Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

A Review of the Effect of Crumb Rubber as an Additive on Hot Mix Asphalt

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ARTICLE INFO

Article history:
Received 19 October 2024
Revised 19 October 2024,
Accepted 08 November 2024,
Available online 20 November 2024

Keywords:
Crumb rubber
Hot mix asphalt
Asphalt binder (AB)

ABSTRACT

Materials recycling has a significant economic and environmental impact; as a result, steel, aluminium, plastic, and other recyclable materials have been pushed for use in construction materials. One of these recyclable materials is the crumb rubber, has been considered as a pavement component. The general behaviour of the composite rubber-hot mix asphalt system would be varied from that of the conventional rubber free mix. In this review, desirable characteristics of hot mix asphalt are highlighted first. Also, effect of gradation and the main types of rubber are specified. Afterward, many studies that considered the crumb rubber as a waste product and its associated mixture and modifiers are reviewed. The factors affect the crumb rubber modifier studied by many investigators are summarized. Findings show an increase in pavement performance after treating with crumb rubber. In addition, crumb rubber modifier meets the local and international standards requirements.

1. Introduction

The noticeable rising in the number of vehicles on the highway of developing countries leads in the annual accumulation of millions of old tires. Each year, approximately 1.4 billion tires are purchased around the world. Tires can be considered as one of the most common and hazardous waste causes due to the enormous number of units generated and their short lifespan [1]. Around 280 million tires are reaching their end-of-life, only 30 million of them reutilized. The reminder of 250 million rubber tires requesting an appropriate recycling. See Figure 1 for more illustration.

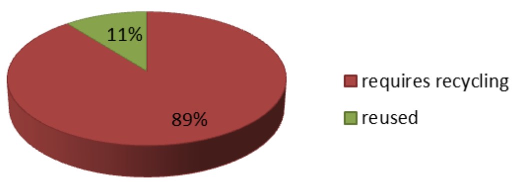

Figure 1 Distribution of tires reaching their end-of-life

For more than three decades, the manufacturing of asphalt has employed recycled tires in mixing applications. Even though an indication of this technique is evidently valid, it is

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https://doi.org/10.61268/qemk0m60

discontinuous, making it difficult to have a synopsis from a historical perspective. Nevertheless, the issue of waste tires has recently gotten much worse than before. Consequently, finding an optimal and practical way to employ crumb rubber tires (CRT) in asphalt mixes has become critical [2]. The design of the crumb rubber (CR) includes many technical benefits in addition to the prospect for environmental protection [3]. In last years, employing the CR as a modifier in asphalt mixes has risen across the world. When compared to roads built with the traditional design, many roads with crumb rubber modifier (CRM) in their asphalt mixes are still in good shape after several years of service. Crumb rubber has been the focus of extensive research regarding its effects on hot mix asphalt (HMA). Incorporating crumb rubber into asphalt mixtures has demonstrated beneficial outcomes in improving various asphalt properties. Research has shown that activation treatment enhances the compatibility between crumb rubber and base asphalt, resulting in superior performance of the modified asphalt [4]. Additionally, the inclusion of crumb rubber in asphalt not only boosts performance at both high and low temperatures but also contributes to increased durability of the pavement [5].

Furthermore, using crumb rubber in asphalt mixtures has been linked to reduced traffic noise, enhanced pavement performance, and lower costs, making it a valuable additive for asphalt concrete[6]. It has also been associated with improved resistance to rutting in high temperatures, better cracking resistance in low temperatures, and increased aging resistance of asphalt mixtures[7] (Yang et al., 2022). In addition, incorporating crumb rubber into asphalt is seen as an eco-friendly approach for managing waste, with crumb rubber modifiers (CRM) recognized as alternative materials that can improve the characteristics of hot mix asphalt. Moreover, the introduction of crumb rubber in asphalt improves the longevity of road surfaces by mitigating the effects of traffic loads on pavements [8]. The environmental advantages of using crumb rubber in asphalt have also been emphasized, as it promotes the recycling of waste materials and lessens the ecological impact of tire waste. Using crumb rubber in the production of hot mix asphalt (HMA) can lead to reduced air pollution. Specifically, emissions of carbon monoxide (CO) and methane (CH_4) can be decreased by 39.7% and 61.7%, respectively, during the manufacturing of rubberized asphalt mixtures. Additionally, incorporating crumb rubber into flexible pavements can enhance their environmental noise performance [9].

The aim of this review is considering the pavement materials with main focus on crumb rubber and its performance on hot mix asphalt. All previous studies are intensively discussed and conclusions are drawn.

2. Hot mix asphalt (HMA)

Globally, HMA is the supreme paving unit broadly utilized. Asphalt binder (AB) and aggregates are the two main components of HMA. Aggregates are a mixture of fine and coarse elements, usually rock and sand of various sizes. The aggregates account for around 95% of the overall weight of the mix. HMA is formed via combining the aggregates with around 5% of AB. About 85% aggregate, 10% of AB, and 5% air spaces make up the average HMA mixture volume. Many HMA mixes have additives added in modest amounts to improve their performance and workability. Because of its high flexibility in comparison to cement concrete pavement, asphalt pavement is known as flexible pavement [10]. Structural units made up of a sequence of stratum of different materials laying down on top of the supporting soil (Subgrade) are defined as asphalt concrete pavements (ACP). The vertical section of a typical asphalt concrete pavement construction is shown in Figure 2.

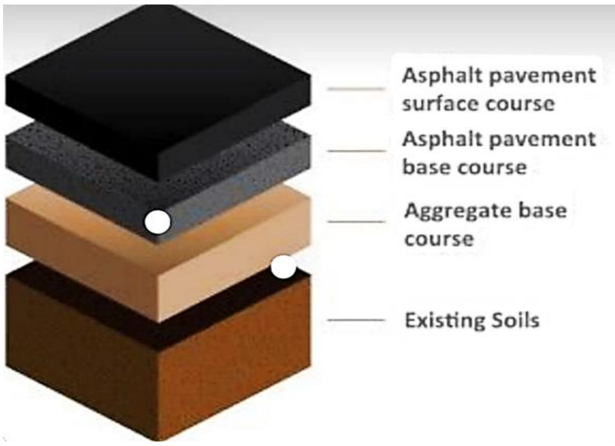

Figure2: The representative vertical layout of an asphalt concrete pavement[10]

2.1. Paving materials

2.1.1. Asphalt binder

The asphalt binder (AB), also is called bitumen and usually grips the particles of HMA in tandem, it is a viscous and heavyweight remainder left over from crude oil refining. The physical characteristics of AB change dramatically as the temperature changes. At high temperature, it behaves as a fluid analogous to oil with low consistence. At the temperature of room, the AB has the own soft rubber consistency. At below zero degree of temperature, it converts extremely frangible. Numerous ABs have low quantities of polymer added to them to enhance their physical qualities, and they are referred to as "polymer modified binders." The majority of ABs specifications were formed to manage consistency oscillations as a temperature function [10].

2.1.2. Aggregate

Crushed rocks, gravel, sand, and rock’s dust are examples of aggregate. The HMA pavement is made from appropriately chosen and graded aggregate combined with an AB. The prime load-bearing components of HMA pavement are aggregates. Because aggregates account up over 95% of the mass of dense-graded HMA. The properties of the aggregate have a significant influence on the performance of HMA pavements. Fine and coarse aggregates along with the mineral filler form the three size categories of HMA aggregates. Coarse aggregate is accumulated on the sieve 4.75 mm, while fine aggregate is passed through the sieve 4.75 mm and retained on the sieve 0.75 mm, and mineral filler is finer than 0.75 mm. The latter is used to increase the density and strength of HMA [11].

2.2. Desirable characteristics of HMA.

The goal of mix designation is obtaining a certain collection of characteristics in the final HMA. Those characteristics are influenced by a variety of factors, including AB concentration and properties, compaction degree, and aggregate’s features such as grain size, texture, form, and chemical formation [12].

Table (1) a list of properties Mixtures of asphalt and aggregates [12].

Characteristic	Description	Examples of Mix Influenced Variables
Stiffness	The stress-strain relationship at a certain loading time and temperature.	Gradation of aggregate ($G_{agg.}$), stiffness of asphalt ($St_{asph.}$), degree of compaction (DoC), sensitivity of water (SoW), and asphalt content (asph. %)
Stability	Permanent deformation resistance	Surface texture of aggregate (Sur.Tex. $_{agg.}$), asphalt cement grade($G_{asph)}$., stiffness of asphalt (St_{asph}) ., asphalt content (asph. %), DoC, and SoW
Durability	Resistance to the abrasive impact of traffic and air and water weathering effects.	asph. %, $G_{agg.}$, DoC and SoW
Fatigue Resistance	Mix's capability for bending repetitively without cracking	$G_{agg.}$, asph. %, DoC, and $St_{asph.}$
Fracture properties	Strength of mix when subjected to a single tensile stress.	Type of aggregate ($Type_{agg.}$), $G_{agg.}$, asph. %, DoC, SoW and $St_{asph.}$
Friction characteristics of surface (Skid Resistance)	Capability of the mix to create an appropriate coefficient of friction among the tires and pavement while "wet."	Texture of aggregates and polishing ($Tex_{agg.}$), resistance (R), $G_{asph.}$, and asph. %
Hydraulic conductivity	Chance to move air, or water through the mixture	$G_{asph.}$, asph. % and DoC
Workability	Capability to locate and condense the mixture to a certain compactness	Placement $St_{asph.}$, Sur.Tex. $_{agg.}$, asph. %, and$G_{agg.}$

2.3. Specifications for asphalt wearing courses' grading and Crumb Rubber Gradation

One of an aggregate's most important qualities is its gradation, or particle size distribution. The most significant qualities of HMA, such as workability, durability, hydraulic conductivity, stability, stiffness, moisture resistance, and fatigue resistance are determined by its grade. A sieve analysis to determine the size distribution (Gradation) is adopted.

According to the standards requirements of ASTM D3515 (Designation D-5), mix should satisfy the gradation illustrated in (Table 2) and Figure (3). The Marshal Test procedures are standardized according to the specifications ASTM D1559 .

Table (2). Requirements for gradation of Topcoat of Asphalt (according to ASTM D-5315)

Sieve number (#)	Size of openings (mm)	Fraction by mass % finer	
		Min	**Max**
3/4"	19.00	100.00	100.00
1/2"	12.50	90.00	100.00
3/8"	39.50	67.00	88.00
4	4.75	44.00	74.00
8	2.36	28.00	58.00
30	0.60	16.00	39.00
50	0.30	5.00	21.00
80	0.18	3.00	15.00
200	0.075	2.00	10.00

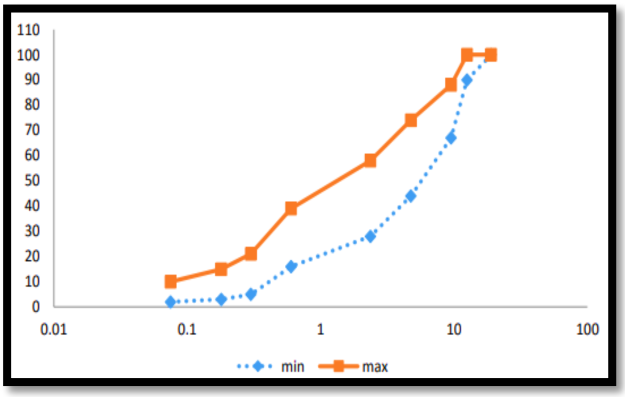

Figure (3): Gradation of Asphalt Wearing Course (ASTM D3515)[10]

When using CR in asphalt mix, coarse rubber grains from the granulated rubber, which pass through a 6.3 mm sieve and have a rough cube-shaped, are exclusively included to enhance the properties of the mixture. However, subsequent experiments on CRM revealed that the improved durability might being attained via adding more of the fine rubber [13]. Therefore, after1980s, coarse rubber grading with a percentage of 20% was initially substituted with fine CR that passes through the specified size of sieve openings of 0.85 mm [14]. Furthermore, Gallego et al., [15] found that mixtures with fine rubber grading (0.15 mm to 1.18 mm) demonstrated improved performance in terms of permanent deformation compared to traditional asphalt mixtures, largely due to the modification of the binder. Additionally, Becker et al., [17] reported that rubberized mixtures containing fine rubber within the range (0.075- 0.42) mm size resulted in lesser void space after densification. For Generic mixtures, the percentage of CR used is slightly lower (1% to 3%). Although, those mixtures are taken into consideration the similar principle of modification by addition of coarse and fine rubber to the mixture in proportions, the foundation behind this procedure is that the coarser rubber to act as elastic aggregates while fine rubber to represent a modified binder in the mixture. Table 3 demonstrates the grading recommended for the rubber in the generic mixtures [13].

Table (3). Recommended Rubber Gradation in the generic mixtures

Sieve No.	Present passing %
4.75	100
2.36	70-100
1.18	40-65
0.6	20-35
0.3	5-15

3. Crumb Rubber modified asphalt mix and background

Recycled rubber from waste tires is utilized as reclaimed rubber, commonly known as crumb rubber (refer to Figure 4). Tire rubber consists of a mixture of natural rubber, artificial rubber, carbon black, fillers, antioxidants, and lubricants that can dissolve in hot pavement grade. The terms scrap, CR, and reclaimed) rubber all refer to recycled rubber. The primary sources of recycled rubber are car and truck tires. Tyres of cars are mainly composed of Styrene Butadiene Rubber or polyisoprene along with carbon black. In contrast, tires of truck contain a higher proportion of natural rubber, which can be more than 30% of the total polymer content [17] and [18].

Figure 4. Waste tires (A,B)

Rubberized bitumen binders are created by mixing crumb rubber from ground tyres with bitumen binder under specific time and temperature conditions. There are three main methods for producing bitumen rubbers termed wet, dry, and terminal blending methods [2] and [19]. Different formulations of rubberized bitumen, created through both dry and wet procedures, have been viewed as effective alternates to traditional bitumen. Consequently, they have been subjected to an extensive research and evaluation on the topic. Heat in the mix of bitumen-rubber throughout the curing result in type of breakage in crosslinks of the rubber, as demonstrated by the phenomenon of DE vulcanization [20]. The characteristics of rubberized bitumen binders created through the wet process are influenced by the types of CR and bitumen binder utilized [21].

Crumb rubber is becoming more popular in asphalt paving in many regions of the world. This is because the material's mechanical and functional properties have improved. In addition, the combination is more suitable for waste product recycling [22]. The global environmental problem of CR car tires is intensified via the growing flow of vehicles on the road. Due to non-biodegradability of the discarded tires, a significant ecological hazard. Common removal methods of the used tires are by underground burial or by burning. Waste tires, on the other hand, contain a wealth of materials that can go through a diversity of forms. Crumb rubber modifier asphalt (CRMA) research and development began on the last few decades in the USA, Canada, and many nations. The first experiments can be traced backward to the fourth decade of the 19th century, when natural rubber was implemented to enhance the bitumen's engineering conduct. The method of modifying bitumen with both natural and artificial rubber began at the beginnings of 1843 [23]. Later on, in the 1923, improvements were made to the use of natural and synthetic rubber in bitumen [24]. Yildrim, [25] notes that the application of rubber in bitumen ingredients for joint sealants, patches, and membranes started at the ends of 1930s. By 1950, the incorporation of scrap tires into asphalt pavement was documented [26]. The integration of rubber into asphalt materials started in the 1960s, as the paving manufacturing recognized the elastic possessions of rubber, which have the practicability to boost skid resistance and the durability of asphalt mixtures [20-27].Charlie MacDonald, who was the head in the department of material engineer in Phoenix, Arizona, began using milled tire rubber as an additive for modifying bitumen binders. He revealed that by adding crumb rubber to the conventional bitumen and permitting the blending for 45 to 60 minutes, the mixture exhibited new material properties. This process caused the rubber particles to swell at higher temperatures, which in turn allowed for higher concentrations of liquid bitumen in the pavement mixes [28]. By the mid-1980s, European researchers started to develop new polymers and additives for modifying bitumen binders [29]. In recent years, there has been growing interest in the use of crumb rubber for pavement modification, with evidence showing that CR of tire can enhance the conduct characteristics of bitumen [30-33].

CRMA, according to previous experience, has a greater viscosity, which enhances rutting resistance. In comparison to the traditional approach, CRM has a lower temperature susceptibility and maintenance expenses, greater durability and softening point, superior resilience, reduction in fatigue and growth in resistance to surface damage, and reflection of cracking. Improved both efficiencies energy and natural sources via the employment of waste supplies [34]. The types and classifications of rubber are as follow:

Natural rubber and Synthetic rubber; Rubber trees, such as latex, are used to make natural rubber. The latex is squeezed after it has been coagulated with formic or acetic acid. Synthetic rubber is made via polymerizing certain chemical substances that possess quality similar to that of rubber further to other desired characteristics. Natural rubbers are elastic hydrocarbon polymers initially sourced from nature in the latex form. Tuntiworawit et al., [35] conducted research on the modification of asphalt mixture by means of latex. The primary goal was to assess the engineering parameters of asphalt-cement and asphalt-concrete mixtures reinforced with varying amounts of latex. The work concluded that incorporating latex as an additive is a beneficial option in modification of bitumen. Furthermore, it was found that natural rubber enhances the attitude of asphalt in roadway, particularly in context of flexibility and stability. The research determined that a latex content of 9% by weight of asphalt was optima. The majority are made from butadiene substances and have double bonds between two carbon atoms. Examples include: Neoprene, styrene, silicones, polyurethane, Thiokol, butadiene rubber (SBR), and rubber [36]. There are two distinct ways to employ tire rubber in bitumen binders. The first involves dissolving tire rubber as a binder modifier in the bitumen. The second method involves replacing some of the fine aggregates with ground rubber that doesn't react with bitumen entirely (Huang et al., 2007) [37]. The base bitumen constituents, the blending time and temperature, the percentage of rubber, the gradation of crumb rubber, the type of mixing (wet or dry), and the grinding process method are just a few of the variables that can affect the modification effects (Huang et al., 2007; Airey et al., 2003; Jeong et al., 2010, Patit et al. (2004))[37- 40]. reported that the bitumen-rubber combination exhibited reduced rutting capability during bitumen-rubber blending, owing to increased stiffness and tensile strength at greater temperatures. The Rubber Pavement Association discovered that tire rubber might reduce tire noise by about 50% when added to an open-graded mixed binder. Furthermore, Zhu and Carlson (2001)[41] found that rubber particles with varying sizes exhibited superior sound-absorbing properties in spray applications. Moreover, utilizing asphalt rubber extends the pavement's lifespan, which is another benefit. Huang et al. (2007) [37], however, offer suggestions for evaluating the asphalt rubber's cost-effectiveness. Some of advantages of use bitumen amended with crumb rubber [36] such as:

1- Less vulnerability to daily and seasonal variations in temperature.

2- Increased pavement temperature resistance to deformation.

3- Enhanced characteristics that resist aging.

4- Improved aggregate-binder adhesion and a longer fatigue life for mixtures.

4. Properties of Crumb Rubber (Physical and Chemical Properties)

The dimensions, shape, and texture of the rubber subdivisions employed to modify the mix differ based on the intended applications for achievement of desired act is met. Figure 3 illustrates various sizes of CR produced for recycling purpose [13].

Figure 5 Size Varity of CR [13]

Rubber grains that own non uniform shapes and great surface area tend to react so effectively with bitumen at elevated temperatures, creating a modified binder. Conversely, cubical grains of rubber that have a lower surface area are commonly utilized as elastic aggregates in the dry process because they are easier to blend into the aggregate mix. Scrap tires can be processed primarily through two methods: ambient granulating (cracker mill process) and cryogenic grinding. Ambient granulating is the more prevalent and productive method, employing a combination of granulators, screeners, conveyors, and magnets to extract steel and fibers from the rubber. This technique results in irregularly shaped particles with a substantial surface area, measuring between 0.425 mm and 4.75 mm. In contrast, cryogenic grinding takes place at very low temperatures using liquid nitrogen, which results in brittle rubber that can be easily broken down into smaller sizes (0.85 mm to 6 mm). The rubber obtained from cryogenic grinding has a glass-like appearance and a smaller surface area compared to rubber produced by ambient granulation [13]. Consequently, ambient granulated crumb rubber yields higher viscosity of binder than modified binders made with an equivalent amount of cryogenic CR, due to the quicker reaction between bitumen and the high-surface-area, irregularly shaped particles from the ambient process. This illustrates that the production method of crumb rubber plays a crucial role in enhancing its properties [42,43]. The size of crumb rubber can have a significant impact. A study by Shen et al. (2009)[44] indicated that the particle size of crumb rubber modified (CRM) influences the high-temperature properties of rubberized bitumen binders, affecting their visco-elastic characteristics. Coarser rubber resulted in a modified binder with higher shear modulus, while increasing the crumb rubber content reduced creep stiffness, contributing to improved resistance to thermal cracking.

For the Chemical properties, tires are primarily made of rubber, with slight compositional differences between car and heavy truck tires. This rubber is a complex blend of elastomers, including polyisoprene, polybutadiene, and styrene, along with important compounds like citric acid, zinc oxide, extender oil, and carbon black (as figure 6 and table 4) [45] . The study by [46] Wang et al (2022) investigated the chemical interactions between aggregate and rubber asphalt, revealing insights into the mineral composition involved. The aggregates have a considerable impact on the interfacial interactions with rubber asphalt. Specifically, calcite aggregates exhibit the lowest adhesion energy, while dolomite aggregates have a moderate level, and quartz aggregates show the highest adhesion energy. López-Moro et al. [47] investigated the chemical interactions between asphalt and rubber and found that crumb rubber particles effectively occupy the spaces between bitumen molecules, leading to a denser and more uniform asphalt mixture. They also offered insights into the microscopic interactions of crumb rubber and bitumen in asphalt blends, which can be leveraged to improve the durability and reliability of road surfaces.

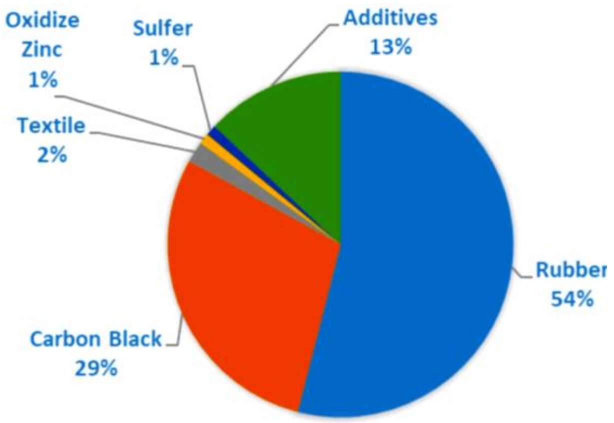

Figure 6 Chemical characterization [48]

Table (4). The typical amounts of the chemical composition of tire rubber

Property, units	Value
Specific gravity Gs, g/cm³	1.15
Moisture content mc, %	0.5
Ash content %	3.6
Carbon black content, %	32.7
Extract content, % (acetone and chloroform%)	7.3
Sulfur content, %	1.5

5. Effect Crumb Rubber on Pavement Distress

distress of pavement represent as: Edge Cracking, Block Cracking, Fatigue Cracking, Longitudinal Cracking, Polished Aggregate, Raveling, Reflection Cracking at Joints, Rutting, Transverse Cracking, Bleeding. In this section will present the effect of adding crumb rubber on distress of pavement, the most characteristic listed as : Fatigue Resistance and Rutting.

in the top 100 mm of the pavement surface. A study by Mahrez (1999) [57] suggested that incorporating rubberized bitumen binder

• Fatigue is a type of cracking that develops in asphalt pavement structures due to repeated heavy traffic loads at low to medium temperatures. This is addressed in the context of utilizing waste tire rubber to improve the mechanical properties of stone mastic asphalt mixtures [49] .Numerous research have demonstrated that using crumb rubber treated with bitumen binder appears to improve the fatigue resistance [50,51,52,53,54] (Raad and Saboundjian, 1998; Soleymani et al., 2004; Mc .Gennis, 1995; Biliter et al., 1997a; Hamed, 2010). The enhanced rheological characteristics of the rubberized bitumen binder have contributed to the better performance of bitumen rubber pavements when compared to traditional bitumen pavements.

Rutting is characterized by longitudinal depressions along the wheel paths caused by ongoing compaction due to traffic loads. According to Sousa and Weissman (1994), [55] rutting in bituminous pavements worsens with increased load applications, appearing as longitudinal depressions in the wheel paths with slight elevations on the sides. This effect is a result of both densification and shear deformation, making it an important measure of pavement performance in different design approaches. Factors such as problematic subgrade conditions and unbound base courses can worsen rutting, particularly due to the impact of heavy truck loads, high tire pressures, and higher pavement temperatures. Therefore, selecting the appropriate bitumen binder and aggregate combinations is essential for enhancing the performance of asphalt pavements. Furthermore, Brown and Cross (1992) [56] indicated that permanent deformation in bituminous mixtures is caused by consolidation and lateral movement under traffic, with shear failure commonly occurring notably enhances the mixture's resistance to rutting deformation. Bahia and Davies [58] performed laboratory experiments on asphalt samples modified with different proportions of rubber, from 0 to 20%, to evaluate the rheological and physical characteristics of the mixtures. They utilized the DSR test to analyze the rheological behavior, and their findings showed that the inclusion of rubber improved both the complex modulus and phase angle of the modified asphalt, resulting in enhanced resistance to rutting in asphalt pavements. In summary, the research indicates that adding waste tire rubber to asphalt binder effectively increases its rutting resistance.

6. Effect of Crumb Rubber on Marshall Properties of HMA:

The properties of hot mix asphalt (HMA) mixtures are critical for evaluating their performance and suitability for various applications. Key properties listed in table 5 below:

Table (5). Effect Crumb Rubber Properties of HMA

Properties of HMA	Effect	Resource
Stability	The Increasing CR to 10%, the stability will increase with Incorporating waste tire rubber into asphalt concrete mixtures improved Marshall stability up to a rubber content of 15%. Beyond this level, particularly with No. 50–200 rubber particle sizes, the stability declined.	[59], [60], [75]
Flow	The flow value of asphalt mixtures increases with the concentration of added waste tire rubber. The highest flow value was noted with rubber particles sized No. 20–50, while the lowest was associated with particles sized No. 16–20. Thus, that greater rubber content enhances the flow of the mixture.	[59], [60]
Void in Mineral Aggregate (VMA)	Augmenting the quantity of tire rubber raises the voids in mineral aggregate (VMA) value. The greatest VMA was recorded with rubber particles sized No. 20–50, whereas the lowest VMA was found with particles sized No. 16–20.	[60], [61]
Void Filled with Asphalt (VFA)	VFA rises gradually as the tire rubber content in the mixture increases. This is due to the thicker asphalt film surrounding the aggregate particles, resulting in fewer voids. As a result, the higher effective asphalt content causes bleeding and a decrease in the mix's stiffness.	[61] ,[62]
Air Void	Elevating the tire rubber content in a mixture results in an increase in air voids. This notable rise in air voids could be linked to the increased hardness of the bitumen resulting from the greater amounts of rubber. This hardness adversely affects the adhesion between the aggregate and bitumen, mainly because rubber crumbs absorb into the lighter asphalt components.	[63], [61]

7. Previous research

Much research has been carried out to investigate the effect of crumb CR on asphalt binder and HMA, as shown in the table 6 below:

Table (6). Previous research and their Insight

Reference	Description
[64]	The main objective of this study is to explore the impact of eco-friendly additives on the physical characteristics of asphalt. Adding 1% waste rubber nanomaterial to the modified binder significantly enhanced the penetration grade and softening point, resulting in greater stiffness of the modified asphalt. Moreover, the inclusion of waste rubber nanomaterial also improved the temperature susceptibility of the binders.
[43]	This research examines how the characteristics of crumb rubber modifier (CRM) affect the viscosity of CRM binders. Two types of binders were mixed with four different concentrations of crumb rubber from various sources. The viscosities of the resulting binders were measured using AASHTO T316 standards. Scanning electron microscopy (SEM) was utilized to analyze the CRM characteristics, while differential scanning calorimetry (DSC) was employed to determine the glass transition temperature (Tg). The findings indicate that both the processing methods and the type of tires used significantly influence the viscosity of CRM binders.
[65]	This study explored the characteristics of crumb rubber modifier (CRM) binders in the lab, focusing on various CRM manipulation techniques and fractions. A total of twenty-four CRM binders were produced, utilizing three binder sources, two CRM manipulation methods, and four CRM fractions. The binders underwent artificial aging using an accelerated aging process. Testing methodologies included assessments of high-temperature viscosity, performance at both high and intermediate temperatures, and low-temperature cracking properties. The results indicated that increasing the percentage of CRM in the binders led to higher viscosity, improved rutting resistance, and reduced low-temperature cracking risk. Overall, ambient CRM proved effective in creating viscous CRM binders with low resistance to cracking and rutting.
[66]	In the laboratory, the interrelationship impacts of CRM binders were examined as a result of different blending processes. CRM binders were made utilizing seven different blending durations (0.083, 0.5, 1, 1.5, 2, 4, and 8 hr.), three different blending degrees of temperature (177, 200, and 223 °C), and four different rubber ratios for this investigation (5 %, 10 % , 15 %, and 20 % by the mass of AB). Findings revealed that the blending duration and temperature for CRM binders had a substantial impact on the binder characteristics. Thus, the blending with longer period of time and greater degree of temperature for CRM binder led to a rise in the failure temperature and viscosity. The behavior may belong to excess in the rubber mass resulted from binder adsorption. The governor binder PG 64-22, on the other hand, showed no change in binder characteristics as an indicator to the blending settings. In addition, the CRM fraction impact on viscosity and G*/sin magnitude is statistically significant. Furthermore, the binder of asphalt with a greater CRM fraction had a larger molecular size magnitude, and the rise in CRM fraction is thought to be a consequence in a deficiency of low molecular weight in the AB to the CRM.
[67]	They researched the relation between CR Morphology and Viscosity of Asphalt Rubber**.** The results obtained from the morphological analyses were consistent with one another and fully aligned with the production process information. A distinct ranking of viscosity for rubber Abs was quantified, emphasizing the unique characteristics of various categories of CR. Additionally, a predictive modelling was developed that illustrates how viscosity is influenced by the morphological traits of crumb rubber. This model demonstrated statistical validity and was consistent with the interaction

	attitude present within rubber Abs.
[68]	Authors looked at how produced rubber bituminous mixtures are responding to plastic deformations. As a result, a collection of asphalt mixtures with various proportions of CRM applied by both processes of dry and wet were examined. Also, the achievement of a CRM mix was parallelled to a high-achievement polymer-modified bitumen mix. The cyclic triaxial tests and wheel-tracking tests were adopted to assess the mixtures performance. To assess bearing capacity, they must also determine its stiffness modulus at various degree of temperatures. Findings revealed that adding CRMs to the traditional bitumen using wet method and dry method CRM to asphalt mi enhanced the plastic deformation resistance for the doses and percentages of CR utilized. Naturally, certain CRM mixtures outperformed the high-performance modified bitumen mix. The values of creep and stiffness moduli significantly enhanced the resistance of plastic deformations triggered by vehicle traffic stresses.
[69]	They used rubber of recycled tires as a fractional substitution for coarse aggregate in concrete mix combined with regional accessible trash tires at Gaza's Islamic university. A total of ten mixes with a goal strength of 25 Mpa were created. The examples were made with varied percentages of coarse aggregate replaced with rubber aggregate (20, 40, and 60%) and a set fraction of Forta Ferro fibers (FF). Outcomes showed that combining FF with rubber of the tires reduce droop significantly. When 20% ,40 % and 60 % of coarse aggregate were substituted for tire rubber, the losses in compressive strength were recorded 42.75%, 60.31%, and 71.73% correspondingly. The tensile strength declined as the percentage of tire rubber raised, however the existence of FF fibers raised the tensile strength by percentages between 25% and-30%. Also, the tensile strength reduced by 33% when the coarse aggregates were substituted with 20% rubber. Although, the impact strength declined with respect to the enlargement in amount of the rubber present, it enhanced when FF fibers were added.
[70]	Laboratory testing considered treating the 60/70 bitumen with the waste of recycled rubber tire resulted from tourist buses and less than five years old, with the knowledge that author adopted two various aggregate gradings of granulated CR and diverse grains percent (0.2, 0.3, 0.4, 0.5, 5, 10, 15) of bitumen. Crumb rubber were constructed using different percentages of rubber additives and the outcomes of tests were analyzed employing the Excel application to find the attributes of modified and unmodified bituminous mixes. Experiments indicated that as the quantity of rubber increased, penetration and ductility reduced and the softening point increased, indicating that rubber-modified asphalt mixes are more stable and have a lower flow rate than conventional asphalt mixtures.
[71]	The study examines the use of crumb rubber (CR) in asphalt mixtures as a sustainable solution for recycling waste materials and enhancing the performance of hot mix asphalt (HMA). It aims to provide a comprehensive assessment of CR's effectiveness in strengthening asphalt pavements, including its impact on stiffness, rutting, and fatigue resistance of road pavement constructs.
[72]	This paper investigates how CR polymers affect the conduct of asphalt pavements. To do this, asphalt mixtures with different proportions of CR were evaluated, upon following a wet process. The statistical analysis showed that the addition of CR notably enhanced the stiffness modulus, resistance to rutting, and the resilience of pavements against moisture damage. The findings indicate that incorporating 20%-24% of CR modifiers into conventional asphalt mixtures produces the most effective results compared to other CR polymer percentages.

[73]	This study examined the effects of different amounts of crumb rubber on an asphalt mixture using a dry processing technique. Four rubber percentages—0.5%, 1%, 1.5%, and 2%—were evaluated and compared to an unmodified asphalt mix. The laboratory results led to several conclusions: • The asphalt mixture with 2% crumb rubber (CR) displayed the greatest resistance to rutting. • The stability of the modified asphalt increases in proportion to the quantity of CR added. • Asphalt mixtures containing CR show enhanced resistance to moisture damage compared to unmodified asphalt. • The processing method (dry or wet) does not affect how CR influences moisture damage in the pavement.
[74]	Crumb rubber in three varied diameters of 0.075 mm, 0.15 mm, and 0.3 mm was added to the asphalt mixture in this investigation at a percent of 5% by overall mass of binder. The CR was blended with origin AB graded 60/70 using the wet process. In this investigation, the aggregate gradation was 9.5 nominal maximum aggregate diameter. The Superpave gyratory compactor was used to make the samples. The influence of the CR grading on the asphalt mix was evaluated using moisture sensitivity (ASSTHO T-283) and indirect tensile strength (ITS) tests. The inclusion of CR enhanced the asphalt mixture's strength, according to the data. Furthermore, when the size of the CR grew larger, the ITS increased. Adding 5% CR resulted in a little decrease in moisture resistance. As a result, a reduction in CR size led to a slight increase in moisture resistance. Overall, the TSR of all asphalt mixes in this investigation was greater than 80%, indicating that they passed the moisture damage test.
[75]	This research investigates the addition of CR from recycled tires to asphalt mixtures to enhance their performance characteristics. The study considers crumb rubber a sustainable solution for waste tire disposal, which poses environmental challenges. Four different proportions of crumb rubber (6%, 9%, 12%, and 15%) by weight of bitumen were added to a 60-70 grade AB, using a particle size that passes through a 0.3 mm sieve. The gradation of aggregates was considered based on the Marshall method for a 12.5 mm nominal maximum aggregate size wearing course to determine the optimum asphalt content and samples preparation for numerous laboratory examinations. The research assessed flow, Marshall stability, indirect tensile strength, permanent deformation and moisture susceptibility of the asphalt blends with changed CR percentages. Results indicated that adding crumb rubber improved the performance of asphalt mixes, with a notable 29.2% increase in Marshall Stability at a 9% CR addition. This enhancement in performance leads to a stiffer asphalt mixture, contributing to a extra rigid paving structure that is lesser susceptible to rutting and moisture damage under traffic loads.

8. Conclusion

Based on previous studies for CRMA mixtures, the subsequent conclusions can be derived:

1. Addition CRM to asphalt mixes is claimed to provide a number of advantages
2. CR can be employed as an asphalt mix additive.
3. The qualities of a rubber–asphalt blend is superior than a standard asphalt pavement.
4. Using CRM, improves the stability of the mixture while lowering the flow.
5. Using CRM as an additive in asphalt enhances the performance by increasing the service life of the road surface.
6. It also enhanced the mixture resistance to plastic deformations generated by traffic stresses of vehicle upon

increasing their stiffness modulus and creep modulus values.

7. The AB with a higher CRM fraction had a greater LMS value, and the rise in CRM proportion is thought to yield a loss of low molecular weight in the AB to the CRM.
8. Asphalt mix modified with CR meets standards requirements locally and internationally.
9. Particle size of crumb rubber employ the important efficiency

In summary, adding crumb rubber to hot mix asphalt offers a significant opportunity to improve the performance and sustainability of asphalt pavements. By taking into account variables such as mixing techniques, activation methods, molecular distribution, and rheological properties, researchers can enhance the effectiveness of crumb rubber in asphalt mixtures, leading to improved pavement performance.

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