix materials quantitatively. From an industry perspective, it is recommended that an economic feasibility study be performed along with conducting a Life Cycle Cost Analysis (LCCA) of the mix to evaluate its cost-effectiveness and market viability for large-scale use of this hybrid mix. Preparation of other eco-friendly waste materials that could be used as alternatives to aggregate or binders could provide other means of constructing sustainable pavements. Moreover, further research could be directed toward developing more precise formulations of asphalt mix by employing simulations of its mechanical and thermal behavior. Finally, it is crucial that field testing be performed by constructing trial roads to ensure that the mix is sufficiently durable, temperature-resistant, and environmentally friendly while meeting quality standards for constructing sustainable roads.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Ramadhani Ramadhani helped in the data curation, formal analysis, investigation, and the original draft preparation.
Hendrik Jimmyanto was in charge of the conceptualization, methodology, software, visualization, writing, review, and editing.
Rindu Twidi Bethary helped with the resources, validation, writing, review, and editing.
Lega Lubis Reskita helped with the project administration and the writing, review, and editing.

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