Flexible Pavement: A Review on the Influence of Waste Rubber Particles in Asphalt and Asphalt Mixtures

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Abstract - Asphalt and aggregates are used in the flexible pavement to form asphalt concrete (AC) as the surface and binder courses. Both materials are essential components of hot mix asphalt (HMA). Conventional asphalt concrete might not fully have the potential to endure heavy traffic loading, high temperature, and intensive rainfall, especially in tropical regions, because of its characteristics, which often develop distresses, including fatigue cracking and permanent deformation. The number of failures caused by these factors reduces the pavement's long-term performance. Until now, the research about newly selected modifiers and techniques to modify asphalt and asphalt mixtures is essential. Using waste rubber particles in HMA for performance improvement has become a technique of great potential for many years round. The modifier makes HMA more resistant to temperature variations, increasing traffic, reducing maintenance costs, and improving the pavement's riding surface. This paper reviews the modifier's influence with particular reference to the dry and wet processes. The review's primary focus was studied, which highlights some critical issues considering design mixes, testing methods, and performance on road pavements. Recommendations called for additional research for performance improvement of the modifier used in asphalt and asphalt mixtures.

***Key Words*: Waste Rubber Particles (WRP), Asphalt, Bitumen, Asphalt Mixtures, Improvement, Flexible Pavement, Road**

1. INTRODUCTION

Highway transportation contributes to the economic growth and social development of a country. A durable pavement has to adhere to some conditions on the performance of the asphalt surface that permits sufficient strength and stiffness. Notably, the pavement layers must be sufficiently strong to carry all traffic load and resist the accumulation of pavement distresses such as rutting, and avoid premature failures, including top-down cracking during their service lives. Asphalt is a complex material used in road pavement and other surfaces. It functions to perform adequately in road pavement is associated with its content and properties. When the adhesion is insufficient, under the influence of load and water, the adhesion between the aggregates and the asphalt fails, resulting in relatively slip occurring between the aggregates. Finally, the adhesion force is lost. The asphalt falls away from the aggregate surface, affecting the performance durability of the asphalt pavements, water damage resistance, strength, and low temperate crack resistance of the asphalt mixture [1].

Asphalt pavement is mainly affected by environmental temperature changes, vehicle loading, and other factors [2]. The improvement in the service life of road pavements leads to sustainability and a tremendous economic advantage. The waste rubber particles are suggested modifiers of asphalt and asphalt mixtures to improve the performance characteristics of flexible pavement [3]. [4] the rapid growth in automobile production globally during the past few decades has caused numerous tires to scrap, and their disposal have become a significant challenge. However, there are two aspects of waste rubber disposal: disposal by burning and landfill. Dispose of the burning waste rubber tire causes smoke and pollution generated while disposal by landfills decreases the capacity of the land. [5] highlighted that if the use of waste or used tires as an additive in asphalt for improving the properties and disposing of the tires, environmental sustainability is guaranteed. **Figure 1** shows the typical disposal of waste rubber tires by landfill. Some design criteria, such as the aggregate gradation, rubber percentages, and asphalt content, highlight the application requirement in asphalt and asphalt mixture.

Fig-1: Typical Dispose of Waste Rubber Tire by Landfill

2. CONCEPT OF WASTE RUBBER PARTICLES

Waste rubber tire has become one of the most recycled products globally and commonly used components for HMA. [6] highlighted that the use of WRP has proven to be additives to hot mix asphalt obtained from waste material that has a beneficial impact and performance. Due to the inherence weaknesses of conventional asphalt, which has been leading to an increment in maintenance cost of the road pavement network, there is a need to modify and enhance the performance of asphalt binder to reduce or avoid pavement distress [7]. The quantities of aggregates used in road construction and maintenance are vital phenomena considered. Also, [8] mentioned that the construction and maintenance of roads consume large amounts of aggregates, more than 90% by weight of the asphalt mixtures. Researchers and pavement engineers have investigated a broad range of technically determined, cost-effect reuse and recycling options available to safeguard natural resources and extend landfill life. On the other hand, the processing of WRP in asphalt and asphalt mixtures is by the dry and wet processes, which are two (2) common established ways the WRP is added to asphalt and asphalt mixtures. The wet process, where rubber particles are mixed with asphalt at an elevated temperature before mixing with the hot aggregates. The second is the dry process, where rubber particles replace a small portion of the mineral aggregate in the asphalt mix before adding the asphalt [9].

3. COMPOSITION OF WASTE RUBBER PARTICLES

The waste tire appears as a whole tire, a slit tire, a shredded or chipped tire, ground rubber, crumb rubber, or waste rubber particles. However, the rubber industry is a highly mature and complex sector, with over twenty-five (25) different generic types of rubber (natural rubber, styrene-butadiene rubber, nitrile, ethylene-propylene-diene monomer rubber, fluorocarbon rubber, silicone) being used in the manufacture M.J. Forrest [10]. According to [11], recycled tire rubber from waste tires has been used in asphalt by the paving industry since the 1960s: the material is used as an asphalt binder modified and asphalt mixture additive in HMA and surface treatment. During the processing of waste rubber, the steel is removed; therefore, the waste rubber can not be considered waste material. It is a valuable commodity with ongoing expansion and growth in diversified markets. **Table 1** presents an elemental composition of a tire.

Table -1: Basic composition of tire

Component	Typical Range
Natural Rubber	14 to 27%
Synthetic rubber	14 to 27%
Carbon black	28%
Steel, Fabric	14 to 15%
Processing oils	16 to 17%

The application of waste rubber particles as an additive or modifier has to go through processing. Components of the waste tire that have to be eliminated or removed before processing are steel and fiber. [12] mentioned that the production of waste rubber particles involves reducing the whole waste tire into smaller granules of sizes ranging from 75 µm to 4.74 mm with the steel, fibers, dust, and any contaminants removed, leaving only the rubber particles. The waste rubber particle shape is processed in two ways: the ambient grinding process and the cryogenic grinding process.

4. PROCESS OF WASTE RUBBER PARTICLES (SIZE PARTICLE)

4.1 Ambient Grinding Processing

[13] expressed that the ambient grinding is obtained by shredding and grinding the tire rubber at or above ordinary room temperature. This process produces a sponge-like surface on the granulated rubber crumbs, which have considerably greater surface area than cryogenic grinding for a given size particle. The increase in the surface area also increases the reaction rate with hot asphalt. [11] pointed out that the ambient grinding process starts the same way as the cryogenic process. In order words, the tires are cut into smaller particles which sharp-cutting blades. The particle size of ambient grinding ranges from small passing the 75 µm sieve, no larger 4 to 5mm size particles. The ambient grinding particle shape has a rough texture which contributes to increment in the surface area due to tearing. **Figure 2** shows the shape of the ambient grinding process.

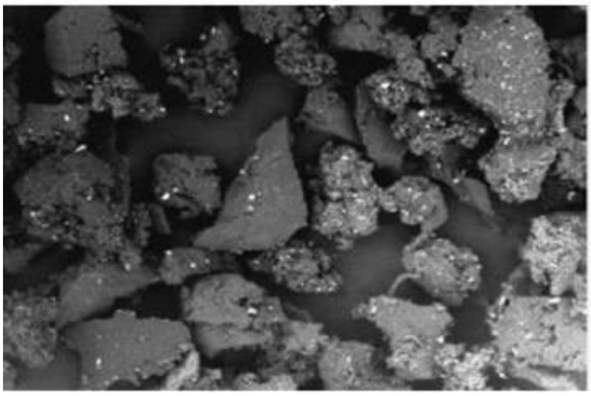

Fig-2: The Shape of the Ambient Grinding Process

4.2 Cryogenic Grinding Processing

Uses liquid nitrogen to freeze the WRP until it reaches the temperature between (87 to 198 ºC) before becoming brittle. It then uses a hammer mill to shatter the frozen rubber into smooth particles with a relatively lower area than the ambient grinding process [14]. [15] defined the cryogenic processing of materials (rubber, plastic, composites, metals, waxes) as the process of cooling or chilling materials and reducing them to small size particles. Moreover, it elaborated that this helps overcome the difficulties of all the elastic materials observed in ambient temperature grinding because they often adhere to lumpy masses and clog the screen. **Figure 3** shows the shape of the cryogenic grinding process.

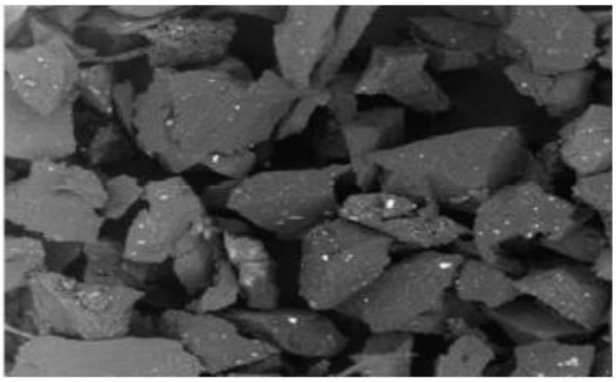

Fig-3: The Shape of the Cryogenic Grinding Process

5. METHOD OF APPLICATION

[11] highlighted that the processes for creating waste rubber particles binder and mixtures are the dry and wet processes. These processes produce asphalt rubber pavement with different properties and different performances. Therefore, agencies need to understand these differences to choose the type of process that will perform best for their desired application.

5.1 Dry Process

[16], the dry process mixed rubberized asphalt mixture developed in Sweden, incorporating relatively large rubber particles in the asphalt pavements. The primary purpose was to improve skid resistance and pavement durability. The dry process of WRP is the replacement or addition of aggregates in the asphalt mixtures. [17] mentioned that, although the dry process presents some advantages as related to the wet process concerning the costs involved and the higher amount of rubber to be used, researchers have studied concentrated mainly on the wet process. **Figure 4** illustrates the dry processing of waste rubber particles. [18] finalized that the manufacturing process with the rubber involved by dry technology is better and enhances the digestion process providing a final cohesion and optimum compaction. [19] the review concluded that rubber aggregates in the bituminous mix, the number of stone aggregates by volume, and increased flexibility and flexural strength. It does not only minimize the pollution occurred due to waste tires but also minimizes the use of conventional aggregates.

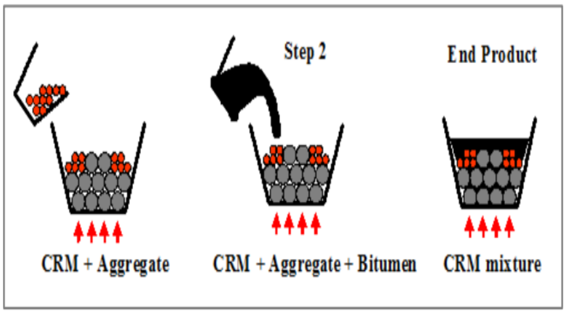

Fig-4: Illustrates the Dry Processing WRP

5.2 Wet Process

Charles first introduced the wet process of WRP with bitumen in 1981, which considered various percentages by mass of fine waste rubber particles at high temperatures. The wet process includes the mixture or blending of the WRP with the bitumen at a specified temperature and produces a viscous fluid through interaction. [20] results from their study showed that adding WRP-derived additive increases the workability of the base binder. The WRP-derived additive appears positive on the high- and low-temperature performance and the fatigue life of the base binder. The waste rubber particles are combined with the asphalt content before blending into the aggregates in the wet process. When all materials are blended, the waste rubber particles swell and soften. The rubber particle reaction influences considering blending temperature, the reaction time, the type and amount of mechanical mixing, the size, the texture of the waste rubber, and the asphalt cement [21]. **Figure 5** illustrates the wet processing of WRP.

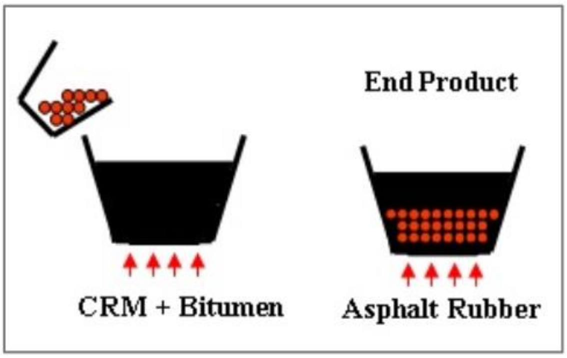

Fig-5: Illustrates the Dry Processing WRP

6. DESIGN MIX CONSIDERATION

The mixed design of WRP performance stability is associated with the gradation types. **Figure 6.0** illustrates the type of HMA**.** **Table 2 & Table 3** present the grading limits used in asphalt pavements [11].

Fig-6: Illustrates Three HMA Type

Table -2: Open-Graded Mixes with and without WRP

MIXTURE DESIGN GRADING LIMITS		
Sieve Size	Percent Passing	
	Without Admixture	With Admixture
3/8 inch (9.5 mm)	100	100
No. 4 (4.75 mm)	30 - 45	31 - 46
No. 8 (2.36 mm)	4 - 8	5 9
No. 200 (75 µm)	0 - 2.0	0 - 3.0

Table -3: Gap-Graded Mixes with and without WRP

MIXTURE DESIGN GRADING LIMITS		
Sieve Size	Percent Passing	
	Without Admixture	With Admixture
3/4 inch (19 mm)	100	100
1/2 inch (12.5 mm)	80 – 100	80 – 100
3/8 inch (9.5 mm)	65 – 80	65 – 80
No. 4 (4.75 mm)	28 – 42	29 – 43
No. 8 (2.36 mm)	14 – 22	15 – 23
No. 200 (75 µm)	0 - 2.5	0 - 3.5

Waste rubber can partially replace the conventional material of flexible pavement to improve its engineering properties [22]. The design mix of waste rubber particles as a partial replacement of aggregates and bitumen depends on the scope of what the engineer wants to achieve. However, both options would improve the desire for mechanical characteristics for a particular road mix design. On the other hand, [23] found that rubber concentration substantially affects the long-term flow properties of asphalt binders for a highly incompatible asphalt. For compatible asphalt, the addition of rubber increased the elasticity of asphalts and reduced viscosity build-up with aging. Also concluded that the particle size of rubber does not show significant differences of the long-term aging characteristics of asphalt binder.

6.1 Aggregate (Dry Process)

The effect of WRP (dry process) as a portion of aggregate considers some engineering properties of the mix, including its particle size, shape, percentage, and reaction time. Aggregates size between 2.0 mm and 6.3 mm, the addition of 1% to 3% of course rubber by weight of the mixture provides an additional benefit improvement in the elastic properties [16]. [24] investigated that the crumb rubber contributes to the significant improvement in the Marshall stability and rutting resistance of asphalt concrete. The optimal crumb rubber content in mixtures of dense gradation and SMA was 1.5 and 2%. [25] investigated concerning moisture sensitivity and plastic deformations was investigated, and the best performance was achieved with a digestion time of 45 min. Crumb rubber percentages were 0.5% and 1.0% of the total weight of the mix. Lastly, [26] investigated that the recycled tire with 9% by total weight of aggregate retained on (2.36mm) sieve exhibited high resistance to water damage.

6.2 Asphalt (Wet Process)

Similarly, the influence of WRP (wet process) as a portion of asphalt binder considers some of the mix's engineering properties, including the asphalt penetration grade, softening point, flash, and fire points. [27] summarized that laboratory tests investigated rubberized asphalt binders' physical and rheological properties that include percentages of (0, 4, 8, 12, 16, & 20%). The result showed that the mix design of 16% of waste rubber modifiers at 180° C blending temperature affected the engineering properties. On the other hand, the content of 20% and above is not suitable as far as pavement construction is concerned due to the high viscosity of the rubberized binder. Besides, [28] investigated rubber replacement with bitumen in various proportions of 10%, 20%, 30%, & 40%, and Performed the Marshall stability test for every replacement of rubber proportions. Finally, the rubber replacement with 30% accumulated a maximum Marshall stability value. In addition to that, the study of using waste rubber tires in bitumen was investigated by [22]. As a result, it found that by adding 0-4% rubber to bitumen, the value of specific gravity, softening point, flash & fire point increased while ductility, penetration values decreased. [29] mentioned that the pavement stability improved after addicting 2% of WRP by weight of bitumen. [30] standard laboratory tests on straight asphalt and crumb rubber modified asphalt after the study concluded that:

1. After carefully evaluating the properties and taking various tests according to standards, the results showed that a 9% addition of rubber crumbs has the best suitability with asphalt.
2. From the ductility test, a 10% addition of crumb rubber has the best suitability for blending it with bitumen.

Lastly, [31] experimental studies showed that waste rubber particles are between the ranges of 5% to 20%. The resilience modulus of a rubberized asphalt was experimentally designed by [32] included the use of two aggregate sources, one rubber type (ambient), four rubber contents (0%, 5%, 10%, and 15%), one crumb rubber size -0.425 mm) and four reclaimed asphalt pavement contents (0%, 15%, 25%, and 30%). The findings showed that an increase in the rubber content in the modified mixtures leads to a decrease in Indirect Tensile Strength and resilient modulus value regardless of rubber content. The increase also improves the aging resistance and increases the viscous characteristics of the modified binder. Lastly, [33] experiment studied found that the reduction in penetration and ductility properties with 15% CRM was 25% and 75%, respectively. Also, CRM observed a considerable increase in viscosity, softening points, flash, and fire points.

7. Test Method

Several laboratory tests are performed to assess the properties and performance of the asphalt mixture. It contains various percentages of waste rubber particles and includes; the Marshall properties, indirect tensile strength test, moisture damage test, resilient modulus test, and permanent deformation test [34]. [35] defined the Marshall stability to be the maximum load carried by a compacted specimen at a standard test temperature at 60° C. [36] discussed that the stability is an essential factor in measuring the quality of asphalt mixture in traffic load. The stability higher value indicates that the pavement has a higher stiffness value, but at certain limits where there is still flexibility is the value of flow as the deformation. As specified in ASTM D! 559-89, the Marshall mix design procedure is used to determine the optimum binder content (OBC) in the mixture to give the proportions of the different materials to be used to produce the conventional hot-mix mixture that satisfies the requirement of the given specifications. [8] conducted a simple test on Marshall specimens by adding 4.5%, 5.0%, 5.5%, and 6.0% of asphalt (by weight of the mix) into the hot aggregates. **Table 4** provides the test results of the sample, and **Charts 1, 2, 3, 4 & 5** illustrate the graph results of the Marshall Test. [37] stressed that Marshall's testing performance is guaranteed to obtain the optimal value of rubber content. At the optimum content, it is determined as the optimum percentage of waste rubber particles after the addition. The Marshall stability refers to the maximum load resistance escalated during applying 50.8 mm/mm of deformation load rate at 60° C before the compacted cylindrical specimen. However, [7] defined Marshall stability as measuring the susceptibility of an asphaltic mixture of deformations, ensuring frequent and heavy traffic loads. [38] investigated that the use of modified mixes of crumb rubber resulted in higher Marshall Stability values than the control mix. Stability increases by nearly 24%. Mixes with modified binders displayed higher flexibility at lower temperatures because of lower resilience modulus and higher stiffness and tensile strength at higher temperatures.

Table -4: Design Mixes

Job mix	WGRTP		Bitumen		Aggregate		Total (g)
	(%)	Wt (g)	(%)	Wt (g)	(%)	Wt (g)	
Mix 1	0	0	5.0	60	95	1140	1200
Mix 2	5	60	5.0	60	90	1080	1200
Mix 3	10	120	5.0	60	85	1020	1200
Mix 4	15	180	5.0	60	80	960	1200

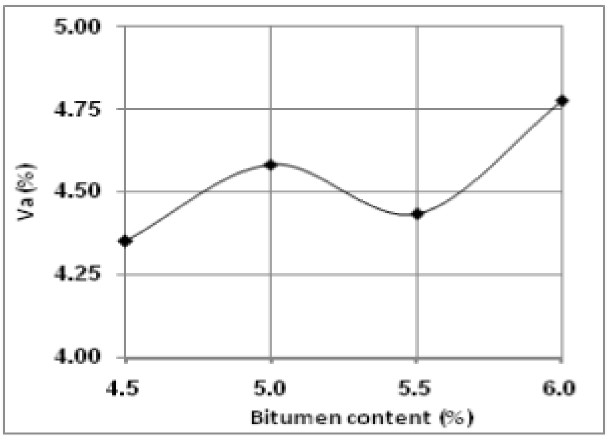

Chart-1: Bulk Air Value versus Bitumen Content

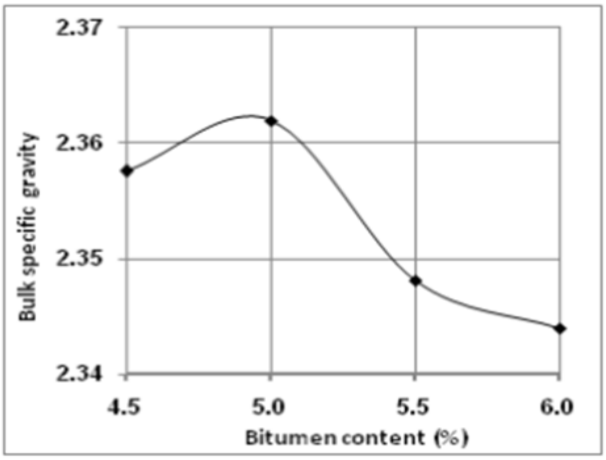

Chart-2: Bulk Specific Gravity Value versus Bitumen Content

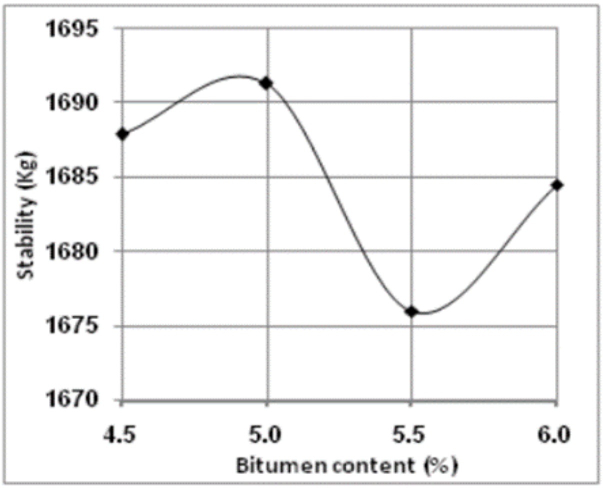

Chart-3: Stability Value versus Bitumen Content

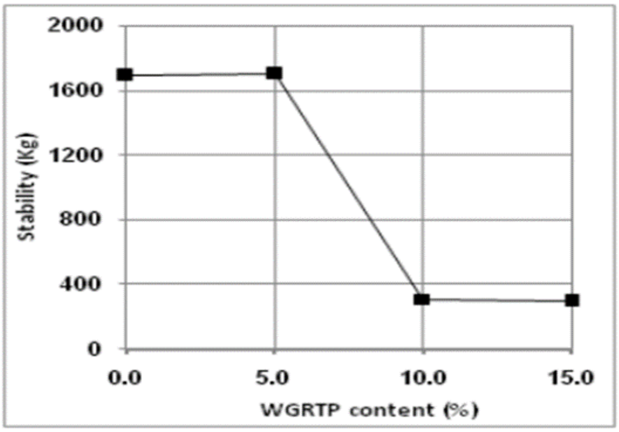

Chart-4: Stability Value Versus WGRTP Content

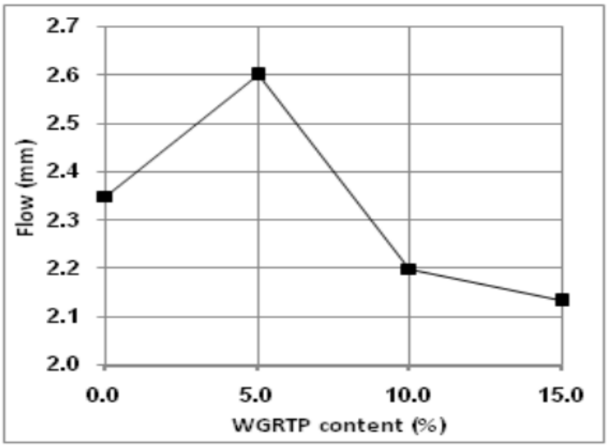

Chart-5: Marshall Flow Value Versus WGRTP Content

Another essential test is the Indirect Tensile Strength (IDT) strength, which is very useful in deciding the performance of porous asphalt mixtures, which depend on the cohesion of bitumen film. The vibrations of the IDT are mentioned with waste rubber for all three sizes in **Chart 6 & Chart 7**. The reduction based on the addition of waste rubber particles significantly decreased the IDT strength except for the 10% content of the waste rubber particles [39].

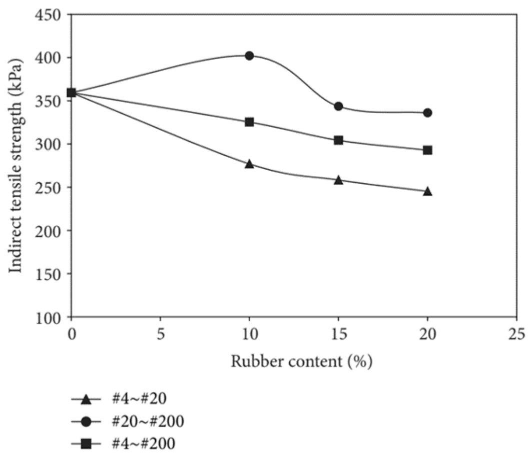

Chart-6: Effect of WRP and content on IDT Strength

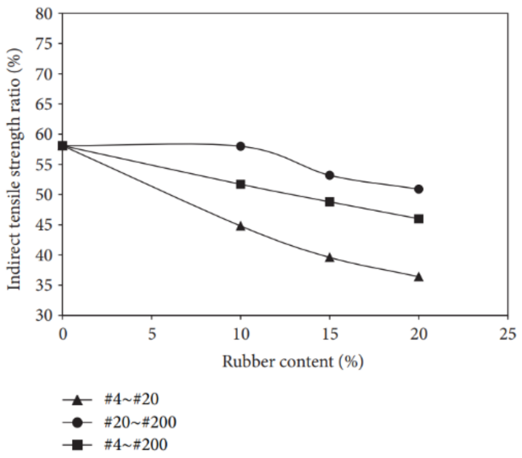

Chart-7: Effect of WRP and Content on Moisture susceptibility

8. PERFORMANCE OF WRP ON ROAD PAVEMENT

Roadway infrastructures are ideal targets for effective, sustainable design and construction initiatives. They are large in project scope and involve considerable financial resources. Besides, road pavement construction and maintenance consume significant amounts of materials and energy and produce large amounts of waste, which may adversely affect the environment and cause social unhappiness [40]. A study by [41] reviewed that flexible pavement is the most favored pavement structure for constructing roads and highways worldwide. Construction materials for flexible pavement are asphalt/bitumen, aggregates, and preferably additive. The waste tire particles have been used in many applications, including road pavements, sports fields, energy sources, distress repair, and various molded products. The performance of waste rubber particles in asphalt as a modified binder and mixtures has shown a promising result in the paving industries for many decades. Incorporating WRP with conventional bitumen was practiced for more than a century. The introduction of the modification process of asphalt by natural and synthetic rubber was in early 1843 [42]. [43] studied the utilization of waste rubber particles and plastics in flexible highway pavement. As a result, it concluded that the examination is not entirely to improve the engineering properties of asphalt but likewise to observe environmental compliance. [44] the use of crumb rubber in the reinforcement of asphalt consider an intelligent solution for sustainable development. Besides, reusing waste materials believes that crumb rubber modifier (CRM) could be an alternative polymer material for improving hot mix asphalt performance properties. [45] mentioned that waste rubber asphalt has a quality of increased durability that allows the asphalt pavement to be more resistant to cracking. Rubberized asphalt has been studied and exhibited resistance to fatigue cracking and pavement deformation. It allows the asphalt to withstand much higher dynamic loading than the conventional asphalt pavements. Enhancing the pavement life is possible with some modifications if possible factors causing deterioration are considered during the design stage [46]. Construction materials for flexible pavement are made of asphalt/bitumen, aggregates, and preferably additives. Additive made of waste rubber particle mixtures considers three types of aggregates gradations of hot mix asphalt: the Open-Graded Mixtures, Gap-Graded Mixtures, and Dense-Graded Mixtures [11]. The modification of bitumen is one of the essential materials for flexible pavement. The use and application of waste rubber particles in construction are gaining prominence. [47] in their study compared the properties of modified bitumen and conventional bitumen. In the specimen with modified bitumen, the penetration and ductility values decreased with increased proportion up to 12% by weight. They have concluded that the life of the pavement surfacing using the modified bitumen is also expected to increase substantially compared to ordinary bitumen. [48] conducted research conducted partially carried out in the laboratory (designing the optimum mixture composition) and on-site, constructing an experimental road segment, 2.5 km in length, in a secondary traffic road located between Salamanca and Ciudad Rodrigo (Spain). The rubber-modified hot-mix asphalt was placed on-site and compacted after a controlled maturation (aging) time of the warm rubber-modified hot-mix asphalt, which promotes close interaction between the rubber particles and the binder. [49] stated that the performance of waste rubber particles in asphalt pavement contributes to noise reduction. [50] discussed the use of waste rubber particles from the economic point of view and stressed that waste rubber particles in bitumen are less costly and eco-friendly, and expected to enhance the bitumen properties. It facilitates the enhancement appearance in increasing asphalt resistance to pavement distresses such as the up-down, bottom-up cracking, and low-temperature cracking. On the other hand [51] investigated two main reasons why the use of waste rubber particles are not widespread because: first, the capital costs for surfacing alternatives is higher than conventional asphalt mixtures by 40 to 80 percent; second, there is a lack of information regarding properties and performance of these surfacing alternatives.

9. CHALLENGES

Asphalt pavement is continuously affected by vehicle load, low environmental temperature, and other factors. The waste tire is a solid waste, and its disposal and management pose environmental concerns in several countries [12]. From another standpoint, [52] mentioned that factors that influence the fatigue life of waste rubber are the mechanical loading history, environmental conditions, formulation of the rubber compound, and specific aspects of stress-strain constitutive behavior. [53] highlighted that transverse and longitudinal cracks are the most frequent pavement distresses, especially for flexible pavements, which commonly occur due to structural failure, tensile stresses, or extreme temperature variations.

Durability, climate, and traffic loading are the biggest challenges to using open-graded friction course (OGFC) pavement, especially in cold climatic conditions. On the other hand, warmer climates are more conducive to constructing OGFCs with rubber, which requires higher surface temperatures during paving. OGFC pavements have less resistance to wear from traffic loading due to the air holes or voids, which decreases the strength of the pavement [54]. [55] reviewed that asphalt rubber is not recommended in dense-graded areas because there is insufficient void space to significantly accommodate modified binders. To justify the added cost of the asphalt rubber binder—one good characteristic of pavement performance is achieving sufficient compaction on the road. WRP as a binder for road pavement may improve the performance, considering proper construction time and practices. [56] studied that modified bitumen with waste rubber has better compaction with aggregates. Over the years, applying WRP mixes in cold climates has resulted in improper material compaction during construction. [14] lastly concluded that the rubber-modified mix had an objectionable odor.

10. CONCLUSION

The review has provided a detailed understanding of the influence of waste rubber particles on asphalt and asphalt mixtures considering the dry and wet processes, design mixes, effects, and applications. The review incorporated critical contributing factors that identify WRP function and behavior in asphalt and asphalt mixture performance evaluation. Therefore, it is vital to identify those factors that contribute to improving the performance of WRP asphalt mixtures. The following recommends the conclusion from the review.

1. The use of WRP in asphalt and asphalt mixtures improves flexible pavement performance and adheres to environmental compliance. The waste rubber particles can be used in open-graded, gap-graded, and dense-graded asphalt pavement, considering gradation limits
2. The application of WRP in flexible road pavement is in two ways. Firstly, it functions as a partial replacement of aggregates known as rubberized asphalt (dry process). Secondly, it functions as a partial replacement of asphalt, called asphalt rubberized binder (wet process). With both processes, the wet process has shown promising outcomes. As a result, the wet process has been more widely applicable than the dry process.
3. The WRP performance stability design mix identifies the aggregate gradation type, waste rubber particles gradation and percentage, the optimum bitumen content, and the asphalt pavement type.
4. The control mix design concerning the percentage dosages of WRP in the dry and wet processes has shown various performance effects.
5. The Marshall Stability Test method is the comprehensive test method to determine the structural strength and deformation of the engineering properties of WRP.
6. The use of WRP in flexible road pavement reduces associated pavement problems like thermal cracking, fatigue, and permanent deformation (rutting), especially in hot temperature regions.

11. RECOMMENDATIONS

However, there are several unsolved issues relative to the performance effect of WRP as a modifier in flexible road pavement:

1. Because of fluctuations in the performance of WRP asphalt mixes in different locations and considering variances in temperature and climatic conditions, additional research is needed to experiment with the performance characteristics considering the optimal particle shape, size, and percentage in consideration of both dry and wet processes.
2. Study to improve the existing WRP contents of the design mixtures in achieving the Resilient

Modulus (M_R) combined with numerical modeling to determine the structural performance of the asphalt mixtures concerning pavement responses (stresses, strains, and deformation).

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