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Material Properties and Environmental Benefits of Hot-Mix Asphalt Mixes Including Local Crumb Rubber Obtained from Scrap Tires

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Abstract: This paper presents the results of a laboratory-based experimental investigation on the properties of asphalt binder and hot-mix asphalt (HMA) mixes modified by locally available crumb rubber, which was used as a partial replacement of asphalt by weight. In this study, fine crumb rubber with a particle size in the range of 0.3–0.6 mm, obtained from scrap tires, was added to the asphalt binder through the wet process. Crumb rubber contents of 5%, 10%, 15%, and 19% by weight of asphalt were added to the virgin binder in order to prepare the modified asphalt binder samples, while the unmodified asphalt binder was used as the control sample. The crumb rubber modified binder samples were examined for measuring viscosity indirectly using the penetration test, and temperature resistance using the softening point test. Later, both the modified and unmodified asphalt binders were used to produce HMA mixes. Two categories of HMA mix commonly used in Malaysia—namely, AC 14 (dense-graded) and SMA 14 (gap-graded)—were produced using the modified asphalt binders containing 5%, 10%, 15%, and 19% crumb rubber. Two AC 14 and SMA 14 control mixes were also produced, incorporating the unmodified asphalt binder (0% crumb rubber). All of the AC 14 and SMA 14 asphalt mixes were examined in order to determine their volumetric properties, such as bulk density, voids in total mix (VTM), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). In addition, the Marshall stability, Marshall flow, and stiffness of all of the AC 14 and SMA 14 mixes were determined. Test results indicated that the modified asphalt binders possessed higher viscosity and temperature resistance than the unmodified asphalt binder. The viscosity and temperature resistance of the asphalt binders increased with the increase in their crumb rubber content. The increased crumb rubber content also led to improvements in the volumetric properties (bulk density, VTM, VMA, and VFA) of the AC 14 and SMA 14 mixes. In addition, the performance characteristics of the AC 14 and SMA 14 mixes—such as Marshall stability, Marshall flow, and stiffness—increased with the increase in crumb rubber content. However, the AC 14 mixes performed much better than the SMA 14 mixes. The overall research findings suggest that crumb rubber can be used to produce durable and sustainable HMA mixes, with manifold environmental benefits, for use in flexible pavements carrying the heavy traffic load of highways.

Keywords: asphalt; crumb rubber; environment; hot-mix asphalt (HMA) mixes; modified binder; performance characteristics; scrap tires; temperature resistance; viscosity; volumetric properties

1. Introduction

Scrap tires are causing environmental hazards in many countries due to inappropriate disposal. They are unquestionably one of the waste products that have been causing environmental issues in Sarawak and other states of Malaysia over the past few years. Therefore, scrap tires should be recycled for use in various construction applications. The crumb rubber extracted from scrap tires can be used in hot-mix asphalt (HMA) mixes to improve their various properties for durable and sustainable application on the roads. Past research has revealed that the incorporation of crumb rubber into asphalt mixes can increase the rutting resistance, reduce the fatigue cracking, and enhance the durability of flexible pavements against traffic loads [1–4]. With the rapid increase in the number of vehicles on the roads today due to economic growth, it is necessary to construct more durable and sustainable pavements, wherein crumb rubber obtained from scrap tires can play a significant role.

Crumb rubber is a commodity that is produced during the reprocessing of scrap tires composed of natural and synthetic rubbers. Although in Malaysia the use of crumb rubber in modified asphalt pavement is relatively uncommon, the United States of America (USA) started using it back in 1950 [5], and since then it has been implemented widely across the different states of the USA. In the 1960s, crumb rubber was also used in the Swedish pavement industry [6]. From more environmentally friendly and sustainable engineering perspectives, there is a necessity for the application of crumb rubber on the roads of Malaysia—particularly in Sarawak state, with its unique local resources, such as aggregate and asphalt materials.

According to a survey conducted by the Natural Resources and Environment Board (NREB) of Sarawak, in collaboration with the Danish Cooperation for Environment and Development (DANCED), back in 2001, the annual production of scrap tires reached a total of 150,000 units [7]. With the rapid increase in the number of vehicles today, it is certain to say that the amount of scrap tires has increased proportionally. The State Government of Sarawak has an environmental program to collect, manage, and recycle scrap tires throughout Sarawak via a waste tire storage and recycling center, as well as to deport tire waste statewide as part of its collection network. Companies collecting scrap tires have been set up in a bid to ease the problem of handling scrap tires in recent years. Their main purpose is to retrieve the fiber and steel contained in tires, which make up only a minor part of tire composition. The majority of scrap tire composition is rubber; a scrap tire typically contains 70% recoverable rubber [8]. This rubber is used as an alternative burning material. In many countries, scrap tires are co-fired with coal or other fuels in cement factories [9], but this still creates environmental pollution. Furthermore, as the number of vehicles on the roads has increased, scrap tire disposal has become a greater environmental concern to the municipal and public health authorities, as sanitary landfills will soon be unable to accommodate the stockpiles of scrap tires, which are also hazardous to human health. Hence, proper recycling and utilization of scrap tires are necessary. Since roads constitute a major part of the infrastructure in any country, a vast amount of scrap tires could be utilized in pavement construction.

Roads play a pivotal role in the daily activities of people, mainly transporting passengers and goods to different points. In East Malaysia, the Trans-Borneo Highway (Pan Borneo Highway) is the major road that not only links cities and small towns throughout Sarawak, but also connects Sarawak and Sabah with Brunei and the Kalimantan region of Indonesia, covering a total length of approximately 2083 km [10]. This highway was officially launched on 31 March 2015 [11]. Thereafter, the road's condition deteriorated rapidly due to its high and heavy usage, mainly by heavy trucks and buses delivering goods and passengers between cities. Millions of MYR (Malaysian Ringgit) are being spent annually on the maintenance and upgrading of the Trans-Borneo Highway for the safety of the road users. Therefore, the application of high-durability pavement to this highway is urgently required in order to slow down its deterioration.

Many investigations have been conducted for finding alternative materials to be used as modifiers in asphalt mixes in order to improve their properties; crumb rubber is one such option among the alternatives. The application of crumb rubber in HMA mixes has been established in advanced countries—most notably in Sweden and the USA [6,12]—as they aimed to tackle the number of scrap tires generated every year without compromising the quality of the roads, rather improving their performance. To date, the USA is the leading country in crumb rubber modified asphalt pavement technology. In Malaysia, this technology is less established, and uncommon in the road construction industry. According to Hassan [13], the use of crumb rubber as a modifying agent in HMA mixes for road construction is not widespread in Malaysia. Hence, there is a need for research in order to evaluate the performance of crumb rubber modified HMA mixes in Malaysian road conditions.

This study aims to examine the effects of crumb rubber when it is used as a modifier of asphalt in HMA mixes. Several modified asphalt binder and HMA mixes were produced incorporating crumb rubber as 5–19% weight replacements of asphalt, and their performance characteristics were examined based on JKR (Jabatan Kerja Raya—Department of Public Works) standards [14], compared with the unmodified asphalt binder and HMA mixes. Specifically, the objectives of this research were to evaluate the performance of the crumb rubber modified HMA mixes compared to the conventional HMA mixes in terms of Marshall stability and flow, as well as major volumetric properties such as bulk density, voids in the total mix (VTM), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). In addition, the stiffness of the HMA mixes was determined based on their Marshall stability and flow values. The penetration resistance (as an indirect measure of viscosity) and softening point (as a direct measure of temperature resistance) of the modified and unmodified asphalt binders were also studied.

2. Research Significance

An enormous quantity of scrap tires is causing environmental issues in Malaysia. As in other states of Malaysia, scrap tires have become an environmental burden in Sarawak. This burden is increasing with the rapid increase in the number of vehicles on the roads. Therefore, it is necessary to repurpose scrap tires in various construction works. Crumb rubber is obtained abundantly during the reprocessing of scrap tires. This study examined the effects of crumb rubber on the key properties of asphalt binder and HMA mixes, which were prepared using the constituent materials locally available in Sarawak. The findings of this study shall provide an opportunity to overcome the environmental problems caused by scrap tires, as well as a feasible means for the future improvement of the performance of flexible pavements in Sarawak, where the lives of the road users can be further safeguarded. The research outcomes would also encourage the implementation of the crumb rubber modified HMA pavements in other states of Malaysia, as well as elsewhere around the globe.

3. Background

3.1. Hot-Mix Asphalt (HMA) Mixes

HMA mix is typically comprised of aggregates, an asphalt binder, and a small portion of mineral filler. This type of asphalt mix is widely used in constructing flexible pavements. Aggregates used in the HMA mixes generally consist of a blend of gravel or crushed stone (or both) and sand. They constitute the structural skeleton of an HMA mix. Asphalt plays the role of a binder in an HMA mix; it is a byproduct of the petroleum industry obtained during the extraction process of gasoline, kerosene, fuel oils, etc., and has normally a black or dark brown appearance. Asphalt acts as an adhesive, gluing the aggregates into a dense mass and waterproofing the aggregate particles because of its sticky physical properties [15]. AC 14 and SMA 14 are the two common types of HMA mix used in Sarawak and other states of Malaysia. They are produced in Malaysia according to JKR standard specifications [14].

AC 14 is an HMA mix that includes dense-graded aggregates. Dense-graded aggregates refer to an aggregate blend consisting of more evenly distributed particle sizes

(ranging from 75 μm to 14 mm). The dense state of the aggregates strengthens the bonds between particles, and thus enhances the strength of the AC 14 mix and the service life of flexible pavements [14]. AC 14 is used as a wearing course in flexible pavements. The binder grade for this type of HMA shall be of the penetration grade of 60/70 or 80/100. The binder content, as recommended by JKR standard specifications, shall be in the range of 4–6% of the total weight of asphalt mix.

SMA 14 is also an HMA mix, but it includes gap-graded aggregates. Stone mastic asphalt (SMA), also called stone-matrix asphalt, was developed in Germany in the 1960s; SMA is a deformation-resistant, durable surfacing material, appropriate for the heavily trafficked roads; it typically contains 70–80% coarse aggregate, 8–12% filler, 6–7% binder, and 0.3% fiber [16]. The high coarse aggregate content enables the formation of a stone skeleton structure with voids filled with high-viscosity asphalt mastic. SMA provides a high resistance to the rutting caused by heavy axle loads [14]. As per JKR standard specifications, SMA 14 mix requires a relatively high binder content of 5–7%, which is higher than that of AC 14 mix. This could be explained as a result of the volume of voids between the interlocking aggregates being much higher in an SMA 14 mix. Alike AC 14 mix, SMA 14 mix is also used as a wearing course in flexible pavements. Polymer-modified asphalt of the penetration grade 80/100 shall be used to produce an SMA 14 mix for application in flexible pavements.

3.2. Scrap Tires and Their Adverse Effects on the Environment

Scrap tire waste is defined as “a type of solid waste that includes any unwanted or discarded tire, regardless of size, that has been removed from its original use” [17]. These are worn, damaged, defective, and unrepairable end-of-life tires, and cannot be reused on a vehicle. The global quantity of scrap tires is increasing every year due to the increased number of vehicles on the roads. In the last decade, the production of motor vehicles in industrialized countries increased by 85% [18]. About 97 million motor vehicles were manufactured, and the amount of scrap tires generated was around 25.6 million tons, in 2016 alone [19]. According to Alfayez et al. [20], the estimated total number of scrap tires will be at least 1.2 billion by 2030. China is the main generator of scrap tires, followed by the USA. In Malaysia, the total amount of scrap tires generated in 2015 was about 311 kilotons [19].

Scrap tires are detrimental to the environment and public health if they are not disposed of properly. Thomas et al. [21] reported that more than 50% of scrap tires are discarded in the environment without any proper treatment. This is very alarming for the environment, because scrap tires are non-biodegradable and hazardous to the environment [6]. They may release toxic ingredients and chemical substances that pollute the air, soil, and even groundwater [18]. In many countries, scrap tires are burned and used as fuel in various factories. However, the burning of scrap tires can contaminate the air and endanger public health [22,23]. This is because a large amount of CO_2 (carbon dioxide) is emitted when scrap tires are burned [24]. The disposal of scrap tires to landfills can also be harmful and unhealthy, as they will allow the rise of insects and rodents [25].

3.3. Extraction of Crumb Rubber from Scrap Tires

Crumb rubber can be extracted from scrap tires through grinding—namely, ambient grinding and cryogenic grinding [5]. Whatever method is used, the crumb rubber extracted should be free of fibers and steel. The ambient grinding process is performed at or near ambient temperature, without any cooling or heating. In this process, the scrap tires are first shredded into the chips of 50 mm in size, and then these chips are passed through a granulator in order to obtain rubber granules of a size smaller than 10 mm, while liberating the steel and fibers [8]. After exiting the granulator, the steel is removed magnetically using a metal separator, while the fibers are removed by means of a shaking screen combined with low-vacuum suction. Later, the rubber granules typically enter one or more finishing mills (e.g., high speed rotary mill, cracker mill, etc.) consecutively for fine grinding, followed

by a gyratory screen or wind sifter. Figure 1 shows the typical flow chart of the ambient grinding process. The crumb rubber produced by this method generally has a very cut, spongy, and rough surface. It possesses a high specific surface area and a relatively narrow particle size distribution.

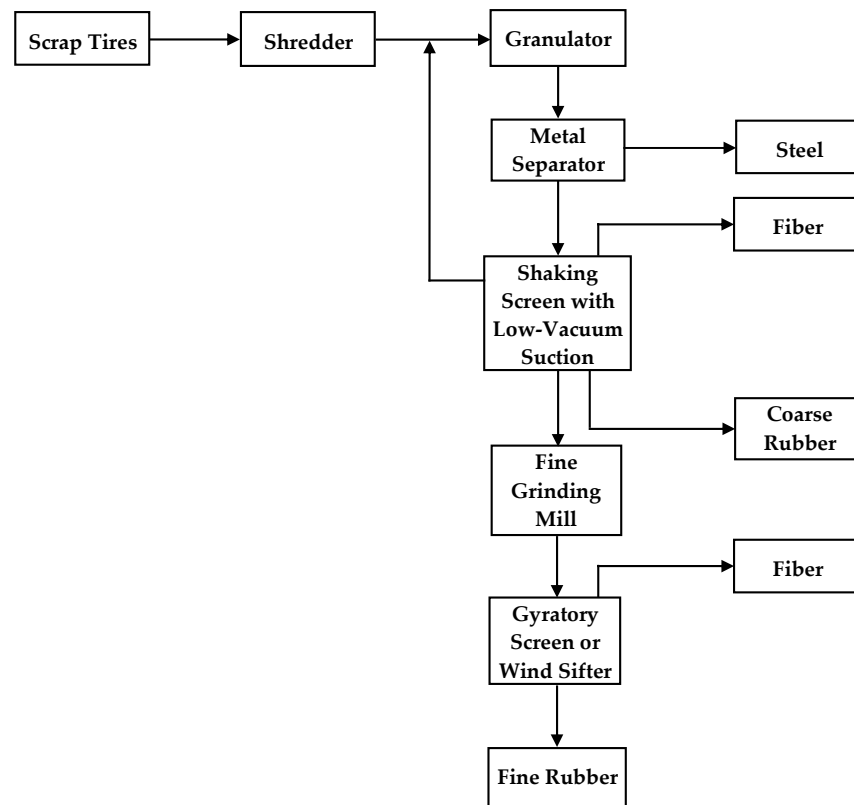


Figure 1. The ambient grinding process.

The cryogenic grinding process is basically composed of four phases—initial size reduction, cooling, separation, and milling. The scrap tires are first shredded into small chips of 50 mm in size, and then these tire chips are cooled to a temperature of below $-80\text{ }^{\circ}\text{C}$ using a continuously operating cryogenic or freezing tunnel using liquid nitrogen or commercial refrigerants [8]. The cooled tire chips are then dropped into a hammer mill, where they are shattered into a wide range of particle sizes, liberating the steel and fibers. After exiting the hammer mill, the fibers are removed by a fabric separator, while the steel is removed magnetically by a metal separator. Later, the rubber material is dried or heated, because it may still be very cold, before classifying into different particle sizes. The drying step also removes humidity from the rubber. After drying and classification, the secondary grinding step can be included to produce a much finer rubber product. Figure 2 shows the flow chart of the cryogenic grinding process. This extraction method is much cleaner and quicker than the ambient grinding process [5]. The crumb rubber obtained via this grinding method is comparatively even and smooth, has a wide particle size distribution, and possesses a relatively shiny and clean appearance.

3.4. Classification of Crumb Rubber

Crumb rubber is described or measured by the mesh screen or sieve size through which it passes during the recycling process [5]. Crumb rubber particles can be of various sizes and shapes, depending on the extraction method and the degree of grinding. Based on the particle size, crumb rubber can be classified into 4 groups: (a) coarse (6.3–9.5 mm); (b) medium (600 μm –2 mm); (c) fine (180–425 μm); and (d) superfine (75–150 μm) [26].

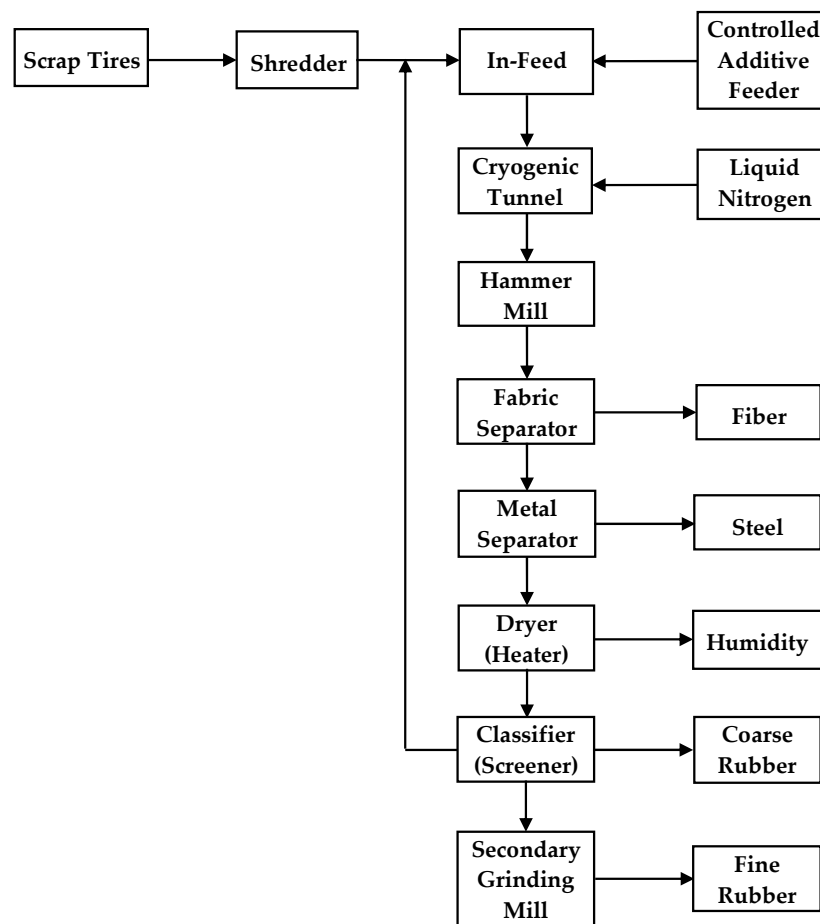


Figure 2. The cryogenic grinding process.

3.5. Mixing of Crumb Rubber

Crumb rubber extracted from scrap tires can be incorporated into an HMA mix using two different methods—the dry process and the wet process. In the dry process, crumb rubber is used in an HMA mix, replacing a certain quantity of aggregates. In this process, the asphalt binder is added only upon the mixing of crumb rubber and heated aggregates, as shown in Figure 3. On the other hand, the wet process refers to the modification of the asphalt binder with crumb rubber, which is used to replace a certain amount of asphalt by weight. In this process, the crumb rubber is heat-mixed with the asphalt binder, before being mixed with the aggregates to produce an HMA mix, as illustrated in Figure 4.

The dry process is much simpler than the wet process, because the procedure of replacing some of the aggregates with crumb rubber is easier than replacing some of the asphalt binder. Moreover, the dry process can be implemented in most cases at a much lower cost, without the necessity of a major revamp of the mixing procedure. However, the application of the dry process is limited compared with the wet process. This is because the crumb rubber modified asphalt mixes prepared using the dry process suffer from volume instability, and possess relatively low strength, since rubber particles replace some of the aggregates [27]. On the other hand, the crumb rubber modified asphalt binder obtained through the wet process shows higher rutting resistance and performs better against fatigue cracking [28], indicating a greater durability of the rubberized HMA mixes.

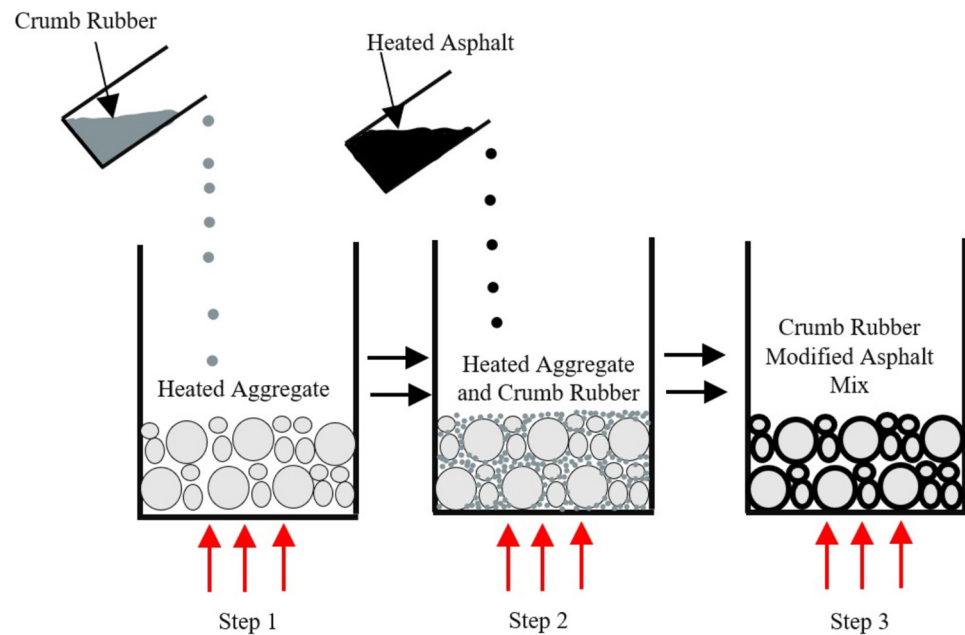


Figure 3. The dry process of mixing crumb rubber to produce an HMA mix.

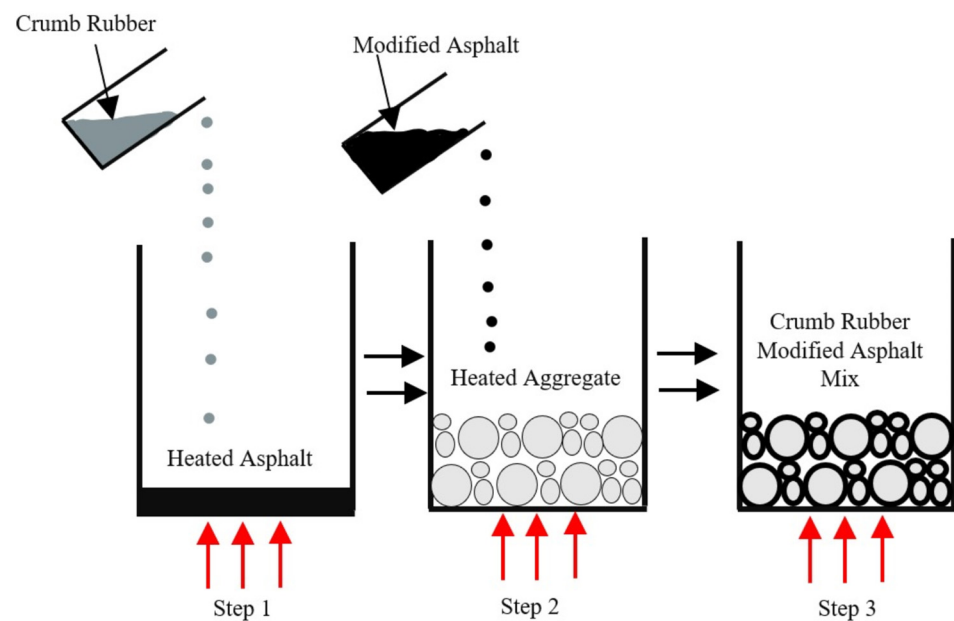


Figure 4. The wet process of mixing crumb rubber to produce an HMA mix.

3.6. Factors Affecting the Properties of Crumb Rubber Modified Asphalt Binder

The blending of asphalt and crumb rubber at elevated temperatures causes the crumb rubber particles to soften and swell, forming a creamy product (gel) around the rubber particles due to the absorption of aromatic oils from the asphalt, thus increasing the viscosity and stiffness of the asphalt binder [12]. Additionally, several factors may affect the digestion process of asphalt and crumb rubber, including the type of rubber. Widyatmoko and Elliot [12] reported that natural rubber, mostly extracted from truck tires, is more heat-sensitive than synthetic rubber, which is mainly obtained from car tires. This is because natural rubbers tend to depolymerize during the digestion period.

The blending effectiveness of asphalt and crumb rubber depends on the mixing time and temperature. Mashaan et al. [29] observed in their study that the blending time in the range of 30–60 min had no significant effect on the performance properties of crumb rubber

modified asphalt. Moreover, Ibrahim et al. [30] stated that a mixing process of 15 min at 177 °C is adequate for 15% crumb rubber with 425–600 µm particle sizes to fully interact with asphalt. In general, the mixing time and temperature should be in the range of 15–60 min and 150–200 °C, respectively, depending on the particle size of crumb rubber [29,30].

The extraction process, particle size, and content of crumb rubber influence the performance of the modified asphalt binder. Compared to the crumb rubber produced by the cryogenic grinding procedure, the crumb rubber obtained through the ambient grinding process performs better in terms of temperature resistance when blended with asphalt. This could be due to differences in surface texture: the crumb rubber produced via the ambient grinding method tends to have a rougher surface texture than the crumb rubber extracted via the cryogenic grinding process [4,12,31]. Regarding the effects of particle size, an earlier study indicated that the modified asphalt binder containing crumb rubber with the particle sizes of 0.2–0.4 mm provides the best laboratory results [5]; a finer rubber reacts better with asphalt, especially during the wet process. Furthermore, the increase in rubber content generally increases the viscosity, resilience, and softening point of asphalt [5]. However, the optimal rubber content varies depending on the particle size of rubber and the type of asphalt binder used.

3.7. Use of Crumb Rubber in HMA Mixes

Researchers have previously used crumb rubber in HMA mixes, either through the dry process or the wet process. Hassan et al. [32] studied the effects of crumb rubber on the volumetric properties and rutting resistance of the modified dense-graded AC 14 and gap-graded SMA 14 HMA mixes, using Marshall specimens. They used crumb rubber through the dry process, replacing 1–3% of the total aggregates by weight in accordance with the Malaysian mix design. Their study showed that the rubberized AC 14 mixes had a greater rutting resistance than the conventional AC 14 mix. In contrast, the rubberized SMA 14 mixes prepared using the penetration grade 80/100 asphalt showed a lower level of performance than the conventional SMA 14 mix. The performance of the crumb rubber modified SMA 14 mixes, including the penetration grade 80/100 asphalt, was also evaluated by Mashaan et al. [33]. They used crumb rubber in the SMA 14 mixes through the dry process, replacing 6%, 12%, 16%, and 19% of asphalt by weight. The SMA 14 mix with 12% crumb rubber resulted in the maximum level of stability based on Marshall testing, and all modified samples—irrespective of their rubber content—had a higher resilient modulus than the unmodified samples.

The effects of the size and content of crumb rubber on the performance of porous HMA mixes were investigated by Cetin [34], who used rubber with three mesh sizes in the ranges of 4.76 mm–840 µm (#4 to #20), 840–74 µm (#20 to #200), and 4.76 mm–74 µm (#4 to #200) and three contents of 10%, 15%, and 19% by weight of the optimal amount of asphalt. It was found that the increases in the crumb rubber particle size and content generally led to degradation of the performance characteristics of the porous HMA mixes. The effects of crumb rubber content on the performance properties of HMA pavements were also examined by Lee et al. [31], who used crumb rubbers obtained through both the ambient and cryogenic grinding methods, and incorporated them into the asphalt mixes via the wet process. Four different rubber contents of 5%, 10%, 15%, and 19% were mixed with asphalt, and the performance of the HMA mixes was evaluated using the Superpave specimens. It was found that a higher amount of crumb rubber leads to greater viscosity, better rutting resistance, and a reduced risk of low-temperature cracking. The study conducted by Lee et al. [31] also showed that the crumb rubber obtained via the ambient grinding process yields better performance when used with asphalt, compared to the crumb rubber derived from the cryogenic grinding process, due to high viscosity and less susceptibility to rutting and cracking.

4. Materials and Methods

4.1. Constituent Materials of HMA Mixes

The penetration grade 80/100 asphalt, complying with JKR/SPJ/REV2008-S4 standard specifications for road works [14], was used to prepare the modified binder and HMA mixes (AC 14 and SMA 14). The viscosity, ductility, softening point, penetration, specific gravity, and flashpoint of the asphalt was 306.7 mPa.s at 135 °C, >100 at 25 °C, 47 °C, 88 at 25 °C, 1.01, and 305 °C, respectively.

Crumb rubber obtained from Zhen Hak Ann Tyre Recycle Sdn. Bhd., Kuching, Malaysia was used as a modifier of the asphalt. This was produced solely from the used passenger car tires using the ambient grinding process (refer to Figure 1). Figure 5 shows the crumb rubber used in the present study. It contained mainly synthetic rubber, with a high quantity of rounded particles. The particle size of the crumb rubber varied from 300 µm to 600 µm. The specific gravity of the crumb rubber was 0.41.

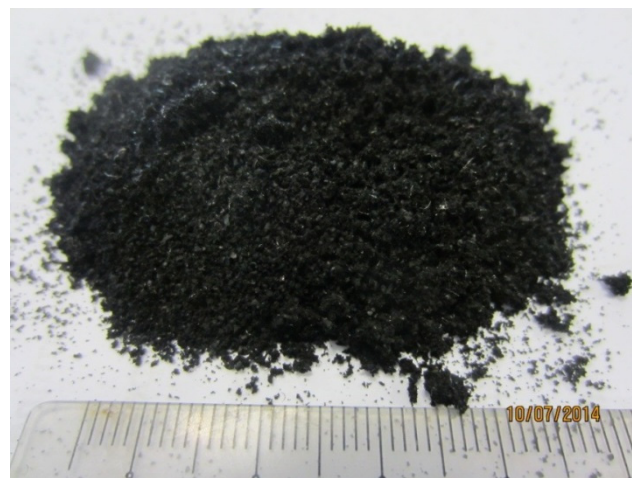


Figure 5. Crumb rubber used in the asphalt binder and HMA mixes.

To produce the AC 14 and SMA 14 HMA mixes, a blend of granite stone and limestone coarse aggregates was used due to the limited source of granite stone. This was anticipated to have a limited effect on the research results, as the aim of the study was to determine the effects of crumb rubber when used in the HMA mixes by replacing a certain amount of asphalt. The specific gravity of the AC 14 aggregate was 2.59, while the specific gravity of the SMA 14 aggregate was 2.57. The aggregates required for the AC 14 and SMA 14 mixes were blended and sieved in accordance with JKR/SPJ/REV2008-S4 standard specifications [14]. The gradation of the combined aggregates for the AC 14 and SMA 14 mixes is shown in Tables 1 and 2, respectively. For both categories of HMA mix, the aggregates conformed to the specified gradation limits given in JKR/SPJ/REV2008-S4 [14]. It should be mentioned that JKR/SPJ/REV2008-S4 uses the BS gradation limits for the AC 14 aggregate, whereas it applies the ASTM gradation limits for the SMA 14 aggregate.

4.2. Preparation of Modified and Unmodified Asphalt Binders

Modified asphalt binder mixes were prepared incorporating 5%, 10%, 15%, and 19% crumb rubber as a partial replacement of the virgin asphalt by weight. An unmodified (0% crumb rubber) asphalt binder was also prepared for use as the control asphalt binder. All of the modified asphalt binders were prepared in the temperature range of 180–190 °C for a better mixing of the rubber with the asphalt. Moreover, this temperature range was chosen in order to avoid the undesirable hardening of the asphalt binders that occurs due to rapid depolymerization at temperatures higher than 200 °C [30]. Crumb rubber modifier, varying in the particle size range of 300–600 µm, was mixed at the above-mentioned temperature for 30 min. In general, the mixing time varies in the range of 15–60 min [29]. In the present study, the mixing time was fixed at 30 min. Throughout the course of the mixing, the

rubberized asphalt binders were manually stirred for a better interaction between the asphalt and crumb rubber particles. It should be mentioned that the unmodified asphalt was also heated at the temperature of 180–190 °C for 30 min so that the effect of heating remained consistent for all asphalt binders.

Table 1. Aggregate * gradation for the AC 14 HMA mix.

BS Sieve Size (mm)	Weight Retained (g)	% Retained	% Passing	BS Limits
20	0	0	100	100
14	64	6	94	90–100
10	151.5	14	80	76–86
5	265.7	24	56	50–62
3.35	115.4	11	45	40–54
1.18	230.5	21	24	18–34
0.425	75.2	7	18	12–24
0.15	115.6	11	7	6–14
0.075	32.5	3	4	4–8
Tray	43.8	4	0	-

* Sample weight: 1094.2 g.

Table 2. Aggregate * gradation for the SMA 14 HMA mix.

ASTM Sieve Size (mm)	Weight Retained (g)	% Retained	% Passing	ASTM Limits
19	0	0	100	100
12.5	0	0	100	100
9.5	253.4	23	77	72–83
4.75	495.3	45	32	25–38
2.36	127.8	12	20	16–24
0.6	70.1	6	13	12–16
0.3	11.8	1	12	12–15
0.075	45.8	4	8	8–10
Tray	90.3	8	0	-

* Sample weight: 1094.5 g.

4.3. Penetration Test

The penetration depths of the unmodified and crumb rubber modified asphalt binders were determined in accordance with ASTM D5-06 standard test method [35]. The asphalt binder samples were tested in order to measure the depth to which a standard needle could penetrate them under a load of 100 g for a duration of 5 s at a temperature of 25 °C. The penetration depth is inversely related to the viscosity of the asphalt binder—it becomes lower when the viscosity is higher. The standard penetration test, using a needle, is the most appropriate method—as opposed to the cone penetration test—for the asphalt binder modified with the fine crumb rubber with particle sizes smaller than 850 µm [12].

4.4. Softening Point Test

The softening points of the unmodified and crumb rubber modified asphalt binder mixes were determined via the ring and ball test, in accordance with ASTM 36-06 standard test method [36]. The softening point was identified as the temperature at which the binder sample could no longer support the weight of a 3.5 g steel ball placed upon it. The softening point indicates the temperature resistance and relative viscosity of asphalt binder.

An asphalt binder with a greater softening point possesses higher temperature resistance and viscosity.

4.5. Preparation of HMA Mixes

Aggregates and asphalt binders (unmodified and modified) were used to prepare the HMA mixes following the wet process. Crumb rubber was added to the heated asphalt in order to prepare the modified asphalt binders. The aggregates were washed and oven-dried to ensure that they remained free from clay, loam, organic matter, and other deleterious substances. The asphalt binders and aggregates were appropriately measured and mixed at elevated temperature (≤ 150 °C), placed in cylindrical molds of 100 mm diameter and 64 mm height, and compacted using a Marshall hammer in accordance with ASTM D6926-10 standard practice [37]. In this study, Marshall specimens were prepared for the modified AC 14 and SMA 14 HMA mixes incorporating 5%, 10%, 15%, and 19% crumb rubber as a partial replacement of the asphalt by weight. Marshall specimens made with the unmodified AC 14 and SMA 14 HMA mixes were also prepared for use as the control specimens (0% crumb rubber). The asphalt binder content of all of the unmodified and modified HMA mixes was 6%. Triplicate specimens were used for each HMA mix. In total, 30 specimens (15 for AC 14 and 15 for SMA 14) were prepared and tested using Marshall apparatus, in accordance with the procedure given in JKR/SPJ/REV2008-S4 standard specifications [14].

4.6. Stability and Flow Tests

The stability test is related to the resistance of asphalt materials to distortion, displacement, rutting, and shearing stress, which mainly depend on internal friction due to the interlocking of aggregates and cohesion caused by the binding force of the binder in specimens. Since flexible pavements are subjected to severe traffic loads from time to time throughout their service life, an asphalt binder with relatively high stability and low flow is required. In this study, the Marshall stability test was conducted in accordance with ASTM D6927-06 [38], in order to determine the maximum load that HMA (AC 14 and SMA 14) specimens can sustain, with a loading rate of 50 mm/min at a temperature of 60 °C. During the loading test, a dial gauge was attached to the specimens in order to measure the plastic flow caused by the applied load. The vertical deformation at the maximum load was recorded as the flow value. In addition, the average stability and flow values of each HMA mix were used to determine its stiffness.

5. Test Results and Discussion

5.1. Penetration

In this study, a total of three asphalt binder samples from a single batch were prepared for respective crumb rubber content. The asphalt binder sample with 0% crumb rubber was used as the unmodified or control sample. The results of the penetration tests are shown in Figure 6. The average penetration value of the control sample was 80.02 mm, which complies with the requirement of the penetration grade 80/100 asphalt. Figure 6 shows that the penetration value decreased as the crumb rubber content increased. An approximately 12–15% decrease in the penetration depth occurred with every 5% increment of crumb rubber added to the asphalt. The average value of 68.08 mm, 58.36 mm, 50.46 mm, and 44.41 mm was recorded for 5%, 10%, 15%, and 19% crumb rubber content, respectively.

The overall penetration results indicate that the viscosity of the modified binder increased with a higher crumb rubber content. Figure 6 shows a consistent trend in terms of the penetration values. The proportional decrease in the penetration depth with the increase in crumb rubber content implies that the asphalt binder progressively stiffened as the rubber content was increased. These results are consistent with the findings of Ibrahim et al. [30], who found a similar trend when increasing quantities of crumb rubber were incorporated into the asphalt binder through the wet process. This kind of trend

was also found by Nejad et al. [39], who noticed that adding crumb rubber reduced the penetration before and after the aging process in a rolling thin film oven.

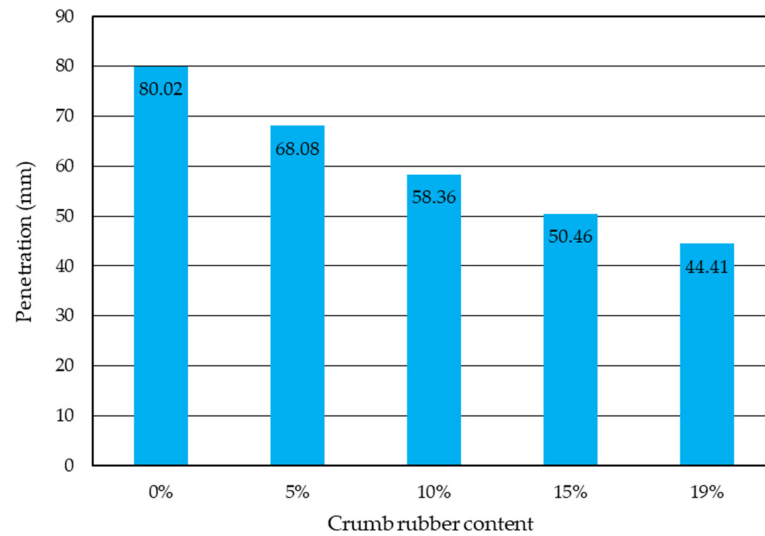


Figure 6. Penetration of the crumb rubber modified asphalt binders (mm).

5.2. Softening Point

The softening point test results of the unmodified and modified asphalt binders obtained from the ring and ball apparatus are presented in Figure 7. The unmodified asphalt binder samples had an average softening point of 47.6 °C, which is within the range of 45–52 °C stipulated for the penetration grade 80/100 asphalt. The asphalt binder with 5% crumb rubber showed an 11.1% increase in its softening point compared to the unmodified sample, while the asphalt binder with 10% crumb rubber had a slight further increase (4%) in its softening point. However, a steep further increase (11.6%) in softening point was observed for the asphalt binder with 15% crumb rubber. Similarly, a 12.5% further increase in softening point was observed for the asphalt binder with 19% crumb rubber.

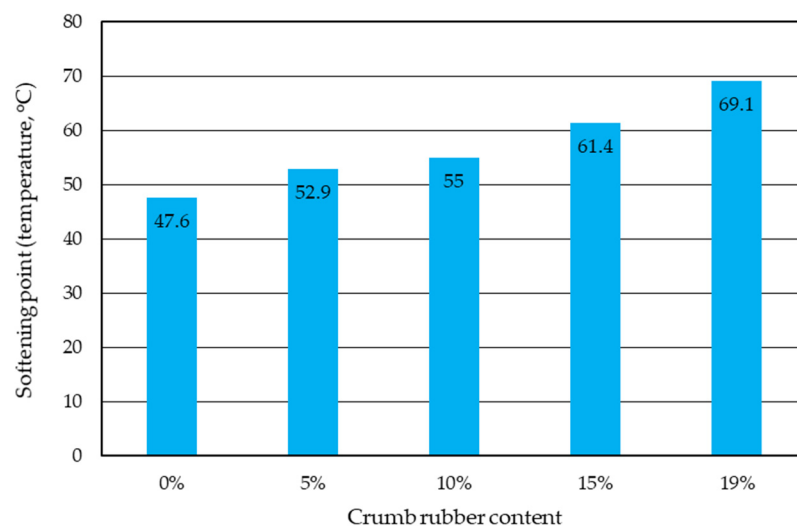


Figure 7. Softening points of the crumb rubber modified asphalt binders (mm).

All of the modified asphalt binder samples (apart from the 10% crumb rubber modified sample) showed a consistent and directly proportional rate of increase (approximately 11.7% on average) in terms of softening point, as evident from Figure 7. This indicates that the increase in crumb rubber content increased the softening point of the modified

asphalt binders to a greater extent. The softening point increased because the asphalt binder became stiffer in the presence of crumb rubber. This is consistent with the findings of Ibrahim et al. [30]. An increase in softening point means a higher temperature resistance. The high temperature resistance of the modified asphalt binders suggests that their viscosity increased due to the inclusion of crumb rubber. It implies that a crumb rubber modified asphalt binder with a higher softening point possesses a greater viscosity. Hence, a higher softening point of the modified asphalt binder will improve its serviceability during actual application in road construction, especially in the warm-climate regions like Sarawak and other states of Malaysia.

5.3. Volumetric Properties

5.3.1. Bulk Density

The bulk density results of all of the AC 14 and SMA 14 HMA mixes, including different crumb rubber contents, are shown in Figure 8. It can be seen from Figure 8 that the bulk density of the AC 14 and SMA 14 mixes did not deviate much with different crumb rubber contents. The bulk density of the AC 14 mixes was slightly higher than that of the SMA 14 mixes. This is credited to the gradation of the aggregates used in the HMA mixes. The AC 14 mixes had a dense-graded aggregate structure, whereas gap-graded aggregates formed a much more porous structure in the SMA 14 mixes.

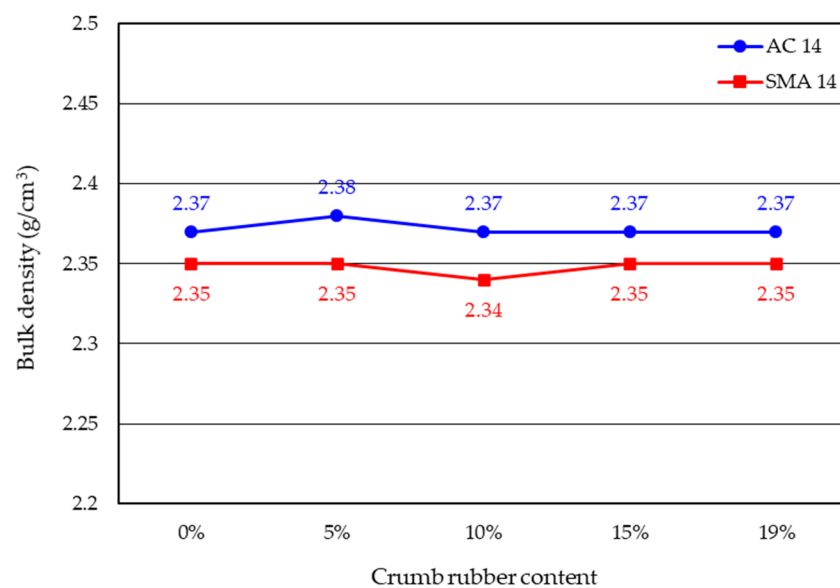


Figure 8. Effect of crumb rubber on the bulk density of the HMA mixes.

The trend of bulk density obtained contradicts the findings from the previous study of Mashaan et al. [33], in which a declining trend was observed as the crumb rubber content increased. This could be due to the different approach used by Mashaan et al. [33], who increased the crumb rubber content without decreasing the binder content. In the present study, crumb rubber was used as a partial replacement of the asphalt by weight. Hence, the total weight of the binder remained the same. Furthermore, there was no increase in bulk volume, because the rubber particles occupied the spaces between relatively large aggregates. Therefore, the bulk density of the HMA mixes was not affected.

5.3.2. Voids in Total Mix (VTM)

The durability of HMA pavements depends on the level of porosity or voids within the asphalt–aggregate mix, and it should be limited to a certain range. A porous HMA mix allows too much passageway for water to enter the pavement. On the other hand, the asphalt will squeeze out to the pavement surface when the HMA mix is too dense.

Therefore, an optimal amount of air voids (typically 3–5%) is desirable for HMA pavements. Figure 9 shows the VTM results of the AC 14 and SMA 14 HMA mixes. It can be noted that the average VTM obtained for the AC 14 and SMA 14 mixes was within 3–5%, and complied with the requirements of JKR/SPJ/REV2008-S4 [14].

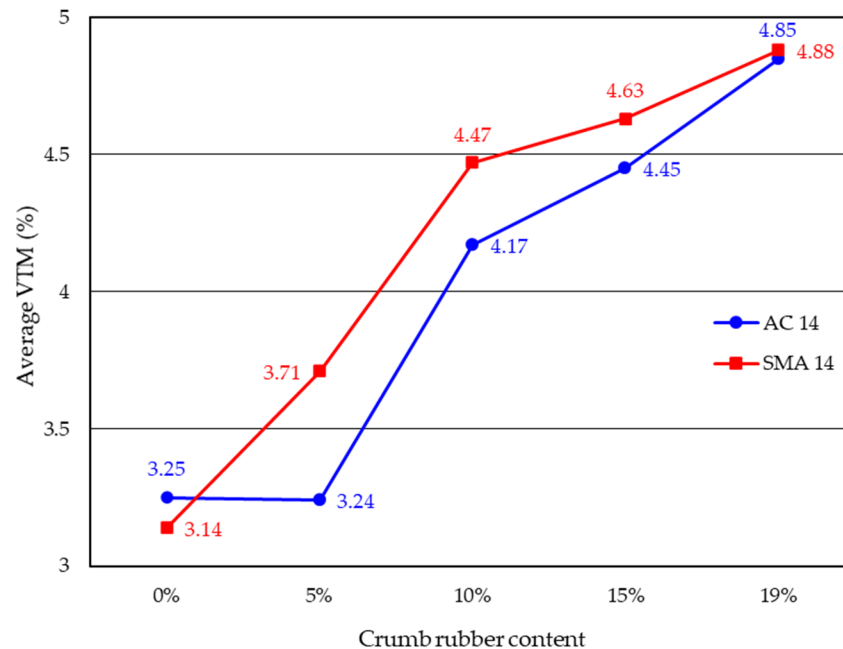


Figure 9. Effect of crumb rubber on the VTM of the HMA mixes.

In general, both types of HMA mix showed a trend of increasing VTM as their crumb rubber content increased. It can be seen from Figure 9 that the VTM of the SMA 14 mixes increased from 3.14% to 4.88% as the crumb rubber content increased from 0% to 19%. The inclusion of 19% crumb rubber content increased the VTM of the SMA 14 mixes by 55.4%. On the other hand, the VTM of the AC 14 mixes increased from 3.25% to 4.85% as the crumb rubber content increased from 0% to 19%. For the inclusion of 19% crumb rubber content, the increase in the VTM of the AC 14 mixes was 49.2%, slightly lower than that of the SMA 14 mixes. However, it was observed that no increase in VTM occurred between the unmodified and the 5% crumb rubber modified AC 14 mixes.

The overall VTM results obtained from this study suggest that an increased crumb rubber content would increase the VTM in an HMA mix. This is due to the greater viscosity and lesser asphalt content of the modified binders with a higher replacement ratio of crumb rubber. Indeed, the penetration and softening point test results confirmed that the viscosity of the modified asphalt binders increased with a higher crumb rubber replacement ratio (refer to Figures 6 and 7). Moreover, the SMA 14 mixes generally had a higher VTM than the AC 14 mixes. A similar trend was observed by Mashaan et al. [33]. An increase in VTM is expected for the SMA 14 mixes. This is because gap-graded aggregates were used in the SMA 14 mixes, whereas dense-graded aggregates were used in the AC 14 mixes.

5.3.3. Voids in Mineral Aggregate (VMA)

VMA refers to the volume of intergranular voids between the aggregates within a compacted asphalt mix. This includes air voids, but not the open and closed pores of the aggregates; hence, VMA is the sum of air voids and the effective volume of asphalt that is not absorbed into the aggregates [40].

The test results for the VMA of all of the AC 14 and SMA 14 HMA mixes, including different crumb rubber contents, are presented in Figure 10. The variation in the VMA results is identical to that observed in the VTM results (refer to Section 5.3.2 and Figure 9).

The lowest VMA obtained for the AC 14 and SMA 14 mixes was 6.56% and 6.42%, respectively. The maximum VMA of the AC 14 and SMA 14 mixes with 19% crumb rubber was 8.2%. In general, the VMA percentages of the AC 14 and SMA 14 mixes were relatively low due to the presence of more fine particles of <0.075 mm in size (refer to Tables 1 and 2).

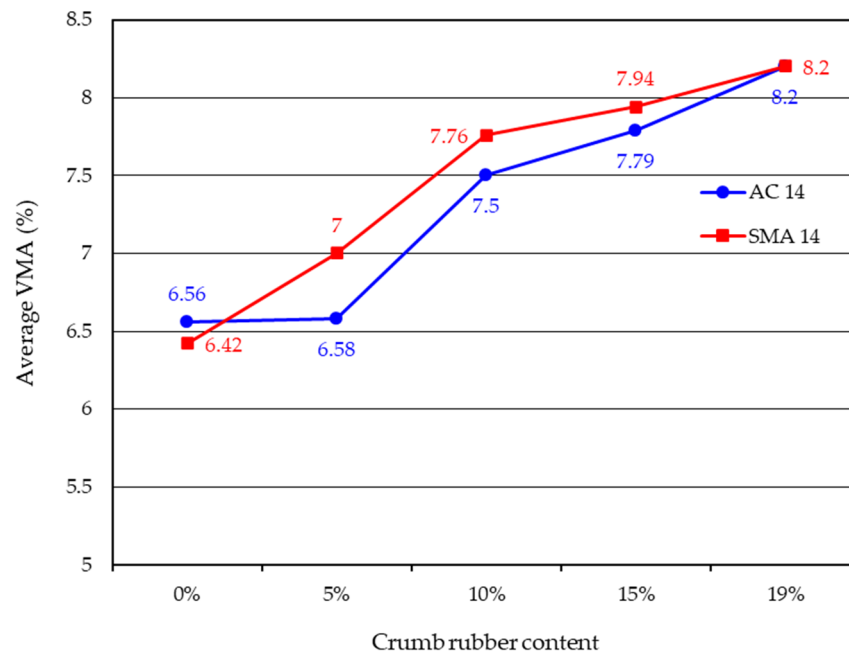


Figure 10. Effect of crumb rubber on the VMA of the HMA mixes.

The VMA of the AC 14 and SMA 14 mixes generally increased with a higher crumb rubber content. This is due to the same reasons as discussed in the case of VTM (refer to Section 5.3.2). Moreover, the VMA of the SMA 14 mixes was typically higher than that of the AC 14 mixes, owing to the same reason as discussed in Section 5.3.2. It should also be mentioned that the VMA of all of the SMA 14 mixes failed to comply with the minimum requirement of 17% as specified in JKR/SPJ/REV2008-S4 [14], while there is no such requirement indicated for the AC 14 mixes. The fine particle fractions of the aggregates used in the SMA 14 mixes were relatively high, although they remained within the ASTM limits; the quantity of fine particles (<0.075 mm) in the aggregates used for the SMA 14 mixes was also significantly higher than that of the AC 14 mixes (refer to Table 2). Moreover, the crumb rubber used in the HMA mixes had a high quantity of rounded particles, which have the potential to fit very densely together because of the reduced internal friction resulting from the lack of angular edges and the smoothness of their surface. For these reasons, the VMA of the SMA 14 mixes was not achieved at the expected level.

5.3.4. Voids Filled with Asphalt (VFA)

VFA refers to the percentage of voids between the aggregate particles that are filled with the asphalt binder. The VFA results for the AC 14 and SMA 14 HMA mixes are presented in Figure 11. This figure shows that the VFA of the AC 14 and SMA 14 mixes had a relatively constant decreasing trend as the crumb rubber content increased.

The VFA of the AC 14 mix decreased a total of 18.71%—from 76.81% to 62.44%—as the crumb rubber content increased from 0% to 19%. In the case of the SMA 14 mixes, the VFA declined a total of 19.74%—from 77.31% to 62.05%—as the crumb rubber content increased from 0% to 19%. The decrease in the VFA of the AC 14 and SMA 14 mixes was due to the increased viscosity of the modified asphalt binder. An increased content of crumb rubber used as a partial replacement of asphalt leads to a higher viscosity, and thus decreases the

VFA of an asphalt mix. In general, the VFA of the AC 14 mixes was higher than that of the SMA 14 mixes. This is because the VMA of the AC 14 mixes was lower than that of the SMA 14 mixes (refer to Section 5.3.3, Figure 10). The degree of void filling is greater for the lower volume of voids existing between the mineral aggregates. JKR/SPJ/REV2008-S4 [14] specifies that the VFA for an AC 14 mix needs to be within the range of 70–80%, which was achieved only for 5% and 10% crumb rubber contents. The SMA 14 mixes with 5% and 10% crumb rubber contents also complied with this range of VFA.

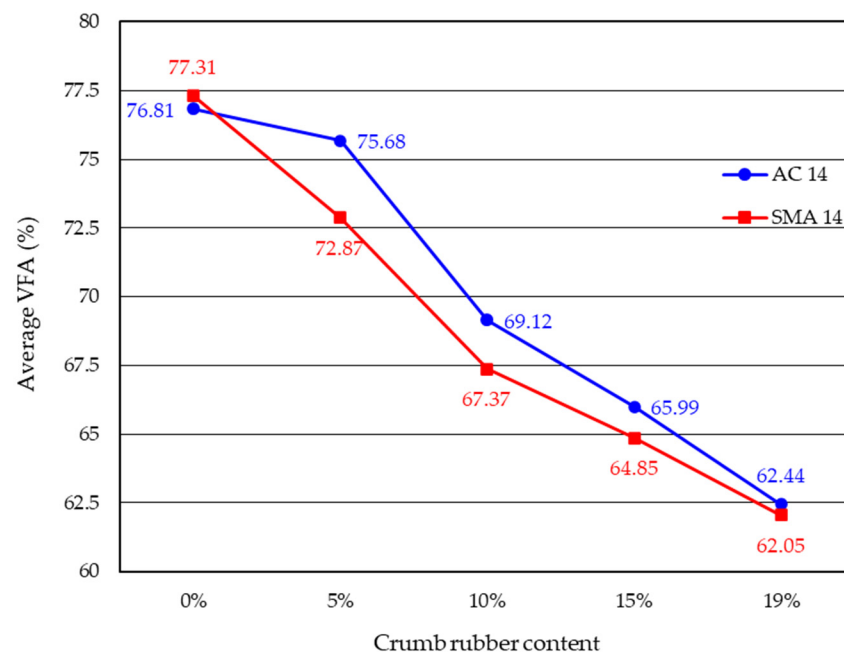


Figure 11. Effect of crumb rubber on the VFA of the HMA mixes.

5.4. Marshall Stability

The results of the Marshall stability tests for the AC 14 and SMA 14 HMA mixes are presented in Figure 12. This figure shows that the AC 14 mixes were significantly more stable than the SMA 14 mixes. All of the AC 14 mixes passed the minimum stability requirement of 6200 N, as specified in JKR/SPJ/REV2008-S4 [14]. In contrast, none of the SMA 14 mixes achieved this minimum level of stability. The bulk density, VTM, VMA, and VFA of the AC 14 mixes (refer to Sections 5.3.1–5.3.4) explain why they were more stable than the SMA 14 mixes. The AC 14 mixes were more densified, with fewer air voids. Furthermore, the AC 14 mixes were prepared with dense-graded aggregates, and therefore their aggregate skeleton was much stronger than that of the SMA 14 mixes. Furthermore, the crumb rubber modified AC 14 and SMA 14 mixes were more stable than the unmodified mixes (0% crumb rubber). This is because the viscosity of the asphalt binder increased with the inclusion of crumb rubber, as observed based on the penetration test results presented in Figure 6. The softening point test results (refer to Figure 7) also indicate that the viscosity of the asphalt binders at a given temperature increased in the presence of crumb rubber. The higher viscosity of the modified asphalt binders made both the AC 14 and SMA 14 mixes much stiffer, thus contributing to enhancing their stability.

The increase in crumb rubber content enhanced the Marshall stability of both the AC 14 and SMA 14 mixes. The AC 14 mixes showed an approximately 4% average increase in stability with each 5% increment of crumb rubber as a partial replacement of the asphalt by weight. On the other hand, the SMA 14 mixes exhibited a 9.5% average increase in stability for each 5% increment of crumb rubber. This trend contradicts the findings of the study completed by Hassan [13], who reported that the increased use of crumb rubber decreased the Marshall stability. In that study, an average of a 20% decrease in Marshall stability was

encountered for each 1% increment of crumb rubber by weight of the total aggregates used in the asphalt mix. This was due to the digestion time (contact time between asphalt and crumb rubber) difference between the dry and wet processes. Moreno et al. [41] found that the digestion time has an impact on the mechanical performance of the rubber-modified asphalt mix. In the present study, crumb rubber was used through the wet process to produce the AC 14 and SMA 14 mixes. The wet process provides a longer and more consistent digestion time for the interaction of crumb rubber and asphalt binder compared to the dry process [42]. Hence, the stability of the crumb rubber modified asphalt mixes was enhanced in this study.

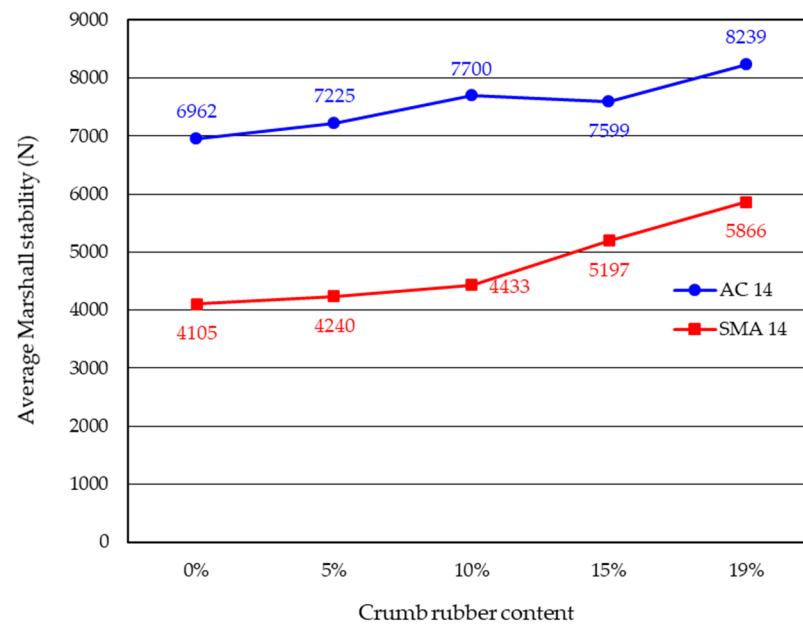


Figure 12. Effect of crumb rubber on the Marshall stability of the HMA mixes.

5.5. Marshall Flow

The Marshall flow results for all of the AC 14 and SMA 14 HMA mixes, with and without crumb rubber, are presented in Figure 13. This figure shows a typical upward trend with each increment of crumb rubber. The flow values of all of the AC 14 and SMA 14 mixes were within the allowable limits specified in JKR/SPJ/REV2008-S4 [14]. However, the AC 14 mixes had a lower flow than the SMA 14 mixes, as evident from Figure 13.

The higher flow values of the SMA 14 specimens indicated that the SMA 14 mixes possessed less stability, which was indeed observed from the Marshall stability test results (see Figure 12). The SMA 14 specimens included higher air voids, as realized from their bulk density, VTM, VMA, and VFB results. Therefore, more deformation occurred in the SMA 14 specimens, resulting in higher flow values, compared to the AC 14 specimens.

The AC 14 mixes showed a relatively constant 2% increase in flow for each 5% increment of crumb rubber. In contrast, the SMA 14 mixes exhibited less consistent flow values, but still showed an overall increasing trend. This trend agrees with the findings from the investigation of Hassan [13], who noticed an average increase of approximately 10% for each 1% crumb rubber by weight of the total aggregates. However, Hassan [13] observed a relatively high flow because of the use of crumb rubber as a partial replacement of aggregates through the dry process. Nevertheless, the higher flow values with the increase in crumb rubber content imply that the ductility of the AC 14 and SMA 14 mixes increases with the inclusion of crumb rubber. This is conducive to reducing the low-temperature cracking when HMA pavements are exposed to the subnormal temperatures prevailing in many winter-region countries. In hot-weather countries, the increased ductility shall be beneficial in reducing the fatigue cracking mainly caused by repeated traffic loads.

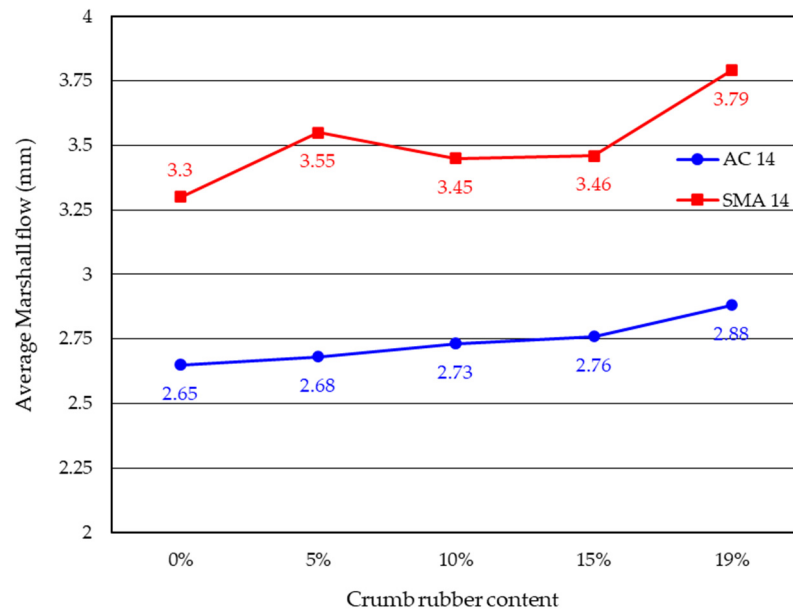


Figure 13. Effect of crumb rubber on the Marshall flow of the HMA mixes.

5.6. Stiffness

The stiffness of all of the AC 14 and SMA 14 HMA mixes was determined based on their Marshall stability and flow results. The average stability values were divided by their average flow values in order to obtain the average stiffness of various asphalt mixes. Figure 14 presents the stiffness of the AC 14 and SMA 14 mixes. This figure shows that the stiffness of the AC 14 mixes was much higher than that of the SMA 14 mixes. The higher stability (see Figure 12) and the lower flow (refer to Figure 13) contributed to the increased stiffness of the AC 14 mixes. Conversely, the lower stability value (see Figure 12) and the higher flow value (refer to Figure 13) resulted in the inferior stiffness values for the SMA 14 mixes.

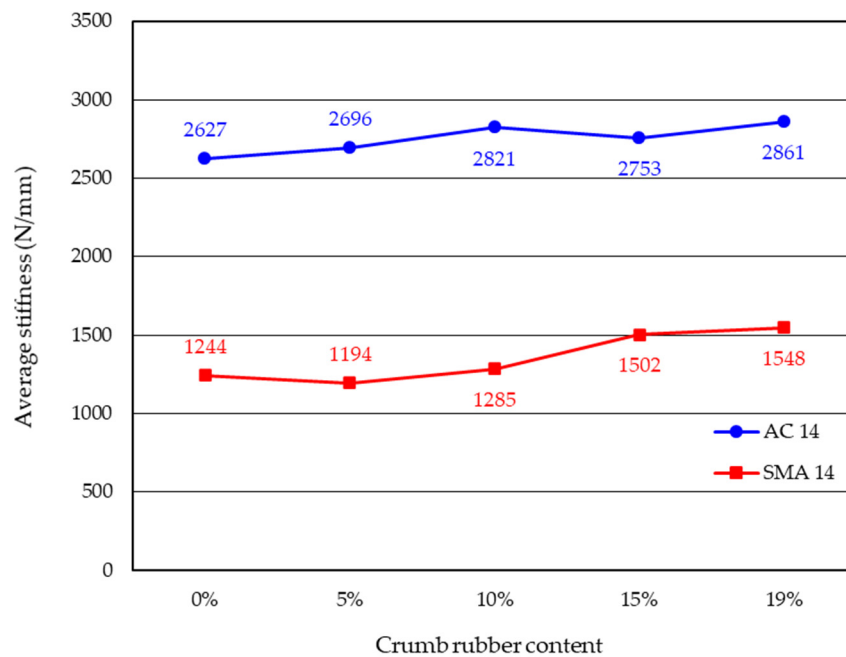


Figure 14. Effect of crumb rubber on the stiffness of the HMA mixes.

In general, the incorporation of crumb rubber increased the stiffness of the AC 14 and SMA 14 mixes. An 8.9% average increase in stiffness occurred for the AC 14 mix incorporating 19% crumb rubber. In comparison, a 24.3% average increase in stiffness was observed for the SMA 14 mix including 19% crumb rubber. In both types of HMA mix, a significant increase in stiffness occurred with 10–19% crumb rubber contents. This trend contradicts the findings of Hassan [13], who noticed a declining trend. However, it should be mentioned that Hassan incorporated crumb rubber into the HMA mixes through the dry process. In the present study, crumb rubber was incorporated into the AC 14 and SMA 14 mixes through the wet process, which contributed to enhance the stiffness of the AC 14 and SMA 14 mixes. As per JKR/SPJ/REV2008-S4 standard specifications, there are not any specific requirements for the stiffness of HMA mixes. The overall stiffness values presented in Figure 14 suggest that crumb rubber modified AC 14 and SMA 14 mixes will sustain larger traffic loads for a given deformation. This implies that the flexible pavements constructed with such HMA mixes will operate for a longer service life.

6. Environmental Benefits

Ever since concerns about environmental pollution due to waste materials have been raised, humans have been looking into innovative solutions to see if some of these materials could be reused or recycled in order to reduce their impact on the environment. The development of the HMA mixes incorporating crumb rubber extracted from scrap tires is such an innovative effort.

The issue of the disposal and handling of scrap tires has become a worldwide problem over the past few decades. This is due to their rapid increase, proportionately with the upsurge of new vehicles on the roads. In many countries, a large portion of scrap tires is improperly disposed of in the environment. Serious environmental problems are caused by the improper disposal of scrap tires—such as burning, land filling, etc. [18,20]. These have led to innovations in the recycling of scrap tires for reuse in various fields—mainly rubber and plastic blends, automotive parts, landscaping, running tracks, and playground surfaces.

The use of crumb rubber derived from scrap tires could be a sustainable solution to the environmental problems caused by the unwanted or discarded tires. Although there are some practices to recycle and reuse scrap tires for energy recovery [43–46], more than 50% of scrap tires are still being discarded without any proper treatment [21]. The utilization of scrap tires could be intensified if the crumb rubber extracted from these tires is incorporated into the HMA mixes for constructing flexible pavements. This is because a huge amount of HMA mix is generally required for such construction work. The results of this study indicate that the crumb rubber obtained from scrap tires can be used sustainably in producing the HMA mixes for flexible pavements, thus reducing various forms of environmental pollution, including soil contamination. Particularly, it could be very useful to resolve the environmental problems caused by scrap tires over the years in Malaysia, especially in Sarawak region.

The environmental issues (e.g., air pollution, noise pollution, waste generation) caused by the repair and maintenance activities on pavements will be reduced if the roads can serve for a longer time without any major damage, as the frequency of such activities will be lessened significantly. This can be achieved if the crumb rubber modified HMA mixes are used to construct durable pavements. Furthermore, the quantity of the end-of-life waste generated from the damaged pavements will be lower and the landfill sites will be less overloaded if the roads can sustain the combined effects of traffic and weather for a longer time. In addition, the consumption of the virgin asphalt and aggregate will be reduced in the case of more sustainable and durable flexible pavements. Consequently, the use of raw materials, and thus the depletion of natural resources, will be decreased. Based on the life cycle assessment of sustainable pavement materials, Praticò et al. [47] stated that the extraction and supply of construction materials are responsible for critical environmental consequences, which could be reduced if crumb rubber is incorporated into the HMA mixes for flexible pavements.

Air pollution will be lower if crumb rubber is used in the production of HMA mixes. The emissions of CO (carbon monoxide) and CH₄ (methane) can be reduced by 39.7% and 61.7%, respectively, during the production of the rubberized asphalt mixes [48]. The environmental noise performance of flexible pavements will also be improved if crumb rubber is incorporated into HMA mixes. Wang et al. [48] reported that the rubberized asphalt mixes can reduce the tire–pavement noise by 40–88%. They also stated that the leachate from crumb rubber modifier does not pose a measurable threat to the environment.

In Malaysia, the estimated amount of motorcar scrap tires generated annually was 8.2 million units—or approximately 63,263 tons—more than a decade ago [49]. The number of scrap tires has certainly increased to date, thus creating a large environmental load. About 60% of the scrap tires are disposed of through unknown routes, and they are neither categorized as solid waste nor hazardous waste in Malaysia [49]. Inappropriate scrap tire management brings forth adverse impacts on the environment. The open burning of scrap tires causes air pollution by releasing harmful contaminants (hydrocarbons, nitrogen oxides, furans, dioxins, etc.). Moreover, the dumps and stockpiles of scrap tires cause aesthetic pollution, enhance mosquito breeding, and become habitat for pests, such as snakes and rats. The dumping of scrap tires in ditches and watercourses may have other impacts, such as changes in the hydrological systems. These environmental problems occur due to the absence of a well-coordinated scrap tire management system. There is a lack of producer responsibility for scrap tire management in Malaysia. The tire manufacturers do not care about the final disposal of the end-of-life tires. They leave it entirely on their dealers to confront this problem. The absence of producer responsibility makes scrap tire management problematic.

The environmental issues caused by scrap tires can be alleviated through recycling of these out-of-use tires. The crumb rubber obtained from the recycling of scrap tires will contribute to environmental sustainability if it is used in the production of the HMA mixes for flexible pavements. The incorporation of crumb rubber into the HMA mixes will allow a large amount of scrap tires to be recycled in Malaysia, particularly in Sarawak, and thus help in reducing air pollution, tire–pavement noise, and other environmental problems.

7. Conclusions

Based on the findings from the present study, the following conclusions have been drawn.

1. Increased crumb rubber content leads to a decrease in the penetration depth, thus contributing to the increase in the stiffness of the modified binder compared with the unmodified binder.
2. The softening point results show that higher temperature is required to soften the modified binder as it becomes stiffer with the increase in crumb rubber content.
3. Test results of volumetric properties exhibited that the increase in crumb rubber content increased VTM and VMA, while decreasing VFB, for both AC 14 and SMA 14 mixes, due to the enhanced viscosity of the modified asphalt binder.
4. The Marshall stability value increased with a higher crumb rubber content, while the Marshall flow value was within the permissible range.
5. The stiffness of the AC 14 mix increased for all crumb rubber contents, whereas the stiffness of the SMA 14 mix mostly increased at 15% and 19% rubber contents.
6. Crumb rubber is likely to increase the service life of flexible pavements, as it improves the temperature resistance and stiffness of HMA mixes.
7. The increased Marshall stability with the increase in crumb rubber content in asphalt mix will minimize the fatigue problem of HMA pavements caused by traffic loads.
8. The overall results are encouraging for the use of crumb rubber as a modifier of asphalt in the HMA mixes for road construction in Sarawak, Malaysia.
9. The main advantage of using crumb rubber in the production of HMA mixes is related to the environmental sustainability of pavements. The use of crumb rubber in HMA mixes will allow scrap tires to be recycled in Malaysia, and thus help to reduce air pollution, tire–pavement noise, and other environmental issues.

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Conflicts of Interest: The authors declare no conflict of interest.

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