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Review

A Review of Rubberised Asphalt for Flexible Pavement Applications: Production, Content, Performance, Motivations and Future Directions

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Abstract: The crumb rubber (CR) recycled from waste tyres could be a viable alternative in achieving green pavements that offer exciting new markets to global investors. Adding CR into flexible pavements enhances their performance and ensures environmental sustainability. This paper will discuss the production variables, CR sizes and contents, blending techniques, optimum bitumen contents, morphology, standard characteristics, rheological characteristics, mechanical performance, greenhouse gas emissions, energy consumption and life cycle cost. This review study found that compared to traditional asphalt mixtures, the CR-modified asphalts had superior performance and longer service life. However, the dearth of information on several factors in CR asphalt production, including greenhouse gas emissions, energy consumption and life cycle cost during recycling, causes many agencies in the global asphalt industry to continue employing costly, energy-consuming additives such as styrene-butadiene-styrene (SBS) instead of CR to enhance asphalt.

Keywords: crumb rubber (CR); characteristics; mechanical performance; greenhouse gas emissions; energy consumption; life cycle cost

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1. Introduction

The road construction industry should follow other related sectors in utilising recycled and waste materials or by-products, for example, glass furnace dross, ashes from the incineration of municipal waste, crushed brick, plastics, glasses and crumb rubbers from waste tyres, to produce asphalt mixtures. However, their applications are still underexplored since few studies have investigated the potential of these materials [1,2].

Generally, crumb rubber is the rubber recycled from automotive and truck scrap tyres. Waste tyre disposal management is challenging because tyres have a long lifespan and are non-biodegradable [3,4]. The United States is the single-largest market for ground rubber, with an annual consumption of 12 million waste tyres (more than 100,000 tons). The conventional waste tyre disposal methods, namely stockpiling, illegal dumping or landfilling, are temporary solutions. The urgent need to recycle waste tyres is apparent given the substantial amount of waste tyres generated (up to nine million tons each year globally. In some countries, the volume of waste tyres reaches 220 thousand tons), limited landfill space and pollution issues. Generally, gathering waste tyres for dumping in landfills is costly and not an environmentally viable disposal method. Therefore, it is imperative to find sustainable solutions for recycling waste tyres to effectively deal with the massive amounts of waste tires produced globally [5].

One way to recycle waste tyres is by using crumb rubbers in asphalt binder modification. Waste tyres have thermo-mechanical, chemical and physical properties that make them suitable for the asphalt construction sector [6]. Crumb rubbers are safe because they are lightweight, durable, non-toxic and inert [7,8]. In addition to using crumb rubber as a chemical de-vulcanisation feedstock and incorporating it into the bitumen as asphalt sealants and roadway laying [9], it has been used as an asphalt modifier for over 40 years. Studies have demonstrated that asphalt–rubber pavements reduce road pavement thickness, traffic noise, pollution and maintenance costs and extend the lifespan of road pavements while reducing refraction and reflection [10,11]. This review paper will present a comprehensive overview of the primary techniques and technological advancements in incorporating crumb rubber into asphalt mixtures to encourage extensive explorations on the fundamental principles of crumb rubber-modified (CR) asphalt, including production parameters, particle sizes and concentrations, mixing methods, optimal bitumen contents, morphology, standard attributes, rheological properties, mechanical behaviour, greenhouse gas emissions, energy consumption and life cycle expenses.

2. Crumb Rubber

CR has been used to modify asphalt mixtures and binders for decades. In 1840, natural rubber was first used in asphalt pavement to increase the durability of conventional asphalt [12], and the paving industry has been using CR since 1950. The research by McDonald's to determine the best method for developing an ideal combination found that a mixing time of 45 min to an hour produced an asphalt mixture with the best engineering characteristics [13]. In 1975, researchers successfully incorporated CR into asphalt mixes, and in 1988, the American Society for Testing and Materials (ASTM) recommended incorporating 15% ground tires into the original asphalt to produce asphalt binders [14]. Between the early 1970s and mid-1980s, South Africa and Australia used bitumen rubber as a sealant and asphalt binder [15]. Two Australian territories (New South Wales and Victoria) began using rubberised asphalt binder for limited application, primarily as a crack-resistant layer through spray sealing applications [16]. In 1991, the United States established federal rules and regulations for the CR asphalt used in stress absorption interlayers, HMA and joint sealants. Since then, researchers have begun exploring new methods to improve CR-modified asphalt manufacturing techniques [17]. Portugal, Spain, Italy, the Czech Republic and Sweden use CR asphalt the most, and Taiwan uses CR-modified asphalt for rehabilitation projects [18]. The Rubber Research Institute of Malaysia (RRIM) and the Malaysian Public Works Department (PWD) investigated the effectiveness of using CR asphalt for road construction. The researchers in the 1950s focused on developing CR asphalt techniques and constructed a 91 m road between Kota Bharu and Kuala Krai by incorporating 5% CR into the asphalt mixture. Between 1988 and 2003, the states of Melaka, Negeri Sembilan, Kedah, Johor and Perlis constructed rubberised paving as part of their research. Unfortunately, the results of these experiments were never published [19].

2.1. Production Methods

Crumb rubber is recycled rubber from the scrap tyres of cars and trucks. The two methods for making crumb rubbers are cryogenic grinding and ambient mechanical grinding [3], and the crumb rubber is ground repeatedly to obtain finer crumb rubber particles [20]. Figure 1 shows the ambient mechanical grinding method for producing crumb rubber by breaking up the scrap tyres at or above the average room temperature (25 °C). This process comprises several steps and uses whole truck tyres to produce rubber shreds or chips. The first step is separating the metals, fabrics and rubber; the next step is shredding the scrap tyres to obtain the chips fed into a granulator that grinds them and removes any remaining steel or fibre using a combination of magnetic separation, shaking screens and wind sifters. The third step grounds the discarded tyres into smaller rubber pieces through the secondary granulators and high-speed rotating mills [3]. Ambient plants use extruders or screw presses and cracker mills for fine grinding.

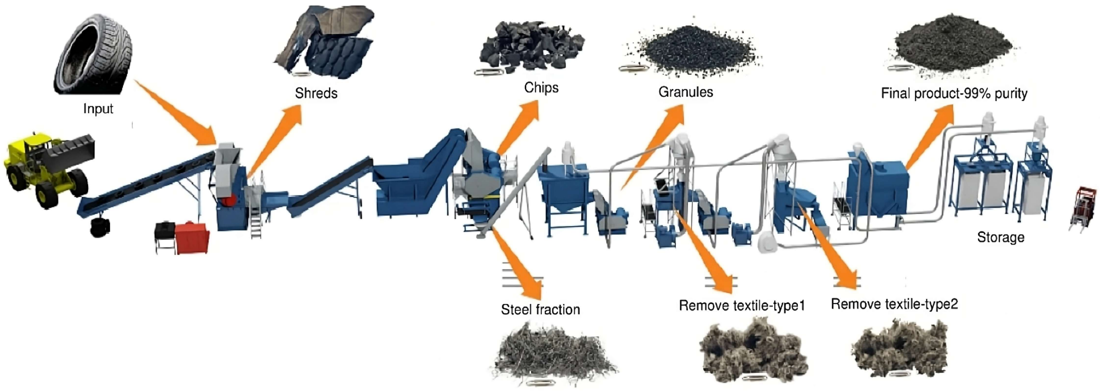

Figure 1. Tyre recycling plant [21].

Cryogenic grinding uses liquid nitrogen or other industrial refrigerants to ground the scrap tyres at about −80 °C. This process uses truck tyres in the form of chips or ambiently formed granulates as feedstock. Even though cryogenic grinding consumes more energy than ambient mechanical grinding, it produces high-quality crumb rubber. This process comprises four stages: initial size reduction, chilling, separating and grinding. In the first stage, the scrap tyres are placed in a freezing chamber containing −80 to −120 °C liquid nitrogen to reduce the rubber's flexibility. A hammer mill then separates the metals from the fibres, and in the last stage, the granules pass through magnetic screens and sifting stations to remove harmful materials [3].

2.2. Physical and Chemical Properties

Tyres are categorised into different rubber compositions and other components to ensure a safe function under various challenging conditions. Figure 2 shows the materials required for tyre production, including natural rubber, artificial polymers, metals, fabric, fillers (such as carbon black and crystalline-precipitated silica), anti-oxidants and curing agents (such as sulphur and zinc oxide).

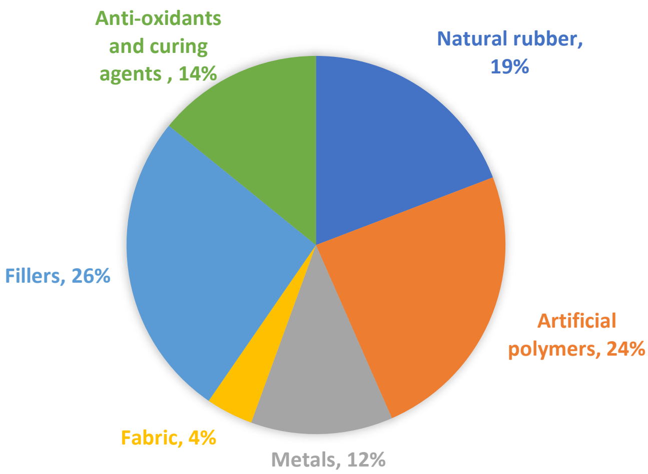

Figure 2. The composition of light truck tyres [22].

Table 1 presents the physical properties of crumb rubbers produced using ambient and cryogenic methods. The specific unit weight of crumb rubber, up to a certain extent, is not affected by the processing method [23]. The chemical characteristics of crumb rubber modifiers are almost identical to the parent rubber tyres [24,25], as shown in Table 2.

The scanning electron microscope images in Figure 3 show the different scales of the CR particles. Table 3 presents the difference between the physical and chemical properties of the CR obtained by Shatanawi et al. [11] using the ambient and cryogenic methods. The values of the physical and chemical properties vary with the steps in CR production.

Table 1. The physical characteristics of crumb rubber [24].

Property	Ambient	Cryogenic
Specific gravity	1.15	1.15
Shape	Irregular	Regular
Steel content	0.1%	-
Fiber content	0.5%	-
Surface area	High	Low

Table 2. The chemical composition of crumb rubber [25,26].

Chemical Composition	Percentage (%)	
Acetone extract %	15.5	9.21
Ash content %	6	6
Carbon black %	29.5	32
Rubber hydrocarbon %	49	52.79

Table 3. The physical and chemical characteristics of crumb rubber [11].

Property	Ambient	Cryogenic
Specific gravity (wt%)	1.042	1.053
Moisture content (wt%)	0.76	0.77
Ash content (wt%)	6.01	4.66
Carbon black content (wt%)	32.98	30.41
Sulfur content (wt%)	2.02	1.24
Acetone and chloroform content (wt%)	9.86	11.69

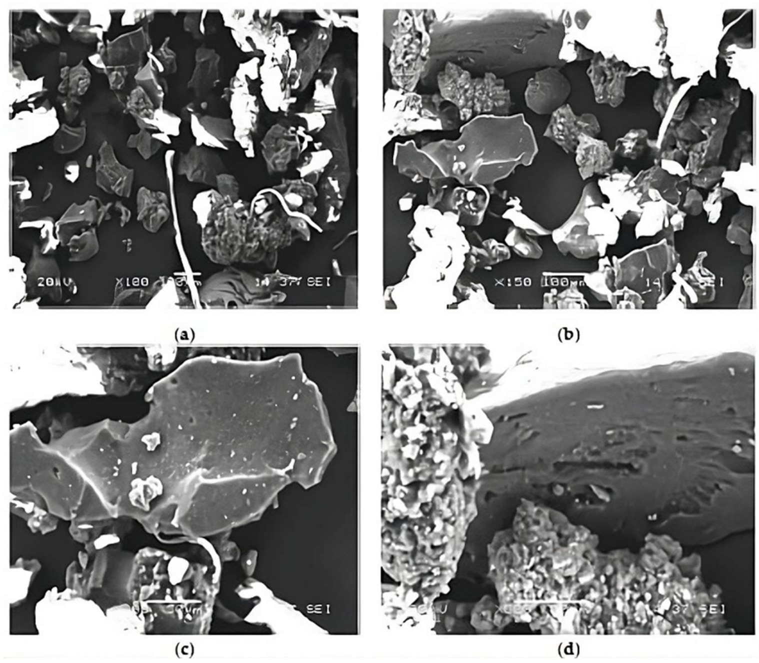

Figure 3. SEM analysis of CR: (**a**) ×100; (**b**) ×150; (**c**) ×400; (**d**) ×600 [27].

Researchers investigated the physical and chemical characteristics of four CRs, two produced by the cryogenic method and the others using the ambient method. They observed that the crumb rubber from each production method has different physical and chemical properties, which determined the behaviour of the asphalt binders and mixtures, as shown in Table 4 [28].

Table 4. The physical and chemical characteristics of crumb rubber produced via different production methods [28].

Property	Cryogenic 1	Cryogenic 2	Ambient 1	Ambient 2
Specific gravity (wt%)	1.04	1.04	1.05	1.06
Moisture content (wt%)	0.76	0.67	0.77	0.67
Ash content (wt%)	6.01	5.36	4.66	5.61
Carbon black content (wt%)	32.98	29.75	30.41	32.74
Sulfur content (wt%)	9.86	11.80	11.69	8.52
Acetone and chloroform content (wt%)	2.02	1.32	1.24	1.47

2.3. Size and Contents

There is a grading system for crumb rubbers with varying particle shapes and sizes, and the particle size of crumb rubbers can be as small as 0.075 mm. The typical CR gradation in rubberised asphalt pavements ranges between 2.0 and 0.075 mm. The crumb rubber size is the screen or mesh size that crumb rubber passes through during manufacturing. Finer screens or meshes have more apertures or holes per linear inch; for example, a 30-mesh screen has 30 openings or holes per inch [29,30]. The permeability coefficient of an asphalt mixture decreases markedly with bigger CR particle sizes and higher CR contents [31]. Cao et al. [32] reported a marked change in the penetration, softening point and ductility of the asphalt binder added with 15% 80-mesh CR. Wong and Wong [33] discovered that the asphalt mixture containing 0.6 mm CR had a higher rutting resistance than that with 0.3 mm CR. Researchers experimented with varying CR sizes and found that larger particle sizes affected the mixture's stiffness and indirectly increased its tensile strength [34]. Another study [35] demonstrated that adding different crumb rubber sizes of 30-mesh 0.6 mm CR, 30-mesh 0.3 mm CR and 40-mesh 0.15 mm CR in varying percentages of 0%, 5%, 10% and 15% by weight of the base binder had a minor effect on the moisture sensitivity of rubberised asphalt. The researchers concluded that the CR sizes and contents influenced asphalt mixture performance. The 50-mesh CR has a better low-temperature performance than the 14-mesh crumb rubber [36]. However, Liu et al. [37] concluded that adding 60-mesh and 80-mesh crumb rubbers to asphalt binder did not considerably impact its performance. Adding 0.15, 0.3 and 0.6 mm CRs to asphalt mixtures resulted in a slight performance difference [33]. Tables 3–5 show that adding less than 20% CR enhanced the performance of CR-modified asphalts. In contrast, high rubberised asphalt contents of 20–50% imparted excellent high-temperature characteristics, low-temperature properties and fatigue resistance compared to virgin asphalt [26]. Figure 4 shows crumb rubber with varying particle sizes.

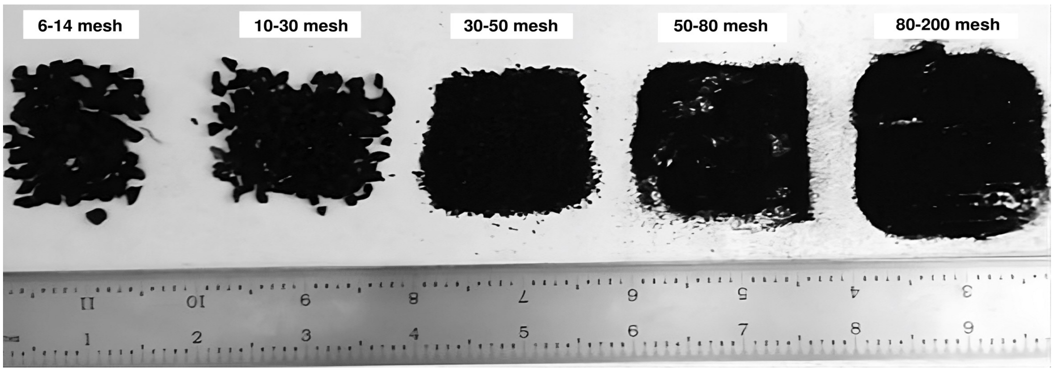

Figure 4. Crumb rubber with varying particle sizes [38].

2.4. Blending Methods

The mixing of crumb rubber and asphalt uses the wet or dry process. The dry process mixes the CR and aggregates in an asphalt mixture, whereas the wet method mixes CR and asphalt binder at a specific temperature [39]. The latter enhances the asphalt mixture's rutting resistance, resilience modulus and fatigue cracking [40]. Moreno et al. [41] observed that the dry method was more effective for producing CR asphalt, while Losa et al. [42] noted that the rubberised asphalt mixtures produced by wet and dry methods showed similar indirect tensile strength (ITS), although those produced through wet mixing have a higher resilient modulus. The rubberised asphalt binders mixed using the wet method had the following characteristics.

- The optimal shearing temperature for ductility at 5 °C ranged from 170 to 180 °C [43], where low shearing temperatures reduced the asphalt's fluidity (higher consistency), making it unsuitable for CR adsorption and swelling, while too high shearing temperatures caused ageing.
- The optimum shearing time ranged between 30 [44] and 60 min [45]. The rubber particles were not sheared properly when the shearing time was too short, but an exceedingly long shearing time accelerated asphalt ageing.
- The recommended shearing rates for rubber-modified asphalt are 700 rpm [35], 1200 rpm [46] or 5000 rpm at 180 °C for 45 min [45]. The shearing outcome was poor when the shearing rate was too low, but an excessively high shearing rate increased the rubber particle temperature rapidly.

According to the American Society for Testing and Materials (ASTM), asphalt–rubber is a mixture of asphalt binder, aggregates, scrap tyres and additives, where the rubber content should be at least 15% of the total mixture weight and react sufficiently with the asphalt binder to ensure swelling of the CR particles. [47]. Increasing the blending time from 30 to 60 min increased the asphalt binder's rutting resistance and elastic recovery [40]. The longer blending duration and higher blending temperature caused the CR asphalt binder to have a higher failure temperature and viscosity at 135 °C [48]. Liu et al. [45] concluded that time, shear and temperature influenced asphalt binder performance, and they recommended mixing at 5000 rpm and 180 °C for 45 min to achieve the optimal rubberised asphalt binder performance. The viscosity of CR asphalt binder decreased considerably with higher mixing temperature and time [32,49]. Figure 5 shows the wet and dry methods for producing rubberised asphalt mixtures. Laboratory experiments and field studies revealed that CR mixtures produced via the dry process showed marginal improvement compared to the wet process. Numerous laboratory investigations have determined the suitable aggregate gradation, optimal bitumen content and appropriate mixture preparation to enhance the consistency and performance of the blends produced via dry mixing. The findings showed that the mechanical characteristics of mixtures produced via dry mixing were more susceptible to varying rubber concentrations. The critical parameters for formulating a CR mixture for both mixing methods are aggregate gradation, bitumen content and air void proportion [50,51].

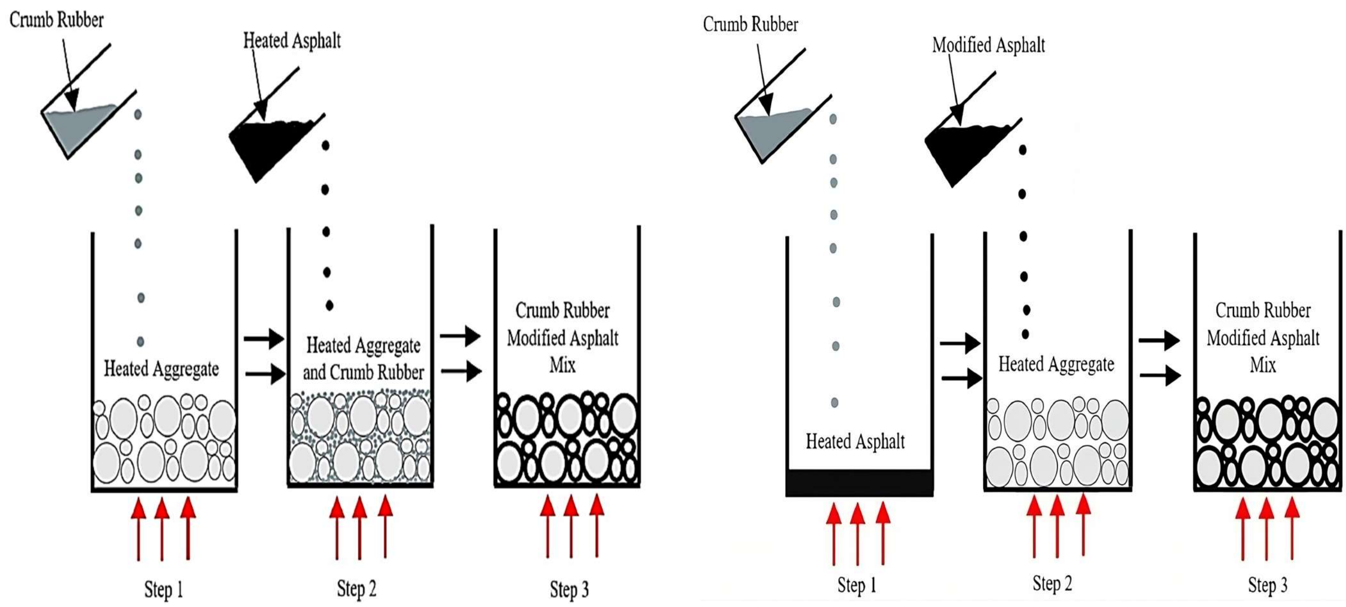

Figure 5. The dry and wet methods for producing rubberised asphalt mixture [52].

2.5. Morphology

A previous investigation found that rubberised mixtures require 1–2% higher bitumen percentages than the original asphalt mixture [53]. A study by Bilema et al. [54] used the Superpave Gyratory Compactor with varying crumb rubber percentages of 5, 10 and 15% asphalt mixture and found that higher crumb rubber contents required 0.25% higher bitumen content since the rubber particles absorbed some of the bitumen in the rubberised asphalt mixture.

Researchers employed modern methods for examining asphalt structure to study the morphology of CR asphalt binders. The compatibility between CR and asphalt binder strongly determines the properties of a CR asphalt binder. Crumb rubber absorbed the lightweight component in the asphalt binder, which expanded the mixture and created a gel-like layer. The CR particles were connected by the gel film surrounding them. A better integration of crumb rubber in the base binder enhanced the asphalt binder's characteristics [9]. Wang et al. [55] classified the interaction between the asphalt binder and CR particles into four stages, as shown in Figure 6. The first stage mixes the asphalt binder with the rubber particles. In the second stage, the rubber particles swell as they absorb the light bitumen fractions, forming a gel layer close to the bitumen–rubber interface. In the third stage, the rubber granules expand, causing the polymer chains and crosslinked network to break down as the chemical reaction occurs. The destruction of the network structure causes the swollen rubber particles to break into smaller components. The deterioration of the rubber particles continues in the fourth stage until they are fully incorporated into the bitumen structure, creating a homogeneous asphalt binder.

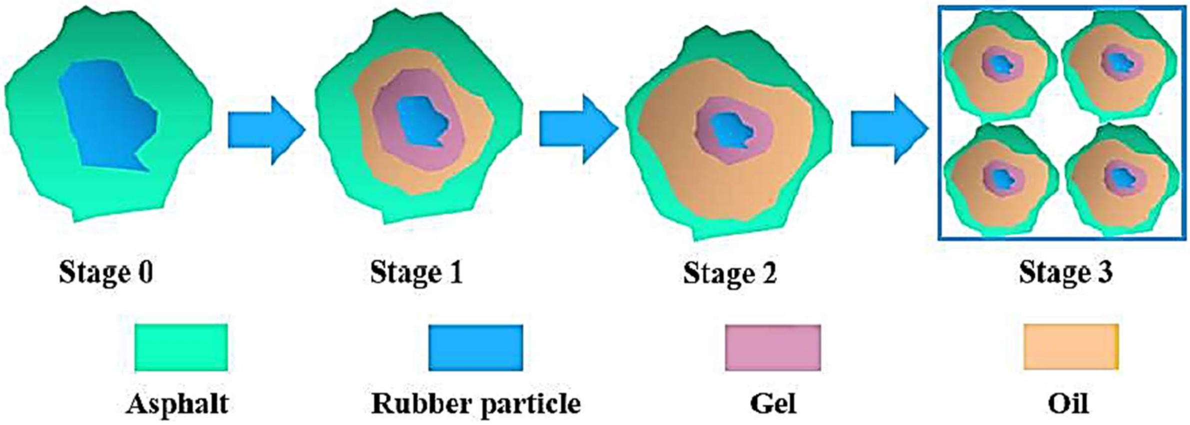

Figure 6. The interaction stages between the rubber particles and asphalt binder [55].

Xu et al. [56] reported that the smooth surface of the crumb rubber particles caused a poor absorption of the lightweight components in the asphalt binder. Researchers used an ambient grinding method to generate CR using untreated CR and CR with polymer-enhanced surface treatment. The largest particle diameter for both CRs was 800 μm. The environmental scanning electron microscope (ESEM) analysis showed no apparent difference between the CR particles, although the surface of the treated CR particles was more porous and open. The chemical activation improves the interaction with the asphalt binder [26]. The AFM images in Figure 6 show asphalt binders with varying percentages of crumb rubber powder and the characteristic changes in the catana phase. The clustered and floating micro-rubber powder had more impact on the interfacial tension than the apparent structural change [55].

Cong et al. [57] used a fluorescence microscope to examine the morphology of rubberised asphalt binders, particularly the discontinuous and continuous phase distribution and observed that the chemical composition of the asphalt binder and CR swelling influenced their low-temperature properties. Zhang et al. [58] examined the morphology of rubberised asphalt binders using a scanning electron microscope after microwave treatment, and they concluded that the CR surface had a strong reactivity, permeability and affinity at the interface with epoxidised soybean oil, which entered the asphalt structure and restored and enhanced the asphalt binder's performance after ageing. The scanning electron microscope (SEM) imaging revealed that the high concentrations of CR powder created an excellent network connection with virgin asphalt. The microscopy of asphalt with high rubber contents showed minor differences before and after ageing, and the compatibility and stability remained satisfactory even after extended ageing [26].

3. The Effects of Crumb Rubbers on Asphalt

Most performance tests assess the physical, rheological and mechanical properties of asphalt to determine the effects of combined factors on CR asphalt mixture. This section summarises the recent research findings to provide a comprehensive knowledge of the fundamental behaviour of rubberised asphalt binders and mixtures.

3.1. Physical Properties

After successfully incorporating crumb rubber into HMA and WMA, researchers continued to explore asphalt rubber applications [59,60]. CR significantly enhanced the penetration, softening point, ductility and viscosity of CR asphalt [61]. One of the main issues with adding CR to asphalt is workability, which can be resolved by reducing the amount of CR added to asphalt rubber binders [62]. Table 5 summarises the laboratory studies on the effects of CR incorporation on the physical characteristics of asphalts. CR increased penetration and viscosity while lowering the ductility and softening point during blending. The aromatic oil absorbed by the crumb rubber particles in the asphalt binder expanded the crumb rubber particles and increased the asphalt binder's hardness [61]. One study concluded that the rubber absorbed the maltene fractions with low molecular weights as it came into contact with the bitumen, leaving the remaining bitumen with a higher proportion of asphaltenes with a high molecular weight, thus increasing its viscosity [28]. Several variables, including the temperature and duration of the rubber–bitumen interaction, the chemical structure of the bitumen and the rubber characteristics and dimensions, influenced the rate of rubber swelling and viscosity [63].

Table 5. The physical characteristics of CR asphalt binders.

Reference	Bitumen	CR Size	CR (%)	Blending Method	Penetration	Softening Point	Ductility	Viscosity
Asgharzadeh et al. [64]	PG 64-22	50–100-mesh	20	- Wet method - 5000 rpm - 185 °C - 60 min	↓	↑	-	↑
Li et al. [65]	80/100 PEN	40-mesh	24, 28 and 32	- Wet method - 1800 rpm - 190 °C - Varying mixing times	↓	-	-	↑
Bilema et al. [66]	60/70 PEN	20-mesh	5	- Wet method - 700 rpm - 177 °C - 30 min	↓	↑	↓	↑
Yu et al. [67]	60/70 PEN	40-mesh	10 and 20	- Wet method - 10,000 rpm - 180 °C - 60 min	↓	↑	-	↑
Geng et al. [68]	70 SK base binder	60-mesh	20	- Wet method - 180–200 °C - 45 min	↓	↑	↓	↑
Poovaneshvaran et al. [2]	60/70 PEN	0.425–0.075 mm	5, 10 and 15	- Wet method - 1000 rpm - 160 °C - 30 min	↓	↑	-	↑
Leng et al. [69]	60/70 PEN	40-mesh	18	- Wet method - 4000 rpm - 176 °C - 60 min	↓	↑	-	↑
Yu et al. [70]	60/70 PEN	-	-	- Wet method - 4000 rpm - 176 °C - 60 min	↓	↑	-	↑
Yu et al. [71]	60/70 PEN	40-mesh	18	- Wet method - 4000 rpm - 176 °C - 60 min	↓	↑	-	↑
Pouranian et al. [72]	PG 67-22	0.6 mm	10, 15, 20 and 25	- Wet method - 4000 rpm - 175 °C - 30, 45 and 60 min	↓	↑	-	↑

Table 5. *Cont.*

Reference	Bitumen	CR Size	CR (%)	Blending Method	Penetration	Softening Point	Ductility	Viscosity
Zumrawi et al. [73]	60/70 PEN	<4.75	5, 10, 15, 20 and 30	- Wet method - 180 °C - 60 min	↓	↑	↓	↑
Mashaan et al. [74]	80/100 PEN	30-mesh	4, 8, 12, 16 and 20	- Wet method - 200 rpm - 180 °C - 60 min	↓	↑	↓	↑
Kedarisetty et al. [75]	VG-30 and VG-40	<0.6 mm	5, 10, 15, 20 and 25	- Wet method - 3000 rpm - 170–180 °C - 5 min	↓	↑	-	↑
Kök et al. [76]	160-220 PEN	-	3, 6, 9, 12 and 15	- Wet method - 1000 rpm - 180 °C - 60 min	↓	↑	-	-
Wulandari and Tjandra [77]	60/70 PEN	40- and 80-mesh	1 and 2	- Dry method - Manual mixing - 135–150 °C - No specific time	↓	↑	↓	-
Xie et al. [78]	70/90 PEN	60–80-mesh	10, 15 and 20	- Wet method - Varying shear times - Varying temperatures	-	↑	-	↑
Palit et al. [59]	80/100 PEN	0.6 mm	5, 10 and 15	- Wet method - 2000 rpm - 175–185 °C - 40 min	↓	↑	↓	-

↓ = decrease and ↑ = increase.

3.2. Rheological Properties

The dynamic shear rheometer (DSR) measurements for the G*/sin rutting parameter yielded values directly proportional to rice husk ash/crumb rubber modifier concentrations. Asphalt binders with higher complex modulus and lower phase angle have higher resistance to permanent deformation and elastic response [79]. The phase angle decreased considerably while the complex shear modulus and rutting factor of the crumb rubber/styrene-butadiene-styrene asphalt increased markedly, indicating that CR/SBS increased the high-temperature deformation resistance [61]. The temperature sweep test showed that SBS and CR lowered the phase angle and increased the complex shear modulus, thus enhancing the behaviour of the modified asphalts in high-temperature conditions. An asphalt binder modified with 20% CR and 5% SBS showed higher high-temperature and rutting resistance. The temperature sweep test also showed that the asphalt binders modified with SBS and CR had higher flexibility at high temperatures. When considering the shear modulus and phase angle of asphalt binders, the viscoelastic balance of the 20% CR and 5% SBS-modified asphalt binder was more suitable for dealing with cracking issues [80]. The higher Superpave values for rutting resistance and complex modulus in the frequency sweeps produced better rheological performance with higher CR contents. The Glover-Rowe (G-R) parameter showed that CR reduced fatigue resistance [27]. CR also reduced the phase angle, increased the complex shear modulus and considerably enhanced the stiffness, modulus and cohesive energy of the asphalt binder, thus enhancing its high-temperature elastic characteristics and making it suitable for various applications [55]. Table 6 summarises the rheological experiments to determine the effects of CR on asphalt.

Table 6. The rheological properties of rubberised asphalt binders.

Reference	Bitumen	CR Size	CR (%)	Blending Method	Complex Modulus	Phase Angle	Rutting Resistance	Fatigue Life
Sol-Sánchez et al. [81]	70/100 PEN grade	0.6–0.063 mm	20	- Wet method - 3500 rpm - 165 °C - 60 min	↑	↓	-	-
Wang et al. [82]	PG 64-22	40-mesh 0.425 mm	10, 15, 20 and 25	- Wet method - 700 rpm - 177 °C - 30 min	↑	↓	-	-
Leng et al. [69]	60/70 PEN	40-mesh	18	- Wet method - 4000 rpm - 176 °C - 60 min	-	-	↑	↓
Yu et al. [70]	60/70 PEN	-	-	- Wet method - 4000 rpm - 176 °C - 60 min	-	-	↑	↓
Mashaan et al. [74]	80/100 PEN	30-mesh	4, 8, 12, 16 and 20	- Wet method - 200 rpm - 180 °C - 60 min	↑	↓	↑	-
Shen et al. [83]	PG 64-22 and PG 52–28	1.35, 0.6 and 0.425 mm	10 and 15	- Wet method - 700 rpm - 176 °C - 15, 30 and 45 min	↑	↓	-	-
Shatanawi et al. [11]	PG 64-22	-	15	- Wet method - 700 rpm - 177 °C - 60 min	↑	-	↑	-
Ziari et al. [36]	85/100 PEN	14- and 50-mesh	10, 15 and 20	- Wet method - 4000 rpm - 190 °C - 120 min	-	-	↑	↓
Poovaneshvaran et al. [2]	60/70 PEN	0.425–0.075 mm	5, 10 and 15	- Wet method - 1000 rpm - 160 °C - 30 min	↑	↓	↑	-
Bilema et al. [84]	80/100 PEN	20-mesh	5, 10 and 15	- Wet method - 700 rpm - 177 °C - 30 min	↑	↓	↑	-
Wang et al. [55]	90/100 PEN	80-mesh	15, 20 and 25	- Wet method - 4000 rpm - 180 °C - 60 min	↑	↓	↑	-

Table 6. *Cont.*

Reference	Bitumen	CR Size	CR (%)	Blending Method	Complex Modulus	Phase Angle	Rutting Resistance	Fatigue Life
Yu et al. [67]	60/70 PEN	-	10 and 20	- Wet method - 10,000 rpm - 180 °C - 60 min	↑	↓	↑	↓
Wang et al. [26]	60/80 PEN	<0.6 mm	20, 25, 30, 35, 40, 45 and 50	- Wet method - 2000 rpm - 180–190 °C - 50 + 15 min	↑	↓	↑	↓
Yu et al. [85]	60/70 PEN	40-mesh	18	- Wet method - 4000 rpm - 176 °C - 60 min	-	-	-	↑
Xiaoming et al. [86]	60/70 PEN	0.125 mm	2, 3, 3.5 and 4	- Wet method - 4000 rpm - 185 ± 5 °C - 120 min	↑	↓	↑	-
Zhang et al. [87]	70/80 PEN	40-mesh	25	- Wet method - 4000 rpm - 175 °C - 60 min	↑	↓	↑	-
Zong et al. [88]	80/100 PEN	25-, 30-, 40- and 60-mesh	12, 16, 20 and 24	- Wet method - 5000 rpm - 205 °C - 60 min	↑	↓	↑	-
Khan et al. [89]	PG 64-10	0.15–0.075 mm	4, 8, 12 and 16	- Wet method - 1000 rpm - 20 min	↑	↓	↑	-
Khan et al. [90]	PG 64-10	0.15–0.075 mm	2, 4, 8 and 10	- Wet method - 165 °C - 120 min	↑	↓	↑	-
Yun et al. [91]	PG 64-22	0.425–0.075mm	5, 10, 15 and 20	- Wet method - 700 rpm - 177 °C - 30 min	-	-	↑	-

↓ = decrease; ↑ = increase.

3.3. Mechanical Performance

Crumb rubber generally improved asphalt mixture behaviour [17]. The asphalt mixture's moisture resistance at a particular temperature decreased with higher CR powder contents [54]. Another research demonstrated that CR asphalt had better moisture sensitivity and permanent resistance than unmodified asphalt mixture [33]. Liu et al. [37] used the Superpave test results to identify the ideal condition for using CR in asphalt, taking into account the granulated CR, fusion temperature, aggregate gradation, CR content, density, temperature, amount of asphalt binder and fusion time as the experimental variables. The investigation mixed the CR and asphalt using the dry blending method. At high temperatures and low production costs, adding 10% rubber powder produced an asphalt mixture with lower thermal sensitivity and higher permanent deformation resistance than the control specimens [1]. CR is an influential determiner of asphalt mixture performance, where the rubberised asphalt mixture had better rutting deformation resistance than ordinary mixtures [92]. Generally, high percentages of crumb rubber were added to the asphalt mixtures to enhance their ability to resist deterioration in the Cantabro abrasion loss test [93]. Table 7 summarises the results of the mechanical performance test to determine the effects of crumb rubber on asphalt.

Table 7. A summary of laboratory research on the effects of crumb rubber on asphalt.

CR (%)	CR Size	Blending Method	Result	Authors
1 and 2	40- and 80-mesh	- Dry method - Manual mixing - 135–150 °C - No specific time	Improved the stiffness and durability of the asphalt mixtures.	Wulandari and Tjandra [77]
1, 2 and 3	2.36–0.075 mm	- Dry method	Adding CR increased the Marshall stability and rutting resistance considerably. The recommended CR dosage in asphalt mixture is 1.5–2%.	Nguyen and Tran [94]
10	2–0.075 mm	- Wet method - 1200 rpm	Waste CR powder reduced the rut depth of asphalt mixes at varying temperatures and pressures.	Shafabakhsh et al. [1]
5, 10 and 15	20-mesh	- Wet method - 700 rpm - 177 °C - 30 min - WMA additives (Sasobit)	The tensile strength ratio (TSR) of the WMA mixtures modified with CR decreased at lower test temperatures and higher CR contents.	Bilema et al. [54]
1	0.8 mm	- Dry method - 160–185 °C - 3.5 min - Conditioning time of 30, 60, 120, 180, 240 and 300 min at 165 °C	The CR-modified bitumen had a higher viscosity than the virgin bitumen. The CR had a significant impact on the mixture's performance. The conditioning time determined the asphalt morphology.	Fernández et al. [95]
20	0.6–0.063 mm	- Wet method - 3500 rpm - 165 °C - 60 min - WMA additives (Sasobit and Zycotherm)	The CR with WMA additives reduced the manufacturing temperature by 45 °C without adversely affecting mechanical performance, energy consumption, costs and GHG emissions.	Sánchez et al. [81]
1.5 and 1.9	0.6–0.063 mm	- Dry method - 160–195 °C	CR mixtures were less sensitive to high temperatures than the virgin asphalt mixture. CR improved fatigue cracking performance. The temperatures of over 190 °C at plants producing CR asphalt mixture had adverse effects on rubber performance (reduced stiffness at intermediate temperatures and lower fatigue resistance).	Dias et al. [96]

Table 7. *Cont.*

CR (%)	CR Size	Blending Method	Result	Authors
10	0.15, 0.3 and 0.6 mm	- Wet method - 3000 rpm - 175–185 °C - 45 min	CR increased the rutting resistance.	Wong and Wong [33]
0.5 1 and 1.5	0.6 mm	- Dry method	CR enhanced the asphalt mixture's stiffness modulus and rutting resistance.	Moreno et al. [41]
20	50–100-mesh	- Wet method - 5000 rpm - 185 °C - 60 min	The fatigue life of the CR-modified mixture was 3.6 times the unmodified asphalt mixtures for highway applications.	Asgharzadeh et al. [64]
1	0.8 mm	- Dry method - 160–185 °C - 3.5 min - Conditioned at 165 °C for 120 min	The CR-modified asphalt mixtures showed satisfactory performance and were less susceptible to ageing than the conventional polymer-modified mixture.	Fernández et al. [97]
5	0.075, 0.15 and 0.3 mm	- Wet method - 700 rpm - 177 °C - 30 min	Larger CR particles increased the ITS and reduced the moisture resistance. The 0.15 mm CR was suitable for improving the asphalt mixture's strength and moisture damage resistance.	Bilema et al. [34]
6, 12, 16 and 20	0.45 mm	- Dry method - 160–165 °C	CR improved the stability of stone mix asphalt by providing better adhesion. The stiffness modulus of SMA samples containing varying CR percentages was significantly higher than the virgin asphalt mixture. The optimal CR percentage was 12% by weight of the bitumen.	Mashaan et al. [7]
5, 10 and 15	0.6 mm	- Wet method - 2000 rpm - 175–185 °C - 40 min	Reduced the asphalt mixture's permanent deformation and increased its resilient modulus.	Palit et al. [59]
0.25, 0.5, 0.75, 1, 2, 3, 4 and 5	0.425 mm	- Dry method - 180 °C	Adding the 0.75 mm CR enhanced the fatigue cracking and rutting resistance.	Kamarudin et al. [98]
15, 17, 20 and 21	2–0.075 mm	- Wet method - 180 °C - 90 min	The CR asphalt mixtures showed improved resistance to permanent deformation.	Fontes et al. [99]
5, 10, 15 and 19	0.3–0.6 mm	- Wet method - 180–190 °C - 30 min	The fatigue resistance decreased with higher CR contents in the asphalt mixture.	Yun et al. [91]

3.4. Emissions and Their Effects on Health

The manufacture of asphalt mixes consumes energy and emits pollutants into the environment. In terms of emissions, studies on life cycle assessments have shown that the materials manufacturing and transportation stages in pavement technology prevail [100]. The amount and constituents of the emissions from asphalt production depend on the type of asphalt, additives and blending temperature [101]. The primary concern with CR mixes is the results of incorporating CR in asphalt mixtures on the released emissions compared to those released by conventional asphalt mixtures. The higher blending temperatures and binder concentrations in CR asphalt production than traditional asphalt production released higher emissions [102]. According to Yang et al. [102], adding CR to asphalt mixes resulted in considerably higher pollutant emissions, particularly hazardous toluene emissions. A contractor in Colorado responsible for developing and investigating the specifications for rubberised asphalt for the 2006 paving season voiced their concerns about the wet or dry methods because of the high levels of fumes and smoke released by their plants into the environment during production. They decided against using the wet or dry method because they were concerned about losing their state environmental certificates unless given the assurance that their operating licences would not be revoked [103]. Burr et al. [104] concluded that the risk of worker exposure to asphalt rubber could be worse than ordinary asphalt mixes.

Unlike the manufacture and use of traditional asphalt mixes, CR does not contribute to a marked increase in harmful emissions, such as greenhouse gases (GHG) [100–102]. Instead, CR asphalt could reduce greenhouse gas emissions [102], and the exposure to emissions in asphalt rubber production was the same as in traditional asphalt production. Moreover, compared to the effects of other factors, including the dryer's fueling rate, blending temperature, asphalt throughput rate and binder dosage [105], CR has minimal impact on emissions. Zanetti et al. [106] contended that the toxic and carcinogenic hazard in CR applications is similar to other asphalt mixes produced with original or polymer-modified bitumen (PMB). Carbon dioxide (CO_2) emissions are the main contributors to global warming. Compared to gap-graded and open-graded mixtures, CR asphalt applications can reduce 154 tonnes and 343 tonnes CO_2 emission per lane mile [107]. It is imperative to conduct more in-depth investigations to determine the type and amount of emissions in CR asphalt technology. According to Carlson, the O_2, N_2, CO_2 and SO_2 emissions in CR asphalt production are similar to traditional asphalt, while the CO and CH_4 emissions are significantly lower [108]. Wang et al. [109] reported that the CO and CH_4 emissions from CR asphalt mixture manufacturing were much lower than ordinary asphalt. Stout et al. [110] compared the greenhouse gases emitted after incorporating CR into asphalt mix to those of unmodified asphalt mix. The O_2, N_2, CO_2, NOx and SO_2 emissions from rubberised asphalt mix manufacturing were comparable to those of unmodified asphalt mix. The production of rubberised asphalt mix released substantially less CO and CH_4 than the unmodified mix. The warm mix asphalt (WMA) technique for manufacturing CR asphalt required lower blending and compaction temperatures and released minimal emissions, besides performance advantages and energy provision. Recent experiments employing WMA technology to incorporate CR required much lower mixing and compaction temperatures, thus significantly reducing emissions during site activities [111,112]. Figure 7 depicts the estimated emissions of greenhouse gases during the production of rubberized asphalt and conventional asphalt mixtures.

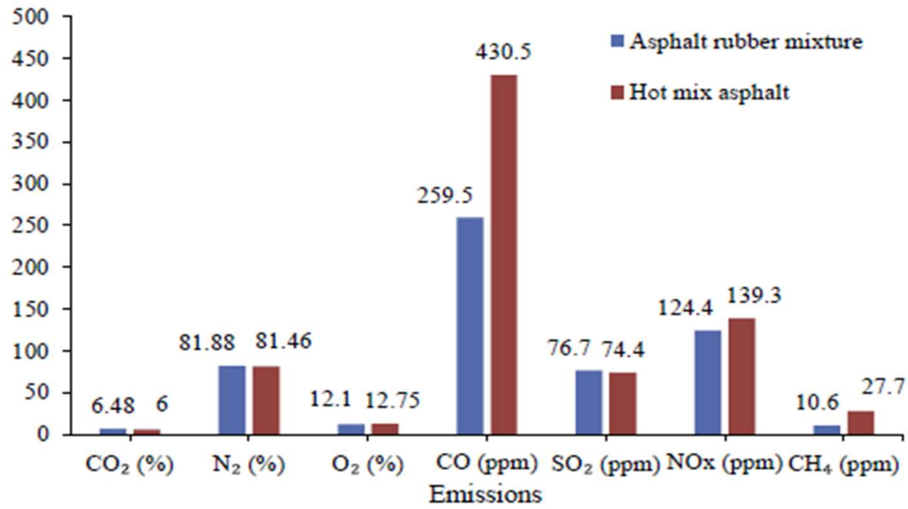

Figure 7. The estimated greenhouse gas emissions in rubber asphalt and unmodified asphalt mixture production [110].

3.5. Energy Consumption

Several studies found that using CR in asphalt manufacturing reduced energy consumption because it used fewer raw materials and had a longer service life. Farina et al. [113] concluded that depending on the life cycle assessment (LCA), the net energy saving in the CR manufacturing chain was 4236 MJ/t, equivalent to 43–46% lower energy consumption. Sousa et al. [107] evaluated the energy consumption of CR asphalt and concluded that using CR in asphalt modification could save energy. Antunes and Murachelli [114] reported a 47% savings from the total energy consumption in the maintenance stage. Bartolozzi et al. [115] observed that using CR in pavement reconstruction consumed about 33% less energy in typical hot mixed asphalt treatments, while Zhu et al. [116] noted a slightly higher energy consumption in asphalt rubber production than unmodified asphalt mixtures, but much less than SBS-modified asphalt mixtures, as shown in Figure 8. Wang et al. [117] conducted a comprehensive analysis of the energy consumption and environmental effects of using CR on asphalt surfaces in each stage of their life cycles, including raw material extractions, construction, service, maintenance and end of life. Extensive use of asphalt rubber ensures a sustainable environment because of the reduced energy and raw material consumption, lower GHG emissions and less noise from roadways. However, incorporating CR increased bitumen viscosity, thus raising the mixing and compaction temperatures. In this case, WMA technology could reduce the CR asphalt blending and compaction temperatures, thus reducing the energy consumption in the manufacturing and construction stages. Recent research explored incorporating additives, including waxes, to reduce the blending temperature and energy consumption [118]. WMA technology could reduce the mixing temperature of rubberised asphalt by 30 °C and fuel consumption by 20–25% [119]. Warm mix agents reduced rubberised asphalt's mixing and compaction temperatures [120]. Alloza et al. [121] produced WMA with CR that consumed 18% less energy than traditional asphalt mixes. Pratico et al. [122] conducted a comparative analysis of bio-binders and technologies employing rubberised asphalts in terms of their impact on the Global Energy Requirement (GER). Their findings indicate that the use of mixtures containing crumb rubber through the dry method has a substantially lower energetic (GER) footprint when contrasted with the bio-binder solution, irrespective of the aggregate gradation employed.

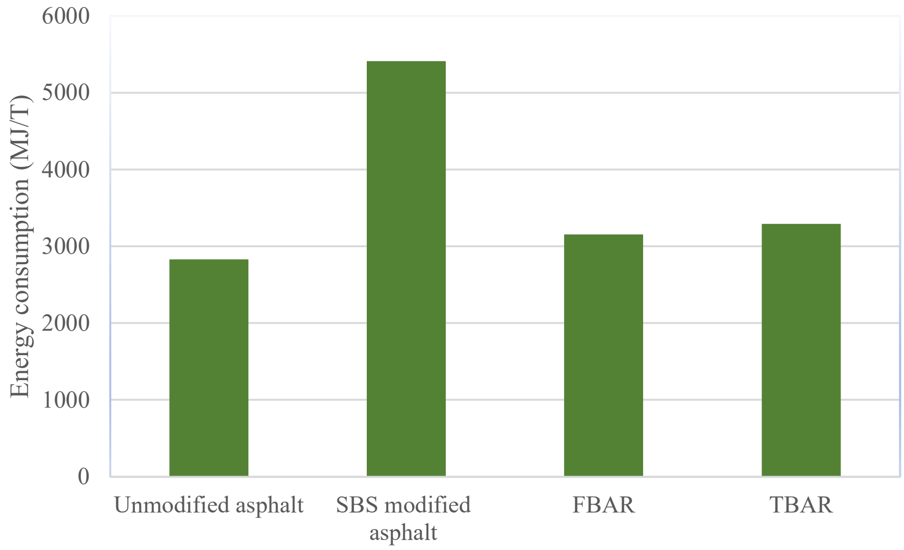

Figure 8. Energy consumption of various asphalt mixtures [116]. FBAR = Filed-blended asphalt rubber; TBAR = Terminal-blended asphalt rubber.

3.6. Life Cycle Costs

When comparing the relative costs of pavement solutions, it is essential to consider the related raw material and manufacturing plant costs and select the appropriate materials when designing, developing and producing the rubber asphalt to achieve the required pavement structure and drainage that ensures superior pavement performance. Dias et al. [123] reported that the direct manufacturing costs for CR asphalt using the dry method were 20% higher than the control asphalt, while the costs for the wet method were 26% higher than traditional asphalt pavement. Hicks and Epps [124] found that the cost of rubber asphalt mixtures could be twice the traditional asphalt. Volle [125] compared the cost of eleven CR asphalt projects between 1991 and 1995 and found that nine projects cost more than the traditional mixture, where the expenses for seven projects were 25% higher, one was 43% higher, and another was 101% higher.

A previous study has proven that thin CR asphalt overlays cost 43% less than unmodified asphalt and increased pavement life by 10% [126]. Similarly, using CR asphalt instead of unmodified mixtures improved performance while reducing pavement thickness by 50% [127].

The initial cost for producing a CR-modified mixture is lower than other premium-modified mixes, such as polymer (SBS)-modified asphalt mixtures. The production cost of SBS asphalt mixture is about $2280 per tonne, and, at present, it could be as high as $4000 per tonne, while the estimated cost for CR asphalt mixture production is $380 per tonne [128]. As a result, several states and organisations, including the Illinois Tollway, Georgia DOT and Oklahoma DOT, have replaced SBS with CR to produce mixtures that fulfil the performance requirements more economically while ensuring durability [129].

Figure 9 shows the maintenance and user cost trends for rubber asphalt and traditional asphalt pavements. Even though the maintenance and user costs differ slightly after five years, the differences were significant after ten years, where the maintenance cost for the traditional asphalt pavement was much higher, and the user cost began to differ considerably after fifteen years. Data analysis showed that the user and maintenance costs for rubber asphalt pavements were lower than for traditional pavements [130]. Cheng et al. [131] investigated the cost-effectiveness of 126 rubber asphalt projects in 12 districts in California and concluded that most medium- to large-scale rubber asphalt paving projects were more economical than traditional pavements. A recent investigation conducted by Riekstins et al. [132] determined that the utilisation of asphalt rubber in asphalt wearing courses through the wet process with high viscosity results in higher expenses in comparison to traditional asphalt wearing courses, assuming there is no extension in the service life of the pavement. Also, their findings indicate that for a pavement constructed using crumb rubber-modified asphalt to be considered more sustainable in various sustainability aspects, it must exhibit a prolonged service life of 2 to 4 years in each maintenance cycle when compared to traditional asphalt for very thin layers, or stone mastic asphalt wearing courses. CR asphalt, owing to its superior performance, necessitates fewer raw materials and less mix production [133]. This results in lower costs when compared to traditional asphalt, primarily due to reduced requirements for maintenance and rehabilitation interventions.

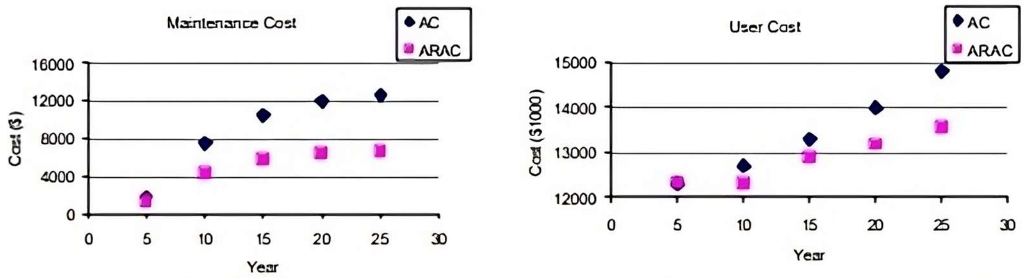

Figure 9. Comparison of the maintenance and user costs for rubber and traditional asphalt pavements [129].

A study by Wang et al. [134] proved that the total cost of the warm mix CR mixtures for Evotherm-DAT and Aspha-Min were US$0.51 and US$0.48 lower, while those of the warm mix CR mixtures for Vestenamer (TOR) and Sasobit increased US$7.2 and US$8.11, respectively, compared to hot-mix asphalt. The typical production cost for hot-mix CR mixture was US$105 to US$135 per metric tonne. The total cost for each metric tonne of CR mixture, including various warm mix agents, could increase the total cost by 7.7% or reduce the total costs by 0.5%, depending on the type of WMA additives. The current economic projection for rubberised asphalt is critical to revitalising the transport infrastructure since a significant percentage of pavement investments is for surface rejuvenation, such as smoothness and skid resistance of existing roadways and airfield pavements. Local and state authorities could optimise their expenses, carry out more pavement maintenance each year and reduce the backlog of the pavements requiring maintenance service by using rubberised asphalt. Motorists would also benefit from lower vehicle maintenance and fuel expenses due to better driving on smoother road surfaces [129].

4. Conclusions and Future Research

4.1. Conclusions

This paper has summarised the procedures and technological advancements for adding crumb rubber to asphalt mixtures to encourage comprehensive examinations of the critical CR asphalt parameters, including production variables, particle size and content, blending method, optimum bitumen content, morphology, standard characteristics, rheological characteristics, mechanical performance, greenhouse gas emissions, energy consumption and life cycle cost. The conclusions drawn from the literature review of previous studies are as follows.

- CR is produced through ambient mechanical grinding or cryogenic grinding, where ambient mechanical grinding is more cost-effective and widely used.
- The recommended CR content for the wet method is 10% of the binder weight without additives and up to 30% with additives. For the dry method, the recommended CR content is 1.5% of the mixture weight without additives and up to 3% with additives.
- Adding CR may increase the optimal bitumen content slightly because the CR particles absorb some bitumen constituents.
- Even though CR increases asphalt viscosity, it can be mitigated with additives, such as warm mix asphalt (WMA) additives or rejuvenators.
- CR improves the physical properties of asphalt mixtures, for example, by reducing the penetration and viscosity values and increasing the softening values. It enhances

the rheological properties by increasing stiffness and rutting resistance and reducing the phase angle.
- Rubberised asphalt production emits similar levels of O_2, N_2, CO_2, NOx and SO_2 as unmodified asphalt but less CO and CH_4. Rubberised asphalt ensures superior functional and structural performance during rehabilitation and less adverse environmental impacts.
- Asphalt rubber has energy-saving benefits throughout its lifecycle through lower energy consumption during construction and maintenance.
- Considering the costs for manufacturing materials, construction, maintenance and rehabilitation, CR asphalt pavement is more economical than traditional pavement.

4.2. Future Research

Researchers have demonstrated the better energy savings, life cycle costs and environmental benefits of rubberised asphalt in the industry. However, many areas of the CR asphalt applications and research gaps require further investigations. The authors recommend further research in the following areas.

- Comprehensive investigations and quantitative analyses to determine the energy consumption patterns of asphalt rubber during construction, recycling and service life.
- An in-depth examination and quantitative evaluation of the costs associated with rubberised asphalt construction, service life and recycling.
- A quantitative appraisal of the environmental implications of recycling rubberised asphalt materials.
- Case studies and analyses to explore various asphalt mixtures, including rubberised asphalt containing SBS-modified components, WMA additives, rejuvenating agents and nano and waste constituents.

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