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Review

Recycling Tire Rubber in Asphalt Pavements: State of the Art

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Abstract: The use of recycled tire rubber in asphalt pavements to improve the overall performance, economy, and sustainability of pavements has gained considerable attention over the last few decades. Several studies have indicated that recycled tire rubber can reduce the permanent deformation of flexible pavements and enhance its resistance to rutting, reduce pavement construction and maintenance costs, and improve the resistance to fatigue damage. This paper provides a systematic and critical overview of the research on and practice of using recycled tire rubber in asphalt pavements in terms of engineering properties, performance, and durability assessment. This critical analysis of the state-of-the-art should enhance the understanding of using recycled tire rubber in asphalt pavements, define pertinent recommendations, identify knowledge gaps, and highlight the need for concerted future research.

Keywords: recycled; tire rubber; asphalt; pavement; rutting; fatigue; durability

1. Introduction

Solid tire wastes are non-biodegradable materials that pose serious environmental and public health concerns [1,2]. Figure 1 shows an example of rubber tire waste. According to Thomas et al. [3], almost one billion tires reach their end of service life every year (end-of-life tires, or ELTs), with over 50% being discarded without any appropriate treatments. It is estimated that by year 2030, the total number of ELTs will reach at least 1.2 billion. In addition, burning tire wastes has a harmful environmental impact by further increasing air, water, and soil pollution [4,5]. Therefore, finding alternative storage and disposal methods for this colossal amount of tire waste is utterly needed to mitigate the ecological damage and the depletion of available disposal sites [6–11].

Figure 1. Rubber tire waste.

Several approaches have been investigated to reuse and recycle tire rubbers in various applications. For example, studies have shown that biofuel can be produced through the combustion of waste tires in boilers and burners for energy recovery [12–14]. According to Rowhani and Rainey [15], thermochemical processes such as gasification, hydrothermal liquefaction, and pyrolysis are used to convert waste tires into fuels.

Table 1 reports the standard requirements for rubber-modified asphalt binder. The use of recycled tire rubber waste in asphalt pavements started more than a century ago. According to Heitzman [16], the first practice of mixing natural rubber and bitumen was in the 1840s. The purpose of this work was to examine the natural flexibility of rubber with asphalt in creating a durable pavement surface. In the 1950s, the Bureau of Public Records of the State of California investigated the effect of rubber applications in pavements by incorporating recycled tire rubber powder in asphalt mixtures. During the 1960s, the wet asphalt process in which recycled tire rubber partially reacts with asphalt binder was first developed and explored by Charles H. McDonald. This work significantly enhanced the rubber asphalt applications for crack sealants, spray applications, and hot mix binder purposes [17]. During the same period, scrap tires were also used in the USA and Sweden pavement industries [2]. By 1997, a standard specification, ASTM D6114-97, for asphalt-rubber binder was proposed by the American Society for Testing Materials.

Table 1. Standard specification for rubber-modified asphalt binder.

Binder	**Asphalt-Rubber Specification (ASTM D6114)**			**Standard**
Designation	**Type I**	**Type II**	**Type III**	
Viscosity in 177.5 °C	1500–5000	1500–5000	1500–5000	ASTM-D2196
Penetration at 25 °C, unit: 0.1 mm	25–75	25–75	50–100	ASTM-D5
Penetration at 4 °C, unit: 0.1 mm	Min 10	Min 15	Min 25	
Softening Point, °C	Min 57.2	Min 54.4	Min 51.7	ASTM-D36
Resilience at 25 °C (%)	Min 25	Min 20	Min 10	ASTM-D5329
Flash Point, °C	Min 232.2	Min 232.2	Min 232.2	ASTM-D93
Thin Film Oven Test (TFOT), residual penetration at 4 °C, (%)	Min 75	Min 75	Min 75	ASTM-D1754, ASTM-D5
Climatic region	Hot	Moderate	Cold	-
Average minimum monthly temperature (°C)	Min -1	Min -9	Min -9	-
Average maximum monthly temperature (°C)	Min 43	Min 43	Max 27	-

Over the last 20 years, several developed countries with large populations have issued various government policies that aim to reprocess landfilling treatments due to the tire landfill sites being hazardous to human health as well as to the environment, with additional negative economic impacts. Disposing of used tires in landfills is no longer acceptable, as the number of available landfill sites is becoming limited. In addition, the complexity of rubber chemical composition delays its degradation process, causing harm to the natural resources surrounding landfills, creating breeding grounds for mosquitoes, and potentially increasing the risk of accidental fires that can be devastating to the environment and neighboring communities [18]. Consequently, recycling scrap tires in a safe way that guarantees no negative impact on the environment has been a challenge.

Considering the colossal worldwide production of waste tires, developing technologies that can recycle large volumes of waste tires in applications with added value is highly attractive and urgently needed. Several studies [19–23] showed that the USA and Japan have about 290 and 110 million waste tire rings, respectively. Moreover, 30% of waste tires in Canada and the USA have been transferred to landfill sanitary centers, which causes environmental and health issues due to possible fires and infestation with mosquitoes and rats [19]. The European Union reacted to the environmental crisis regarding tire stockpiles by banning the landfilling of whole tires in July 2003. It also banned shredded tires in July 2006 [20]. The government of China also developed a green plan, the "Twelfth Five-Year Plan", directed at the construction industry. The policy was based on reusing recycled tire rubber as part of the Chinese building evaluation standard, in order to protect the environment and reduce pollution [21]. With the help of this policy, tire waste rubbers were used in asphaltic concrete mixtures and as a filler material in road construction [22,23].

2. Properties and Compositions of Tire Wastes

Recycled tire rubber granules are obtained by shredding scrap tires in relation to the required particle sizes, terminologies (Table 2a), and properties (Table 2b), as per the recycled waste tire particles defined by ASTM D-6270 and the standard practice for using scrap tires in civil engineering applications.

Manufacturing tires requires primary materials that include natural and synthetic rubber (14%), carbon black (28%), steel (14–15%), fabric, filler, accelerators, and antiozonants (16–17%) (Table 2c). The primary chemical composition of waste tire rubber consists of carbon black (29%) and additives (13%), complex chemical mixtures including extender oil (1.9%), elastomers, polyisoprene, polybutadiene, and styrene butadiene [24,25].

Different tires can have different intrinsic compositions. Automobile tires, for example, have a significantly different composition than truck tires. This difference is most significant in the contents of natural and synthetic rubber. In general, recycled rubber can be classified into the three following main categories: (a) shredded rubber, also known as chipped rubber, which is used to partially replace gravel. Manufacturing this category requires the tire to be shredded in two stages. The first stage produces rubber with a length of 300 to 430 mm and a width of 100 to 230 mm. The second stage cuts the length to 100 to 150 mm. Shredded particles can be acquired by continuing the process of shredding, which leads to the production of rubber particles with a size of around 13 to 76 mm; (b) crumb rubber, which has particles with a size of 0.425 to 4.75 mm and can be used to substitute for the fine aggregate portion in concrete production and hot asphalt mixtures [26]. This type of rubber is produced by turning large rubber into smaller particles, where the variety of rubber particle size is mainly dependent on the mills used and the temperature level; and (c) ground rubber particles, which are manufactured through the micro-milling process, which produces a particle size that ranges from 0.075 to 0.475 mm. The size of equipment plays an essential role in reducing the size of particles. The process is subjected to magnetic separation and screening. This type of recycled tire rubber can be used as a filler in concrete and asphalt paving mixtures [27,28].

Table 2. Typical terminologies, properties, and compositions of tire wastes.

(a) Terminology for Recycled Waste Tire Particles Referring to [29]		
Classification	**Lower Limit (mm)**	**Upper Limit (mm)**
Chopped Tire	Unspecified dimensions	Unspecified dimensions
Rough Shred	50 × 50 × 50	762 × 50 × 100
Tire Derived Aggregate	12	305
Tire Shreds	50	305
Tire Chips	12	50
Granulated Rubber	0.425	12
Ground Rubber	-	<0.425
Powdered Rubber	-	<0.425

(b) Recycled tire Materials Properties [30]			
Material	**Tire Chips (%)**	**Crumb Rubber (%)**	**Steel Cords (%)**
Rubber volume	95–99	99–100	35–75
Steel volume	1.5–8	0	35–75
Density (g/cm^3)	0.8–1.6	0.7–1.1	1.5–3.9

Table 2. *Cont.*

(c) Essential Compositions of Tires [31]			**(d) Chemical Compositions of Waste Tire Rubber [24]**	
Composition Weight (%)	**Automobile Tire (wt%)**	**Truck Tire (wt%)**	**Material**	**Mass Percentage (%)**
Natural Rubber	14	27	Rubber	54
Synthetic Rubber	27	14	Textile	2
Carbon black	28	28	Carbon black	29
Steel	14–15	14–15	Oxidize zinc	1
Fabre, Filler, Accelerator, and Antiozonants	16–17	16–17	Sulfur	1
			Additive	13

3. Methods of Crumb Rubber Addition to Asphalt Mixtures

Figure 2 illustrates two methods, namely the wet and dry processes, for asphalt-rubber mixture production. In the wet process, crumb rubber is added to the asphalt cement in order to modify the chemical and physical properties of the asphalt cement used to produce rubberized pavements [32].

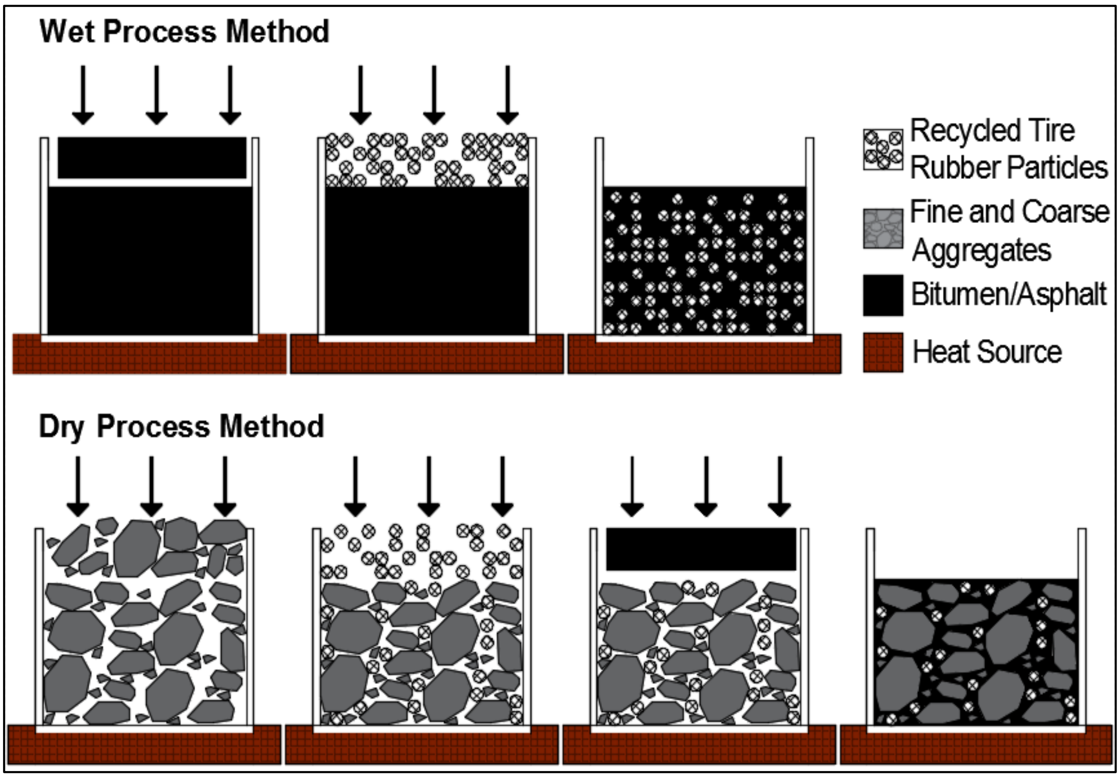

Figure 2. Wet and dry process methods of asphalt-rubber mixture production.

The wet process (Arizona Refinery system) was introduced in the early 1970s as a solution to prevent early reflection of fatigue cracking in resurfaced pavements. In this method, 18% to 22% of ground crumb rubber by weight of binder is mixed with hot asphalt cement and diluted with an oil extender for ease of application [29]. In the dry process, part of the aggregate in the asphalt mixtures is replaced with crumb rubber waste. Two systems use the dry process, the Plus Ride system and the generic system. The Plus Ride system was developed by the Swedish companies Skega AB and AB Vaegfoerbaettringar (ABV) in the 1960s; it typically uses 3%, by weight of total mix, granulated coarse and fine rubber particles to replace part of the aggregate in the mixture [32]. In the generic system, the rubber gradation is modified to be compatible with the aggregate gradations at the rate of 1, 2, and 3% rubber. This system was originated in 1989 by H. B. Takallou, and it uses mixture designs and standards similar to that of conventional asphalt concrete [32].

Applications of the dry process are limited in comparison to the wet process. Although the application of the dry process is simpler than the wet process, asphalt mixtures prepared by the dry process exhibit volume instability and strength reduction due to the partial replacement of aggregates by rubber granules [33]. To improve the asphalt mixture properties prepared by the dry process, Gong et al. [33] investigated the strength of dry processed stone matrix asphalt containing cement precoated crumb tire rubber particles. Their results showed that the stone matrix asphalt with precoated rubber aggregate exhibited higher strength and better performance than those of the mixture with untreated rubber aggregate.

4. Interaction Effects of Crumb Rubber-Modified Asphalt Binder

Figure 3 shows a typical distribution of the recycled tire rubber waste in rubberized asphalt. The addition of recycled tire rubber waste in asphalt mixtures affects the overall binder properties. For example, Khalili et al. [34] reported that the particle size, shape, and content of crumb rubber had significant effects on the rheological properties of the modified asphalt binder. Kim et al. [35] studied the flow behavior, elasticity, loading, and temperature dependency of crumb rubber-modified binders. Their results showed that the use of crumb rubber as a modifier increased the viscosity of the binder, changed the flow characteristics from Newtonian to shear thinning flow, lowered creep compliance values, improved the elasticity, increased the stiffness, increased the complex modulus at higher temperatures, and lowered the phase angle at lower temperatures. Mashaan and Karim [36] investigated the effects of different crumb rubber contents on the properties of rubber-modified asphalt binder. Their results showed that increasing the rubber content led to an increase in the complex shear modulus, storage modulus, and loss modulus of the rubber-modified asphalt binder. Chang et al. [37] studied the behavior of asphalt binder mixed with untreated and plasticized crumb rubbers, including a compounding coupling agent. Their results showed that the storage moduli of asphalt rubbers increased with the plasticized rubber content. They also found that increasing the plasticized crumb rubber content decreased the relaxation rate of the asphalt rubber. Similarly, Xie et al. [38] reported that using activated crumb rubber in asphalt binder improved the binder's stiffness modulus and creep properties at different temperatures.

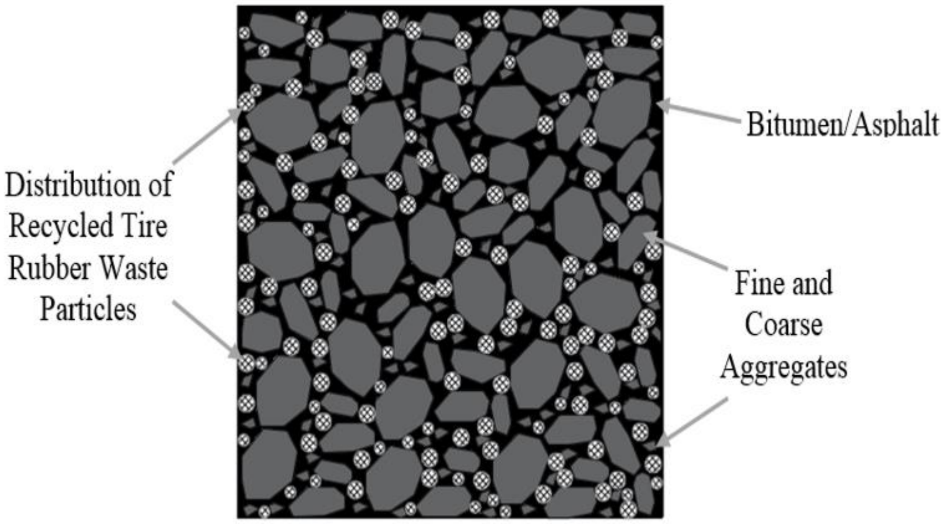

Figure 3. Illustration of recycled tire rubber waste distribution in rubberized asphalt.

According to Wang et al. [39], the asphalt-rubber interaction highly depends on time and mixing temperature. Other studies also reported that the use of recycled tire rubber waste in asphalt mixtures lowered thermal susceptibility [2,40], reduced penetration, enhanced the softening point temperature, and, as a result, increased the stability of the asphalt mixtures [41,42]. In addition, the rough surface of the crumb rubber particles increased the cohesion between the asphalt and rubber particles, leading to enhanced functionality and performance of the crumb rubber-modified asphalts [43].

According to Daly et al. [44], most of the reported studies on the influence of synthetic crumb rubbers on asphalt binder have focused on factors such as crumb rubber particle size, rubber concentration, and blending temperature. On the other hand, fewer studies have investigated the effect of rubber composition on asphalt binder properties. Daly et al. [44] studied the effects of the crumb rubber type (e.g., ambiently ground, cryogenically ground, and Ecorphalt rubber) on the properties of asphalt at two temperatures, namely 170 °C and 190 °C. Their results showed that a significant amount of the Ecorphalt rubber dissolved in the asphalt binder compared to the other types of rubber tested, indicating that Ecorphalt rubber was more compatible with the binder chemistry, leading to overall improved performance of the asphalt binder. Xie et al. [38] reported that adding acrylamide with a double bond and amide group to the modified rubber-asphalt binder reacted with acidic groups in the asphalt and activated the crumb rubber through chemical graft action, and thus improved the compatibility between the crumb rubber and asphalt.

Table 3 shows the effect of temperature on the overall physical properties of end-of-life tires. Several studies have shown that the blending temperature affects the behavior of the crumb-modified asphalt binder. For example, Mashaan [45] investigated the effect of the blending temperature on both crumb rubber-modified asphalt binder and unmodified asphalt binder and found that the blending temperature had a significant effect on the performance of the crumb rubber-modified asphalt binder than on the performance of the unmodified asphalt binder. Aflaki and Memarzadeh [46] studied the influence of the crumb rubber modification aspects on the rheological properties of asphalt binder in terms of improvement in the performance grade for low, intermediate, and high service temperatures through measuring the dynamic viscosity changes. Their results showed that high shear blending has more effect on improving the performance grade for low temperature, while low shear bleeding showed more effect on the performance grade of intermediate and high temperatures.

Table 3. Effect of temperature on the overall physical properties of end-of-life tires.

Properties of Rubber [47]		**Effect of Temperature on Physical Properties of Rubber [2]**	
Feature	**Property**	**Temperature °C**	**Effect**
Compacted density	2.3–4.8 kN/m^3 compared to compacted density of soil 15.6–19.5 kN/m^3	−10	Brittle and opaque
Compacted dry unit weight	1/3 that of soil	20	Soft, resilient and translucent
Compressibility	3 times more compressible than soil	50	Plastic and sticky
Density	1/3 to 1/2 less dense than granular fill		
Durability	Non-biodegradable		
Earth pressure	50% less pressure than soil or sand	120–160	Vulcanized when agents (e.g., Sulphur) are added
Friction characteristics	Higher friction than soil		
Horizontal stress	Lower than in conventional backfills		
Modulus in elastic range	1/10 of sand	180	Break down as in the masticator
Permeability	>10 cm/s (>0.39 in/s)		
Poisson's ratio	0.2–0.3 corresponding to 0.3–0.4 earth pressure coefficient (k_0) values		
Specific gravity	±1.14–1.27 kg/m^3	200	Decomposes
Thermal insulation	8 times more effective than gravel		
Unit weight	50% of the typical unit weight of gravel		
Vertical stress	On weak base: smaller than granular backfill		

Bargegol et al. [48] investigated the influence of different recycled additives, including aromatic oil, tire thread, waste iron, and crushed glass, on asphalt binder's fatigue parameters. They found that adding 5% waste tire thread to the asphalt mixtures better increased the stiffness and improved fatigue cracking resistance compared to the other recycled additives used. Ren et al. [49] studied the effect of nano-montmorillonite on the properties of modified asphalt with different modifiers including crumb rubber, styrene-butadiene rubber, and styrene-butadiene-styrene. Their results showed that the incorporation of nano-montmorillonite had a positive effect on enhancing the storage stability of the crumb rubber-modified binder compared to the styrene-butadiene rubber and styrene-butadiene-styrene modified binders. Kök and Çolak [50] reported that using crumb rubber in asphalt pavements provided significant cost saving over the use of styrene-butadiene-styrene.

The size of the rubber granules also affects the level of the viscosity in the asphalt mixture. Adding larger particle size enhanced the viscosity [51], leading to improved resistance to deformation [41]. Furthermore, large particle surface areas eased the absorption process in the binder and enhanced the digestion of the added rubber into the bitumen. It is highly recommended to use recycled ground tire rubber with particle size of less than 1 mm as it provides enhanced stiffness and better resistance to frost, fatigue, and deformation than adding larger particles [52], thus leading to improved overall properties of the rubber-modified asphalt mixtures [51] The addition of tire rubber waste with particle size ranges between 2 and 8 mm reduced the stiffness of rubberized asphalt mixtures [53]. Therefore, using large particle size of recycled tire rubber in the asphalt mixture created voids, which weakened the asphaltic matrix. However, many studies agree that incorporating rubber particles with less than 2 mm size in the asphalt mixture fills air voids [54]. Therefore, the rheological properties of the asphalt mixtures depend on the crumb rubber particle size.

5. Durability and Performance of Asphalt Rubber Pavements

5.1. Durability and Aging of Asphalt Rubber Pavements

The durability of asphalt pavements is typically defined as the ability of the asphalt pavement to uphold its structural integrity through its designed service life when exposed to diverse environments and traffic actions. Factors such as the mixture design, properties of the binder, drainage adequacy, and asphalt construction methods affect the overall durability of asphalt pavements [55]. Moreover, the compatibility among the asphalt mixture components plays a significant role in improving the durability of asphalt binder [42,56,57]. According to Cui et al. [56], in order to improve the durability performance of road surfaces, it is essential to increase the interfacial adhesion between the aggregates and the bitumen in the asphalt matrix. This can be achieved by incorporating adhesion promoters such as silane, amine, or rubbery polymer into the bitumen.

Mashaan [45] studied the durability performance of rubberized bitumen binders and found that the use of crumb rubber in asphalt mixtures could improve the performance properties of asphalt pavement in terms of resistance to deformation during both construction and traffic actions. Other studies also showed that the ductile behavior of rubber in the asphalt mixture reduced the vulnerability of asphalt-rubber modified pavement to fatigue failure [57]. In addition, during freezing conditions, the protruding rubber granules and surface texture improved the skid resistance of the rubber-asphalt pavement. This ice control mechanism is likely due to the flexing of the protruding rubber particles and the high flexibility of the rubber-asphalt modified mixture under traffic loads. Consequently, multiple breakdowns of surface ice deposits will develop due to the lack of adhesion between the surface of the rubberized asphalt pavement and the ice layer [32].

Age hardening of asphalt occurs during the time of mixing and construction and over the service life of the pavement. Asphalt age hardening can lead to premature cracking and disintegration of the pavement surface. During the hardening process, asphalt mixtures can exhibit brittle behavior and incur distress during oxidation (age hardening), volatilization (evaporation of light components during production of the hot mix asphalt at elevated temperature), polymerization (an increase in the brittleness due to the combination of resins and asphalt), and thixotropy (an increase in viscosity over time) [58].

Several studies have shown that adding crumb rubber into asphalt mixtures increases the asphalt's elasticity, flexibility, and durability against aging [34,46,59–61]. For example, Khalili et al. [34] evaluated the effects of aging on asphalt binders mixed with crumb rubber waste using the rolling thin-film oven (RTFO) and pressure-aging vessel (PAV) tests. Their results showed that the elastic component of the dynamic shear modulus increased with the increase in rubber content for aged and unaged asphalt binders. Mashaan [45] studied the effects of long-term aging and short-term aging on the permanent deformation properties of crumb-modified asphalt binders. It was found that the rubberized asphalt binder exhibited a decrease in penetration and increase in both viscosity and softening point during the different aging conditions. According to Wang [62], the addition of crumb rubber into the asphalt binder can increase the resistance to age hardening of the asphalt binder owing to the anti-aging element (carbon black) in crumb rubber powders. In addition, adding crumb rubber into the asphalt binder increased the asphalt binder's aging resistance by increasing the asphalt film thickness on the aggregate surface [62]. Therefore, adding crumb rubber into the asphalt binder improved the durability of asphalt against aging effects.

5.2. Fatigue Cracking

Figure 4 illustrates fatigue cracking, which is one of the most frequently occurring damages in asphalt pavements [45,62]. Fatigue cracking is classified as thermal cracking or load-associated fatigue cracking. Thermal cracking occurs as a result of a combination of thermal tensile stress alongside the stress applied by the passing traffic. Load-associated fatigue initiates when repeated or fluctuating stresses, which cause the pavement to flex, and the base of the asphalt layer reach the maximum tensile strain, leading to various pavement surface fractures and fatigues. Fatigue cracks continue to propagate with the increase in traffic loading and appear as longitudinal cracks connected with transverse cracks, forming a pattern that resembles a spider's web on the pavement surface, as shown in the Figure 4. Since the resistance to fatigue cracking depends on to the tensile strength and elastic properties of the asphalt mixture [63], adding crumb rubber into the asphalt mixture proved to enhance the elastic properties, thus improving the resistance to tensile stresses caused by repeated traffic loads [64–66].

Figure 4. Fatigue cracking in asphalt pavements.

Aflaki and Memarzadeh [46] explored the use of crumb rubber in the modification of asphalt binder. They found that the resistance to fatigue cracking was improved for the modified binder made with low shear blending. Wang [62] investigated the effects of gradation type, asphalt content, test temperature, stress ratio, loading frequency, rubber powder concentration, and rubber size on crumb rubber-modified asphalt mixture's fatigue life and crack growth. Their results showed that the gap-graded crumb rubber-modified asphalt mixture had a lower crack growth rate and longer fatigue life than that of the continuous graded mixtures. They also found that the crumb rubber-asphalt mixture with 20% crumb rubber concentration had the best anti-fatigue property. Similarly, Mashaan [45] examined the effect of rubber content on the performance of crumb rubber-modified asphalt and found that increasing the rubber content improved the resistance to fatigue cracking. However, it was found that increasing the rubber content by 16% and 20% increased the binder viscosity to a limit where it became impractical for field construction.

5.3. Resistance to Rutting

Figure 5 illustrates rutting in asphalt pavements. Rutting or permanent deformation is one of the most common forms of distress in asphalt pavements and has a significant impact on the performance and service life of asphalt pavements. It can be caused by various mechanisms including consolidation or later movement of the pavement materials under repeated heavy-load traffics. Factors such as the binder type, air void content, and bonding stress between aggregates and the binder in asphalt mixtures influence the resistance to rutting [67,68].

(**a**)

(**b**) (**c**)

Figure 5. Rutting in asphalt pavements, adapted from (**a**) [69], (**b**) [70], and (**c**) [71].

Typically, two types of rutting could form in asphalt pavements, consolidation rutting and instability rutting. Consolidation rutting can develop due to excessive consolidation of the pavement along the tire path due to the deformation of the subgrade layer or reduction in the air voids content in the asphalt concrete layer. On the other hand, instability rutting can form due to instability or volume change of the asphalt mixture. Although volume change has some effect, rutting is mainly caused by shear deformation due to repetitive traffic loading [72]. Simms et al. [73] studied the development of instability rutting in asphalt pavements using a finite element model of a radial truck tire on a flexible pavement structure. Their results showed that stress states induced by a radial truck tire, including the reduction in asphalt mixture shear strength caused by traffic loads and high temperatures, may promote the development of lateral humps and presence of dilation (rotation of a slipped zone) rather than volume change alone.

Several studies have reported that crumb-rubber asphalt has better resistance to rutting than that of conventional asphalt pavements [34,39,45,46,61,62,64,65,74]. For instance, Mashaan [36] investigated the influence of rubber content on the rutting resistance of crumb-modified asphalt binder and found that the increase in rubber content induced an increase in elastic recovery, which could improve the resistance of modified asphalt pavement to rutting. Similar results were also reported by Khalili et al. [34], Lee et al. [74], and Khalid et al. [75]. Shen et al. [76] showed that asphalt binder modified with larger rubber particles exhibited larger complex modulus, which is beneficial for the resistance to rutting. Ge et al. [59] studied the performance of asphalt binder modified with both waste tire rubber and recycled polyethylene using the dynamic shear rheometer and bending beam rheometer under different temperatures. Their results showed that the addition of waste tire rubber and recycled polyethylene resulted in an enhancement in rutting resistance of the asphalt binder at high temperatures. Wang et al. [39] explored the high-, intermediate-, and low-temperature performance of crumb rubber-modified asphalt binders containing warm mix asphalt additives (wax-based and chemical-based products) using multiple stress creep and recovery test, linear amplitude sweep (LAS) test, and low-temperature frequency sweep test. They found that warm mix asphalt additives had adverse effects on the resistance to rutting of crumb rubber-modified binders due to the potential physical or chemical interactions between asphalt, rubber, and warm-mix additives, which needs more research.

5.4. Field Performance

In terms of field performance, several studies have been conducted to investigate the performance of rubberized asphalt pavements constructed in the United States, mostly in regions with warm climates [64,77]. For example, in California, although some pavements showed premature distress due to the lack of experience, several rubberized asphalt pavements exhibited excellent performance for up to 15 and 20 years when properly designed and constructed. According to Khalili et al. [64], the distresses in the well-performing rubberized asphalt pavements progressed at a much slower rate in comparison with those in conventional asphalt pavements.

In 2011, a pilot study was carried out in Ontario, Canada by the Centre for Pavement and Transportation Technology, the Ontario Tire Stewardship, the Ontario Ministry of Transportation, and the Ontario Hot Mix Producers Association to investigate the performance of rubberized asphalt pavements in three highways. During the pavement construction, several test specimens were collected and tested using the Thermal Stress Restrained Specimen Test to investigate the ability of the modified asphalt mixture to withstand cold temperatures. The results showed that the rubber-modified asphalt was able to withstand colder temperatures than the conventional hot mix asphalt (HMA) [77].

6. Summary and Conclusions

The rapid development of automobile manufacturing and the transportation industries has remarkably increased tire consumption, resulting in a massive amount of scrap tire waste needing to be discarded annually. At the same time, the continuous increase in traffic loads and the delay of proper highway and road maintenance have resulted in the premature damage of many asphalt pavements around the world. Several studies have reported that modifying asphalt mixtures using waste tire rubber additions as a low-cost and environmentally friendly modifier improved the overall properties of asphalt pavements. Based on this review of the state of the art, the following concluding remarks on the use of recycled tire rubber in asphalt pavements can be drawn:

- The use of recycled tire rubber as an additive in asphalt binder can improve various binder properties by reducing the temperature susceptibility of the asphalt binder.
- The addition of crumb rubber from waste scrap tires to asphalt binder can improve the resistance to rutting and permanent deformation of the pavement (owing to an increase in viscosity), reduce fatigue cracking, improve durability against traffic loads, and enhance pavement sustainability by saving energy and natural resources and lowering the maintenance and repair costs of asphalt pavements.
- Factors such as the shape, content, and particle size of the crumb rubber waste significantly affect the rheological properties of the rubber-modified asphalt binder.
- Adding warm-mix additives to crumb rubber-modified asphalt can have adverse effects on the rutting and fatigue resistance of crumb rubber-modified asphalt, which needs further research.
- Adding crumb rubber into asphalt binders can enhance the asphalt's resistance to age hardening.
- An increase in the rubber content in asphalt binder increases the elastic component of the dynamic shear modulus, leading to improved recovery and rutting resistance of asphalt pavements.
- However, a large increase in the rubber content increases the binder viscosity (and changes flow characteristics from Newtonian to shear thinning), which can lead to construction difficulties.
- Further field testing, such as non-destructive testing, is required on rubberized asphalt pavements constructed in different zones to gain a more profound understanding of the behavior of rubberized asphalt in aggressive exposure conditions.
- Crumb rubber-modified asphalt binder contains less asphalt than conventional asphalt binder. This reduction in asphalt content can increase air voids within the binder matrix, thus increasing permeability, which could negatively affect the durability of rubberized asphalt pavements. Further research is needed to examine the permeability and moisture damage characteristics of rubberized asphalt pavements in various exposure conditions.

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