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Enhancing Asphalt Mix Performance Through The Incorporation of Crumb Rubber

Herish Jaf [1]*, and Asmaa Abdulmajeed Mamhusseini [1]

[1] Civil Engineering Department, Faculty of Engineering, Tishk International University, Erbil-Iraq

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**Email address:*
heersh.faraj@tiu.edu.iq
**Corresponding Author*

Abstract:

The aim of this study is to evaluate the effects of incorporating crumb rubber as a modifier into asphalt mixtures and to achieve an improved blend for pavement applications. The study involved testing of hot mix asphalt samples through the Marshall method procedure. In total, 15 samples were meticulously prepared and tested to ascertain the Optimum Binder Content, which was determined to be 4.8%. Various tests of bitumen having PG 40/50 taken from a company in Sulaymaniyah City, are conducted to assess the quality and properties of bitumen. The study encompassed the incorporation of three distinct percentages of crumb rubber (10%, 20%, and 30% by weight of bitumen). A comprehensive comparative analysis was conducted between conventional and modified asphalt concrete mixtures, focusing on parameters such as Marshall Stability, Flow value, and other volumetric characteristics. Through a rigorous process involving the preparation of 25 samples, it was conclusively determined that 11.3% of crumb rubber content represents the most effective percentage for enhancing stability and flow characteristics within the asphalt concrete mix compared to the conventional results. The maintenance of an important balance between stability and flow is of utmost importance in the Marshall mix design process, as it guarantees that the asphalt mixture possesses the necessary durability to endure the load and movement of traffic without experiencing undue deformation.

Keywords: *Crumb Rubber; Modified Asphalt Concrete; Marshall Stability Test; Durability Properties*

1. Introduction

Innovative and eco-friendly technologies have improved civil engineering and infrastructure materials and procedures. Recently, various efforts have been made to improve asphalt concrete and asphalt mixtures. Modern researchers and scientists have found several waste and leftover materials that may be repurposed for technological uses [1]. Crumb Rubber Modifier (CRM) has been used to improve asphalt mixes, attracting attention. Asphalt, a key road construction material, must be durable, pressure-resistant, and environmentally friendly [2]. This has prompted much research and experimentation to exploit the advantages of CRM, which is obtained from recycled rubber components. Without a doubt, environmental contamination stands out as one of the most urgent global concerns. This issue has received significant attention as the focus for case studies and research efforts in recent times. The escalation of waste production remains a central factor contributing to environmental pollution. Approximately 1.5 billion tires globally achieve their maximum utility and become redundant annually [3]. The issue is particularly pronounced in the United Kingdom, where over 55 million discarded tires are generated annually. Similarly, in the United States, an estimated 300 million tires are disposed of every year. An illustrative example can be found in Kuwait City's

Sulaibiya, where massive excavations are conducted yearly to create large cavities in the earth, which are then filled with discarded tires as shown in Figure 1 and Figure 2 To provide context. Currently, the number of tires interred in that location exceeds seven million [4].

Figure 1: An aerial view of a desert [4]

Figure 2: A pile of tires on a hill [4]

The increasing expenses associated with energy and materials, together with the growing recognition of emissions as a pressing concern in modified asphalt mixture production, have underlined the possible advantages of lowering the temperature during the creation of asphalt mixtures. In this regard, the characteristics of the asphalt are developing by the addition of modifiers. There are many additives that can be used as asphalt mix modifiers [5]. Out of all the modifiers, the crumb rubber is usually added, keeping in mind the environmental and financial aspects.

There are several mix design methods commonly used in the asphalt industry, including Marshall Mix design, Superpave Mix Design, Bailey method, and Hveem method etc. Both Marshall and Superpave are volume design methods [6]. The Marshall mix design method helps ensure that the asphalt concrete mix meets the required strength, durability, and workability criteria for a specific project. Iraqi agencies continue to employ the Marshall method as their distinctive mix design approach for road projects [7]. It is a widely used process for designing and evaluating asphalt concrete mixtures, primarily for use in road and pavement construction. There are primarily two methods or processes used to determine the Optimum Asphalt Binder Content (OBC) for an asphalt mixture: the dry process and the wet process. The wet process adds modifiers to the binder directly, while the dry process adds modifiers to the mixture.

While it is widely acknowledged in various literature and research that CRM asphalt production through the dry process is considered less popular and often deemed inferior to the wet process, it is important to recognize that the dry process offers several advantages that outweigh its wet counterpart [8]. Firstly, one key benefit of the dry process is its reduced bitumen consumption compared to the wet process. In the wet process, a greater amount of bitumen is required to produce CRM binder, leading to additional binder costs. This financial aspect alone makes the dry process economically attractive. In both procedures, the compatibility between the rubber and the binder is crucial. However, this compatibility was previously less important in the dry process. Yet, a new study [8] shows that high compatibility is crucial even without moisture, particularly with small rubber particles. These findings emphasize the importance of method compatibility. The dry technique recycles end-of-life tires better than the wet method. Sustainability fits with environmental concerns and the increased emphasis on recycling and waste reduction. In conclusion, the dry method is less popular than the wet process but offers several benefits, including reduced bitumen consumption, careful rubber-binder compatibility evaluation, efficient transportation, improved temperature resistance, and increased tire recycling. These qualities make it useful and appealing in particular situations [8].

This study examines the effects of adding dry crumb rubber modifiers to asphalt mixtures in order to improve their performance and durability. In order to investigate this, samples of hot mix asphalt were made and subjected to testing using the Marshall technique, with different ratios of crumb rubber. An extensive comparative examination was performed on the original and modified asphalt mixtures, with a specific focus on crucial characteristics, including Marshall Stability, Flow value, and other vital volumetric qualities.

2. Materials and Methodology

2.1 Aggregates

The term "aggregate" collectively refers to various mineral materials such as sand, crushed stone, and gravel. These materials are commonly combined with substances like water, bitumen, Portland cement, lime, etc., to create composite materials like Portland cement, concrete, and asphalt concrete [10]. This study identifies four primary types of aggregate: coarse aggregates, crushed sand, fine aggregates, and filler which was taken from a place in Suleymaniyah City. Each of these types is subjected to specific sieves, ranging from 19.5mm to 0.075mm in size. Mineral aggregates used in asphalt and concrete mixes are categorized as either coarse or fine. Coarse aggregates are defined by sieve sizes with openings greater than 4.75mm (No. 4), while fine aggregates encompass sizes smaller than 4.75mm (No. 4) and go down to 75µm (No. 200) as shown in Table 1, the sieve sizes are according to ASTM E11 [11]. By incorporating 9% coarse aggregates, 38% crushed sand, 50% fine aggregates, and 3% filler, a blend of diverse sizes and characteristics is produced, each contributing to the mixture with their respective weights.

Table 1: Aggregate gradation for surface course based on ASTM C131

Standard Sieve Designation (mm)	Coarse aggregate 9%		Crush sand 38%		Fine aggregate 50%		Filler 3%	
	Passing %	Retained %	Passing %	Retained %	Passing %	Retained %	Passing %	Retained %
19.0	100	0	100	0	100	0	100	0
12.5	27.6	72.4	100	0	100	0	100	0
9.5	1.3	26.3	100	0	76	24	100	0
4.75	0.3	1	93.5	6.5	6.6	69.4	100	0
2.36	0	0.3	66.8	26.7	1	5.6	100	0
0.3	0	0	19.4	47.4	0	1	100	0
0.075	0	0	7.5	11.9	0	0	95.5	4.5
pan	0	0	0	7.5	0	0	0	95.5

The physical properties of aggregates, which are used in asphalt and concrete mixes, play a crucial part in verifying the quality and performance of the resulting construction material. It is clear in Table 2 that one of the most important properties of aggregate is specific gravity, which is the ratio of the density of the aggregate to the density of water. It helps determine the aggregate's relative density. A higher specific gravity often indicates a denser and heavier aggregate, which can contribute to higher strength and durability. Absorption property quantifies the amount of water the aggregate can absorb when soaked. It is typically articulated as a percentage of the aggregate's weight. Low absorption is desirable as it reduces the risk of excess water in the mix, which can weaken the concrete or asphalt. Aggregates possessing favorable abrasion resistance characteristics play a significant role in enhancing the durability and lifetime of asphalt pavements, particularly in regions experiencing heavy traffic volumes.

Table 2: Basic physical properties of the aggregate

Properties	Test Methods	Aggregate			
		Coarse Agg.	Fine Agg.	Crushed sand	Filler
Specific gravity	ASTM C127	2.654	2.649	2.602	2.721
Absorption, %	ASTM C127	0.8	0.9	0.6	….
Apparent specific gravity	ASTM C127	2.714	2.711	2.644	….
Los Angeles Abrasion, %	ASTM C535	19			

2.2 Crumb Rubber

Crumb rubber is a material that is obtained from the recycling of rubber tires or other rubber products through a mechanical process that reduces them into small, granular particles. The used crumb rubber was rubberized and recycled from a scrap passenger car in the Kurdistan Region. These particles are often irregularly shaped and have various sizes, typically ranging from fractions of an inch to a few millimeters in diameter. Crumb rubber has gained popularity due to its versatility and its ability to address various environmental and industrial challenges. Rubberized concrete offers several advantages compared to conventional concrete, including reduced density, enhanced impact and toughness resistance, improved ductility, enhanced insulation properties, and environmental benefits [12]. The incorporation of rubber crumbs into aggregate blends within asphalt mixtures can be achieved through a dry process or by amalgamating them with asphalt at a specific temperature, where the rubber crumbs act as a bitumen modifier in a wet process. Research into wet-process crumb rubber modification has demonstrated noteworthy enhancements in bituminous mixture properties, such as enhanced rutting resistance, resilience modulus, and fatigue cracking resistance [13]. These improvements stem from the alteration of the bituminous binder's characteristics, including its viscosity and softening point [14]. The procedure of rubber crumb interaction with bitumen affects the composition of asphalt, type of rubber, rubber particle size, temperature, time, and energy of mixing [15].

2.3 Bitumen

Bitumen is a black, highly viscous combination of hydrocarbons [10]. It's a black, sticky, thick, and gummy fluid or semi-solid form of petroleum. Bitumen is generated by the distillation of crude oil and comes from nature. Bitumen comprises of complex hydrocarbons, calcium, iron, sulfur, and hydrogen. Also, bitumen is the by-product of the distillation of crude oil during the refining process of petroleum [16]. The characteristics of bitumen rely upon the construction and the kind of asphalt mix. Generally, bitumen should have the following suitable features: It must not be highly temperature vulnerable; during the hot climate, the mix should not get softened or should not lose its stability; and during the winter, the asphalt must not become crumbly in order not to cause cracks. The binder can go through a number of issues in the field, such as stripping from the aggregate, which can further be followed by rutting, cracking depressions, etc. Therefore, the asphalt binders can be improved by the addition of a modifier to improve its diverse features.

The bitumen used in this study has PG 40/50 based on the results shown in Table 3 various tests are conducted to assess the quality and properties of bitumen. Some of the important bitumen tests include the Ductility test, Ring and Ball Softening Point test, Penetration Test, and Flash & Fire Point test. Testing procedures are outlined in the American Standard for Testing and Materials book, specifically described in ASTM D113, ASTM D36, ASTM D5, and ASTM D92, respectively.

Table 3: Properties of bitumen tests

Bitumen Tests	Units	Test Method	Result	Limits
Ductility, (25˚C, 5 cm/min)	cm	ASTM D113	150	>100
Softening point (Ring & Ball)	˚C	ASTM D36	52	51-62
Penetration, (25˚C, 5 sec., 100gr)	0.1 mm	ASTM D5	46	40-50
Flash point (Clev. Open Cup)	˚C	ASTM D92	281	>232
Burning point (Clev. Open Cup)	˚C	ASTM D92	287	---

Table 3 provides insights into some bitumen properties; for instance, the penetration value is expressed as the distance the needle has penetrated the bitumen in millimeters (mm) (since 0.1 mm is equivalent to one penetration unit) under the specified conditions. The penetration value of the bitumen used at 25˚C is 46. This means that at 25°C, the needle penetrated 4.6 mm into the bitumen in 5 seconds. The penetration test helps engineers and researchers assess the suitability of bitumen for specific applications. For example, softer bitumen may be more appropriate for areas with cold climates as it remains flexible at lower temperatures, while harder bitumen may be used in regions with high temperatures to prevent the deformation of road surfaces.

The test results for bitumen can vary depending on factors such as the grade of bitumen, the source, and the specific testing standards used. The typical range of the ductility test is between 50mm - 200 mm or more based on the standard test method ASTM D113, while for softening point test typical range is between 30˚C - 80˚C based on the standard test method ASTM D36. These are general ranges, and the exact values may vary depending on the specific grade and application of bitumen. Different standards organizations may also have slightly different test methods and specifications.

3. Marshall Mix Design Method

Mix design is a critical process in the production of asphalt mixtures. It involves determining the appropriate combination of materials and their proportions to achieve the desired performance characteristics for a specific application. The Marshall mix method was used in this study to design asphalt mix properties such as stability, unit weight, flow, air voids, volumetric properties, and durability under repeated loads for the surface course of the pavement. It is essential to choose the most appropriate mix design method based on the project's location, traffic conditions, and performance requirements [1]. These methods help ensure that the asphalt mixture will perform well over its intended service life, providing adequate durability and resistance to distresses such as rutting, cracking, and moisture damage. There are primarily two methods or processes used to determine the OBC for an asphalt mixture: the dry process and the wet process. These processes differ in how they manage the asphalt binder during the mix design procedure. The dry process is used in this study to determine OBC for the mix.

4. Results and Calculations

4.1 OBC Results

Ten samples were meticulously prepared to ascertain the OBC for the mix. Each sample comprises 1150 grams of aggregate. Two specimens were prepared at each bitumen content trial, ranging from 4% to 6%, with increments of 0.5%. This mix is designed with a gradation recommended for heavy traffic surface courses. Table 4 is the summary of the specifications and conditions for each sample.

Table 4: Specifications and conditions for each sample

Total weight of each sample, gr	1150
Bitumen Content (BC), %	4%, 4.5%, 5%, 5.5%, 6%
Heavy Traffic Compaction, number of blows/sides	75
Heating temperature before starting the test, °C	170
Compacting temperature, °C	150 - 160
Sample condition, °C	60

Determining the suitability of the asphalt paving mix at the chosen design asphalt content relies on the application of specific criteria to the test data for the mixture. The Asphalt Institute recommends the Marshall method mix design criteria, as outlined in Table 5.

Table 5: Marshall mix design criteria [17]

Traffic Property	Light Traffic Surface & Base		Medium Traffic Surface & Base		Heavy Traffic Surface & Base	
	Max.	Min.	Max.	Min.	Max.	Min.
Compaction number of blows at each end of the specimen	35		50		75	
Stability, *N (Ib.)*	3336 - (750)		5338 - (1200)		8006 - (1800)	
Flow, *0.25mm (0.01 in.)*	18	8	16	8	14	8
Air Voids, V_a *%*	5	3	5	3	5	3
Void in mineral aggregate, *VMA, %*	See Table 6.					
Voids filled with asphalt, *VFA, %*	80	70	78	65	75	65

The optimal binder content for the asphalt paving mix is determined by a comprehensive evaluation of the previously discussed data. Typically, the Asphalt Institute advises selecting the asphalt content at the median point of the specified percent air voids limits, which is typically around 4%. If, at this asphalt content, all calculated and measured mix properties align with the criteria listed in Table 5, it is considered the ideal binder content for the mix design. However, if the mix does not meet all the design criteria, adjustments or compromises may be required. In some cases, a complete redesign of the mix may be necessary to achieve the desired performance characteristics [17].

Table 6 specifically provides information for determining the minimum VMA (Voids in Mineral Aggregate) and the design Va (Air Voids) for different nominal maximum particle sizes of aggregate material (expressed in millimeters). Nominal particle size lists various sizes of the aggregate particles typically used in asphalt mixtures. The "nominal" size indicates the maximum dimension of the aggregate particles in the mix.

Table 6: Minimum percent for VMA [17]

Nominal Max. Particle Size (mm)	Minimum VMA, %		
	Design V_a, %		
	3	4	5
1.18	21.5	22.5	23.5
2.36	19	20	21
4.75	16	17	18
9.5	14	15	16
12.5	13	14	15
19	12	13	14
25	11	12	13
37.5	10	11	12
50	9.5	10.5	11.5
63	9	10	11

VMA in Table 6 is a critical parameter in asphalt mix design. It stands for "Voids in Mineral Aggregate," and it represents the void spaces or air gaps between the aggregate particles. This column provides the minimum acceptable VMA percentage for each of the nominal maximum particle sizes listed. The minimum VMA percentage is crucial for ensuring that there is enough space in the mix to accommodate asphalt binder and provide durability and performance. While Va represents the percentage of air voids within the asphalt mixture. This column provides the recommended or designed Va percentage for each of the nominal maximum particle sizes. The design Va percentage is essential for controlling the workability, compactibility, and performance of the asphalt mix.

Table 7: Results for OBC

No.	Bitumen Content		Specific Gravity	Average Specific Gravity	V_a (%)	VMA (%)	VFB (%)	Flow (mm)	Average Flow (mm)	Stability (kN)	Average Stability (kN)
	BC (%)	BC (gm)									
S1	4	45.6	2.313	2.309	8.2	15.7	47.7	2.5	2.5	11.81	12.50
S2			2.31					2.4		12.84	
S3			2.306					2.5		12.84	
S1	4.5	51.3	2.335	2.328	5.7	15.5	62.4	2.3	2.3	14.12	14.04
S2			2.334					2.2		14.12	
S3			2.314					2.3		13.87	
S1	5.0	57.0	2.338	2.333	3.4	15.7	78.3	2.9	2.9	13.52	13.84
S2			2.334					2.8		13.87	
S3			2.328					3		14.12	
S1	5.5	62.7	2.307	2.305	3.3	17.2	80.8	2.9	2.9	12.79	12.46
S2			2.302					3		12.30	
S3			2.306					2.9		12.30	
S1	6	68.4	2.282	2.281	2.5	18.5	86.5	3.4	3.4	9.88	10.34
S2			2.275					3.3		10.82	
S3			2.285					3.4		10.35	

Six graphical representations illustrate the correlation between bitumen content and the parameters outlined in Table 7. Determining the OBC for the current mixture involves considering previously discussed data. Generally, following the Asphalt Institute's recommendation [15], the asphalt content is determined by selecting the median value within the stated range of air void limits, resulting in a value of 4 percent. If the computed and measured properties of the mixture at the selected asphalt content conform to the criteria specified in Tables 5 and 6 for mix design, then it can be considered as the optimal binder content. For this mixture, the optimal bitumen percentage is chosen as the average content, ensuring maximum specific gravity, maximum stability, and a 4% air void ratio across the entire mix. This led to the determination of an OBC of 4.8%. This 4.8% result satisfies all the stipulated requirements in Tables 5 and 6. For instance, the maximum stability at 4.8% is 14.1 kN, as indicated in Figure 4, while the maximum specific gravity at this bitumen content is 2.33, as demonstrated in Figure 9. Additionally, the air void at 4.8% is 3.8, as shown in Figure 8, and so on. Ultimately, all the design parameters, including Marshall stability, flow, air voids, VMA, and VFB, are evaluated at the OBC. The results conform to the specified mixed design criteria, meeting all the requirements. In cases where the mix design falls short of any of the criteria, adjustments are made to the aggregate gradation, filler content, bitumen content, or a combination thereof, followed by iterative design testing until all the requirements are simultaneously satisfied.

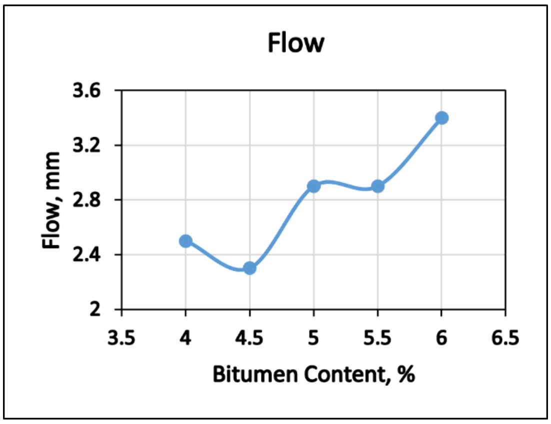

Figure 3: Flow vs. Bitumen Content

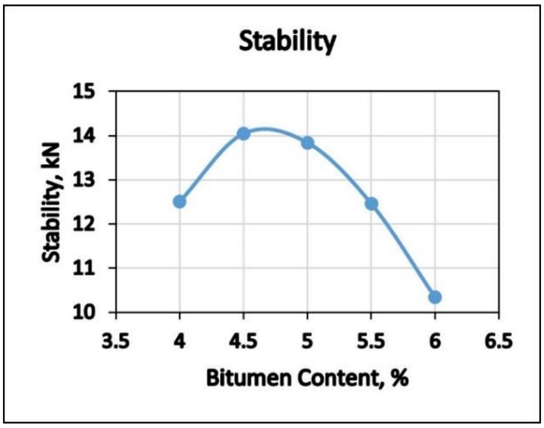

Figure 4: Stability vs. Bitumen Content

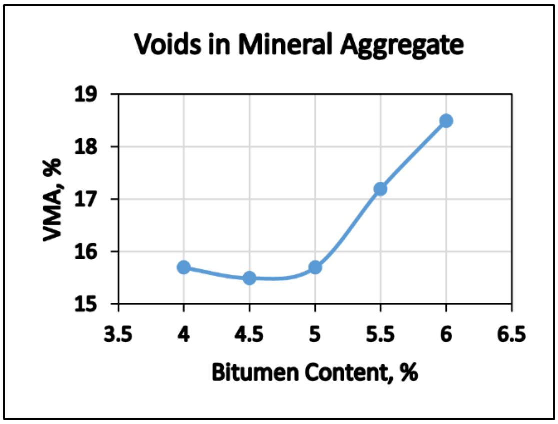

Figure 5: VMA vs. Bitumen Content

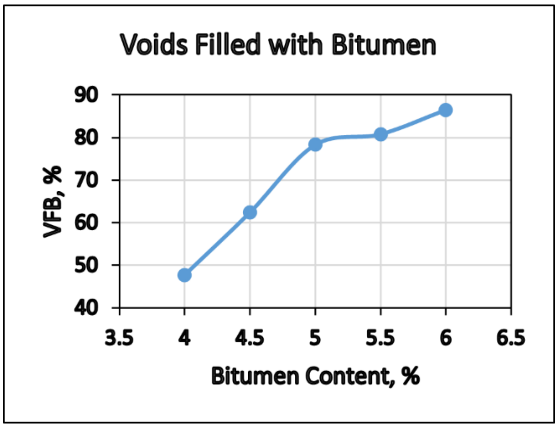

Figure 6: VFB vs. Bitumen Content

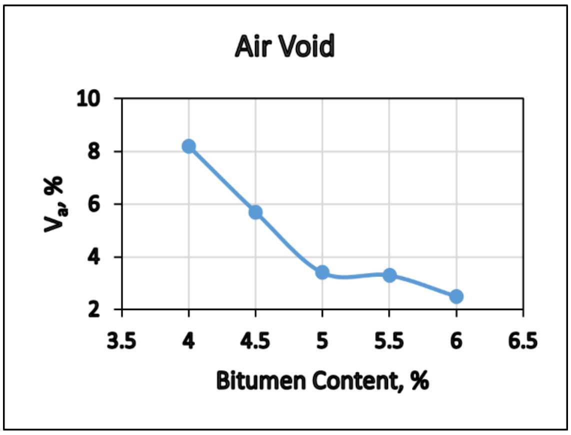

Figure 7: V_a vs. Bitumen Content

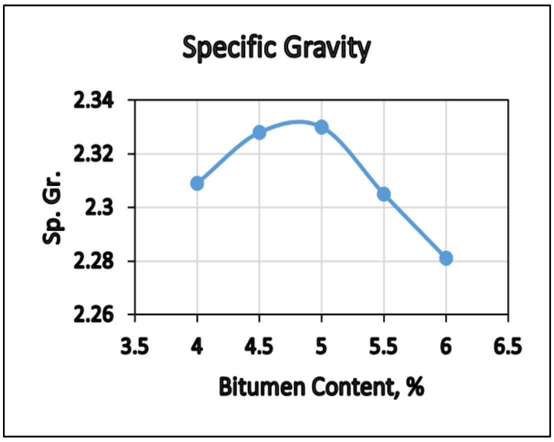

Figure 8: Sp. Gr. vs. Bitumen Content

4.2 Modified Asphalt Concrete with CR Results

As discussed previously, modified asphalt concrete with crumb rubber, often referred to as rubberized asphalt, is a sustainable and innovative material used in road construction. It combines traditional asphalt with recycled crumb rubber from discarded tires. This combination offers several advantages, including improved road performance, enhanced durability, and environmental benefits. There are four contents of CR used in this study to find the most perfect value of CR to be used. The ratio of CR contents is taken according to the percentage bitumen content which are (0%, 10%, 20%, and 30%) as shown in Table 8.

Table 8: CR ratio based on bitumen content

CR (%)	CR (gm)	OBC
0%	0	4.8
10%	5.52	4.8
20%	11.04	4.8
30%	16.56	4.8

For the modified mixture, eight samples were meticulously prepared and blended with crumb rubber (CR) using a dry process. Among these samples, two were conventional, while the remaining samples incorporated varying percentages of binder content (BC) at 10%, 20%, and 30%. Subsequently, these samples underwent comprehensive testing using a Marshall stability and flow test device. The outcomes, as presented in Table 9, reveal a noteworthy trend: as the CR content increases to 10%, there is an observable enhancement in stability. However, this upward trend is followed by a notable decrease in stability when CR content reaches 20% and 30%.

Table 9: Determination of optimum modifier content

CR		Sp. Gr.	Average Sp. Gr.	V_a (%)	VMA (%)	Flow (mm)	Average Flow (mm)	Stability (kN)	Average Stability (kN)
%	gm								
0	0.0	2.37	2.38	4.41	13.85	2	2.15	10.8	11.3
		2.39				2.3		11.8	
10	14.4	2.43	2.405	4.18	12.94	3.9	3.85	11.3	11.4
		2.38				3.8		11.4	
20	28.8	2.34	2.355	3.87	14.75	4	4	10.8	10.9

		2.37				4		10.9	
30	43.2	2.35	2.335	4.9	15.47	4	3.9	9.9	10.4
		2.32				3.8		10.8	

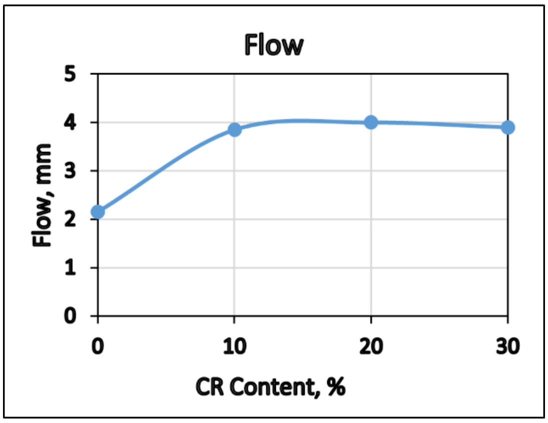

Figure 9: Flow & CR content

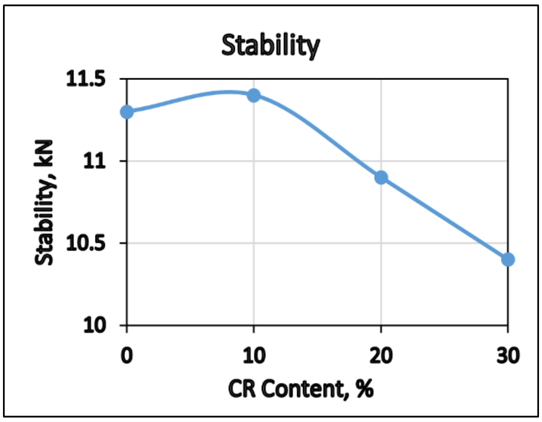

Figure 10: Stability & CR content

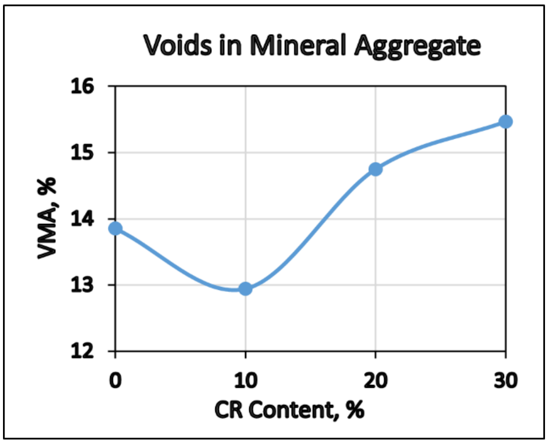

Figure 11: VMA & CR content

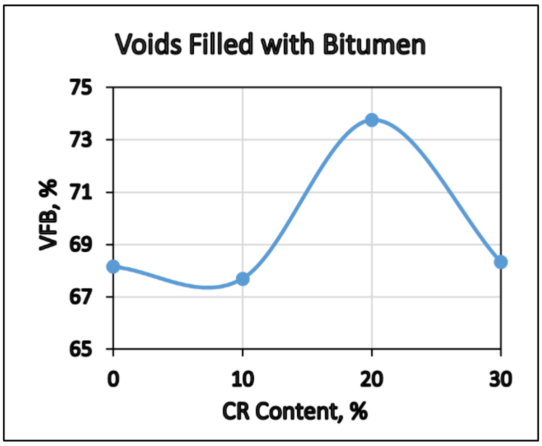

Figure 12: VFB & CR content

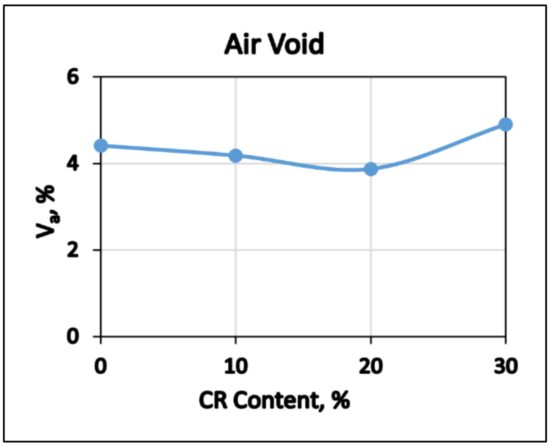

Figure 13: V_a & CR content

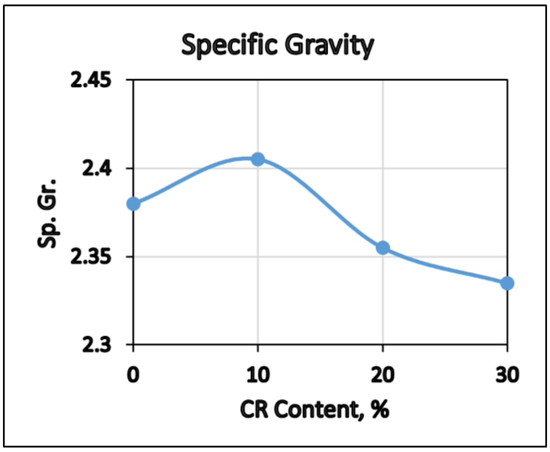

Figure 14: Specific Gravity & CR content

To determine the Optimal Crumb Rubber Content (OCRC), the following procedure was carried out:

1. Specific Gravity Graph (Figure 17): Identify the peak point on the specific gravity curve and record the corresponding bitumen content as the first value.

2. Stability Graph (Figure 13): Locate the maximum value on the stability graph and note the associated bitumen content as the second value.
3. Air Void (Figure 14): Extend a line representing 4% air voids to intersect the curve. Read the bitumen content at this intersection point as the third value.
4. Calculate the Average: Calculate the average of these three values to obtain the best modifier content.
   - The results obtained are as follows:
   - Optimum CR Content based on Maximum Density: 10%
   - Optimum CR Content based on Maximum Stability: 10%
   - Optimum CR Content based on 4% Air Void: 14%

By averaging these three values, the optimum crumb rubber content is determined to be approximately 11.3%.

5. Conclusion

Extensive research has focused on using rubber in asphalt mixtures to enhance the performance and sustainability of pavements. Adding waste tire rubber to asphalt binders effectively advances resistance against pavement damage like rutting and fatigue cracking. This eco-friendly approach does not decrease costs only; it also reduces environmental impact by repurposing waste materials and promoting the sustainable use of resources.

In bituminous mix design, the Marshall method is widely used to assess stability, flow characteristics, density, and binder content. The key goal is to determine the Optimal Binder Content (OBC) for achieving the desired pavement properties of stability, durability and flexibility. This study pinpointed the OBC at 4.8% through testing.

To identify the Optimal Crumb Rubber Content (OCRC), this study utilized the process in Marshall Mix design by blending rubber with aggregate in different ratios (0%, 10%, 20%, 30%). After conducting preparation and testing on eight samples, the research found that an 11.3% CR content was optimal, meeting the Asphalt Institutes guidelines and greatly improving the quality of the mixture in terms of its resistance to rutting and fatigue. Crumb rubber is widely accepted as a preferred additive, for asphalt binders because of its cost efficiency and its capacity to enhance the rheological characteristics of both asphalt binders and blends.

6. Conflict of Interest

There is no conflict of interest for this paper.

7. Author's Contribution

We confirm that all named authors have read and approved the manuscript. We also confirm that each author has the same contribution to the paper. We further confirm that all authors have approved the order of authors listed in the manuscript.

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