Effects of utilizing Crumb Rubber as Aggregate in Asphalt Mixtures

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ABSTRACT

Experts have given much attention on the use of waste in asphalt paving because of its significance from a sustainability perspective. This paper evaluated the performance properties of asphalt concrete mixes modified with Crumb Rubber (CR) as a partial replacement for two grade sizes of fine aggregate (2.36, and 0.3 mm) at six replacement rates: 0%, 2%, 4%, 6%, 8%, and 10% by weight. Asphalt concrete mixes were prepared at their Optimum Asphalt Content (OAC) and then tested for their engineering properties. Marshall properties, fatigue, rutting, ideal CT index test, Scanning Electron Microscopy (SEM), and Energy-Dispersive X-ray (EDX) spectroscopy were deployed to examine the crystalline structure and elemental composition of the CR-modified and unmodified asphalt concrete mixtures. The results showed a difference in Marshall's characteristics. The CT index revealed that the optimum cracking tolerance was achieved with a 2% CR substitution. Wheel track test results indicated that a 4% CR addition improved the rutting resistance of the asphalt mixture. SEM and EDX analyses exhibited significant changes in microstructure and elemental composition with the addition of CR. The main findings reveal that the use of 2% CR as a partial replacement of fine aggregate contributes to the production of more durable asphalt concrete mixtures with better serviceability. However, these results are based on laboratory experiments and require field verification to ensure practical applicability and long-term performance.

Keywords-asphalt; crumb rubber; dry process; Marshall test; CT index

I. INTRODUCTION

Most road pavements are built with asphalt mixtures because they latter satisfactory long-term performance and ride quality [1]. An asphalt mixture is a typical viscoelastic material, consisting mainly of asphalt binders, mineral fillers, and aggregates [2]. The performance of asphalt mixtures is dependent on filler properties. The asphalt binder and filler are combined during the blending process to form asphalt mastic, and the interaction between the filler and binder in asphalt mastic can greatly influence the mechanical performance of the asphalt mix [3, 4].

Environmentally sustainable development in modern road construction requires consuming a minimum of raw materials and energy during construction [5]. The global shortage of non-renewable natural resources promotes consumption efficiency and the use of alternative by-products and waste materials [6, 19]. Recycling waste solid and rubber materials in asphalt pavements needs to be considerably expanded, and the effects of these waste materials on asphalt mix performance should be analyzed [7, 8]. Due to the rising environmental and economic concerns, the use of waste materials in asphalt pavement has become an urgent priority for both administrations and researchers. This approach helps conserve limited resources, decrease construction costs, and reduce environmental pollution [9, 10, 23]. In the United States, 300 million waste tires are produced annually [11, 21]. Globally, an estimated 1 billion of scrap tires are generated each year [12]. The disposal of end-of-life tires is one of the biggest challenges for the 21st-century waste management. Scrap tires are non-biodegradable substances, and their flammability and chemical characteristics make them a major source of hazardous fumes, with toxic chemicals leaching into the soil and water [1, 2, 20]. Despite various methods of handling end-of-life tires, the most common approach is to deposit them in landfills, leading to a stockpile of scrap tires [3, 6]. Inappropriate disposal of large amounts of scrap tires can cause severe environmental problems, such as conflagration and soil pollution. However, scrap tires are composed of vulcanized rubber and various reinforcing materials, which should be viewed not only as environmental pollutants, but also as a significant economic loss [13, 14].

Recycling and utilizing discarded tires in asphalt pavements can be a promising option for reducing the number of waste tires [12, 24]. The disposal or management of used and damaged tires can be done in three ways: burying, burning, or recycling. Tire recycling and its use in paving roads with asphalt is a promising topic. Researchers around the world are exploring ways to use recycled rubber from tires with asphalt to improve the properties of asphalt. The results have shown improved crack resistance compared to mixes that do not contain recycled rubber. Authors in [42-44] enhanced asphalt properties by adding recycled rubber to resist permanent deformation, with the results suggesting significant improvement.

Modified asphalt types, such as those containing polymers, CR, or other additives, can substantially alter the properties of asphalt mixtures. Several studies have investigated the effects of modified asphalt on Marshall mix design parameters, such as stability, which was generally improved. This is attributed to the enhanced stiffness and elasticity of the modified binder. Also the flow can be decreased, indicating reduced susceptibility to rutting, and Voids in the Mineral Aggregate (VMA), which affects the durability and resistance to moisture damage. The effect of modified asphalt on VMA can vary depending on the type and amount of modifier used [43]. Also there are some limitations of the Marshall mix design for modified asphalt such as its empirical nature, meaning it relies on observed relationships between mix properties and performance rather than fundamental material behavior. This can limit its applicability to modified asphalt, as the behavior of modified binders can differ significantly from that of conventional binders. In addition, the Marshall mix design method primarily focuses on stability and flow, neglecting other important properties such as fatigue resistance and low-temperature cracking susceptibility [37].

The incorporation of CR into Hot Mix Asphalt (HMA) has been investigated, and it was found that the mixtures containing rubber exhibited the highest resistance to cracking compared to modified and ordinary mixtures [15, 22]. Authors in [45] studied the incorporation of CR powder as a filler in high percentages (20%, 40%, and 60%) into asphalt mixtures using the dry process. The results displayed improved resistance to failure, but the performance of the prepared mixes was weakened with increasing percentages of CR. Authors in [46] explored the deformation resistance of mixtures of CR and asphalt by monitoring Wheel Tracking Slope (WTS). The results exhibited excellent performance in deformation resistance, characterized by significantly lower WTS than others. Authors in [47] studied rubberized asphalt and concluded that the Optimum Bitumen Content (OBC) and CR content were 5.5% and 1%, respectively.

To this end, the purpose of this study is to examine the effect of partially substituting fine aggregates with CR at percentages of 2%, 4%, 6%, 8%, and 10%, deploying the dry process. The study uses CR in two sizes, 2.36 mm and 0.30 mm, to evaluate the properties of asphalt mixtures. The objectives include assessing the impact on Marshall properties, fatigue characteristics, and rutting (permanent deformation) resistance, using tests such as the Marshall test, Ideal CT index test, and wheel tracking. Additionally, SEM and EDX were employed to examine the microstructure and elemental composition of the CR modified and unmodified asphalt concrete mixtures, aiming to optimize the use of waste materials in road construction and enhance the sustainability and performance of asphalt pavements.

II. MATERIALS

A. Asphalt Cement

The asphalt cement utilized in this work is of 40-50 penetration grade. It was obtained from the Dora refinery, located southwest of Baghdad. The asphalt cement physical properties are portrayed in Table I.

TABLE I. PROPERTIES OF ASPHALT CEMENT

Property	**ASTM designation**	**Penetration grade 40-50**	
		Test results	**SCRB specification**
Penetration at 25 °C, 100 gm, 5 s. (0.1 mm)	D 5	47	40-50
Rotational viscosity at 135 °C (cP.s)	D 4402	519	………
Softening point (°C)	D 36	47	………
Ductility at 25 C, 5 cm/min (cm)	D 113	>100	>100
Flash point (°C)	D 92	289	Min 232
Specific gravity	D 70	1.041	………….
Residue from thin film oven test	D 1754		
Retained penetration % of original	D 5	59.5	>55
Ductility at 25 °C, 5 cm/min (cm)	D 113	80	>25

B. Aggregate

The aggregate used in this study was crushed quartz from the Amanat Baghdad asphalt concrete mix plant located in Taji, north of Baghdad. The source of this aggregate is the Al-Nibaie quarry, which is commonly utilized for asphaltic mixes in Baghdad. The coarse and fine aggregates were sieved and recombined in certain proportions to meet the wearing course gradation requirements specified by SCRB (SCRB, R/9 2003). The gradation curve of the aggregate is presented in Figure 1 and numerically provided in Table II. To assess the physical properties of the aggregate, routine tests were conducted. The results, along with the specification limits set by the SCRB, are summarized in Tables III and IV. The test results confirm that the selected aggregate complies with SCRB specifications.

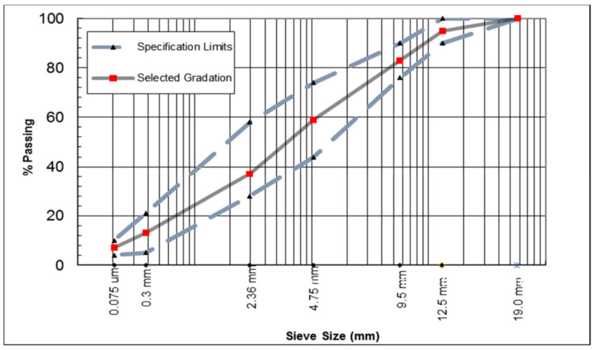


Fig. 1. Gradation graph representing aggregate particle distribution.

TABLE II. AGGREGATE GRADATION

Sieve opening		**Passing by weight, (%)**	
mm	**inch**	**Selected gradation**	**Specification limits**
19	3/4	100	100
12.5	1/2	95	90-100
9.5	3/8	83	76-90
4.75	No. 4	59	44-74
2.36	No. 8	43	28-58
0.3	No. 50	13	5-21
0.075	No. 200	7	4-10

TABLE III. PHYSICAL PROPERTIES OF COARSE AGGREGATE

Property	**ASTM designation**	**Results**	**SCRB specification limit**
Bulk specific gravity	C 127	2.6	----
Apparent specific gravity	C 127	2.82	----
Water absorption percentage	C 127	0.138	------
Wear percentage (Los Angeles abrasion)	C 131	21.8%	Max. 35%

TABLE IV. PHYSICAL PROPERTIES OF FINE AGGREGATE

Property	**ASTM designation**	**Results**	**SCRB specification limit**
Bulk specific gravity	C 128	2.65	-----
Apparent specific gravity	C 128	2.76	------
Water absorption percentage	C 128	0.56	----
Clay lump and friable particles	C 142	1.1	3 Max.

C. Mineral Filler

Ordinary Portland Cement (OPC) was used as the mineral filler in this study. It was supplied by the Almas factory in the Sulaimanya governorate, north Iraq. Table V shows the physical properties of OPC that passed through sieve No. 200 (0.075 mm).

TABLE V. PHYSICAL PROPERTIES OF PORTLAND CEMENT

Property	**Result**
Bulk specific gravity	3.15
Passing sieve No.200 (0.075mm)	97%

D. Crumb Rubber (CR)

The CR deployed in this study was sourced from Abraj Alkot Company, located in Aldiwanyah, Iraq. The company acquires old tires from Aldiwanyah Tires Company and recycles them through a process involving several steps: collection, transfer to the recycling site, removing steel and fiber, and finally grinding the rubber into small particles. The recycling process employed ambient grinding, which involves mechanical size reduction at or above normal room temperature. This method produces CR of varying particle sizes and qualities. In this study, two sizes of CR, 2.36 mm and 0.300 mm, were used. The selection of the percentages of CR substitution (0%, 2%, 4%, 6%, 8%, and 10% by weight of aggregate) was decided after a thorough review of previous studies and in accordance with many research articles [16-18]. Figure 2 illustrates these sizes, and Table VI details the chemical composition of the CR.

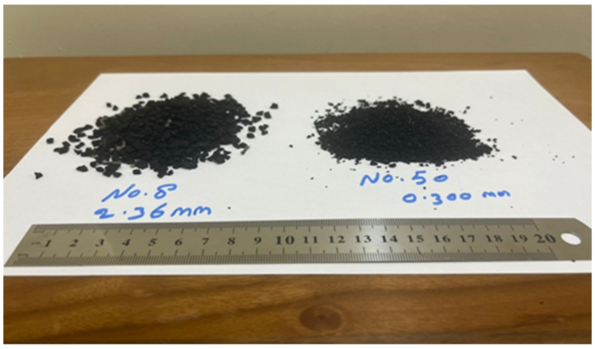


Fig. 2. CR (size 2.36 and 0.3 mm).

TABLE VI. PROPERTIES OF CR

Property	**Feature and Result**
Source	Scrap truck tires
Color	Black
Morphology	porous
Specific gravity (g/cm^3)	1.15
Decomposition temperature (°C)	200
Total rubber (natural and synthetic)	55
Carbon black (%)	30
Zinc oxide (%)	1.5
Sulfur (%)	1
Benzene extraction (%)	5.5
Ash content (%)	7

III. EXPERIMENTAL TESTS

The experimental work began by determining the OAC for all the asphalt concrete mixes with different CR contents using the Marshall mix design method. Thereafter, the asphalt concrete mixes were prepared at their OAC and tested to evaluate their engineering properties, including Marshall properties, fatigue characteristics, and rutting (permanent deformation). These properties were assessed using the Marshall test, Ideal CT index test, and wheel tracking.

A. Marshall Test

The Marshall test (ASTM D6927) was implemented to assess the resistance of asphalt concrete to plastic deformation. This test determined stability, flow values, and volumetric properties of asphalt concrete specimens, including Air Void (%AV) content, (%VMA), and %VFA. To determine these volumetric properties, bulk specific gravity and density were measured according to ASTM D2726, while the theoretical maximum specific gravity was calculated using ASTM D2041.

Specimens in cylindrical molds were compacted with 75 blows on each end to simulate high traffic conditions (>106 ESAL). After compaction, the specimens were demolded and immersed in water for 45 min before conducting the Marshall tests. Each test was conducted in triplicate to ensure accuracy and repeatability. Figure 3 displays photos of the specimens during preparation and testing.

Fig. 3. Marshall test.

The Indirect Tensile Cracking Test (IDEAL-CT), performed in accordance with ASTM D8225 standards, was used to evaluate the fatigue resistance of asphalt concrete mixes. Cylindrical specimens, measuring 101.6 mm (4 inches) in height and 63 mm (2.5 inches) in diameter, were subjected to a uniform vertical load at a rate of 50 mm/min along their diametrical axis. Both the applied load and the resulting displacement were continuously monitored throughout the test.

Fig. 4. IDEAL CT index test.

The specimens were compacted to an AV level of approximately 7% utilizing a Marshall compactor, and each test was conducted in triplicate at a constant temperature of 20°C. The increasing popularity of this test is due to its straightforward implementation, requiring no instrumentation, cutting, gluing, drilling, or notching of specimens. Additionally, its practicality (minimal training required for routine operation), efficiency (completed in less than one minute), repeatability (coefficient of variance less than 25%), and low cost of the test apparatus contribute to its widespread use. The CT Index of the asphalt concrete specimen is calculated by:

$$CT_{index} = \frac{t}{62} \times \frac{i_{75}}{D} \times \frac{G_f}{m_{75}} \times 10^6 \qquad (1)$$

where Gf represents the fracture energy, which is the area under the load-displacement curve divided by the specimen's cross-sectional area. The term m_{75} denotes the post-peak slope, defined as the absolute value of the slope of the load-displacement curve at the point where the post-peak load decreases to 75% of the peak load. The deformation tolerance, i_{75}, is the displacement measured at the point where the load is 75% of the peak load. Additionally, t refers to the specimen thickness, and D is the specimen's diameter.

The rutting susceptibility of asphalt blends was evaluated using the wheel tracking system test, designed to simulate road conditions. This procedure adheres to BS EN 12697-22 (2003) and AASHTO T324 (2013) standards. Figure 5 illustrates the wheel tracking machine used in the laboratory.

The test involved applying cycles of wheel load to test specimens (300×400×50 mm) and measuring the accumulation of permanent deformation with the wheel load passages. A steel wheel, with an applied stress of 70 psi (483 kPa), was employed to roll over the surface of the asphalt mix specimen. All asphalt concrete specimens were tested at a temperature of 50°C to mimic the elevated temperature conditions typically experienced in Iraq. The test was conducted for a total of 10,000 cycles (20,000 passes) or until the rutting depth reached 20 mm. Every 500 cycles, the deformation was measured with a dial gauge. The motion was being stopped every 20 min, and the dial gauge measurement was being recorded to determine the rut depth in each set of passes.

Fig. 5. Wheel tracking machine.

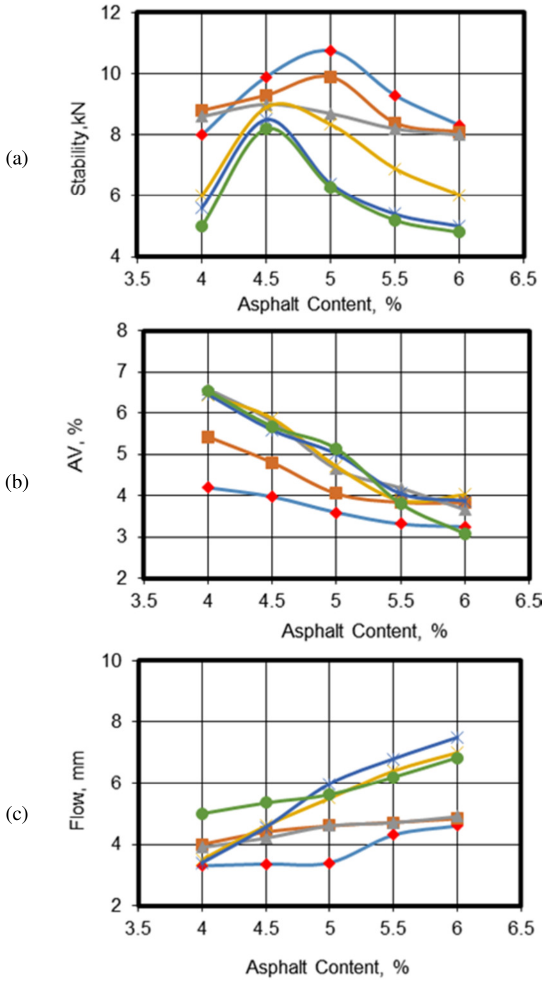
B. *Specimen Preparation*

The aggregate was sieved and sorted using dry sieve analysis into fractions retained on 12.5, 9.5, 4.75, 2.36, 0.3, and 0.075 mm sieves, along with a pan. The aggregate was then recombined according to the gradation curve, illustrated in Figure 1, which represents the mid-range for asphalt concrete mix Type III A, as specified by SCRB/R9 (2003). The aggregate was blended to the required weight based on the specimen geometry and test type. Cylindrical specimens for the Marshall and IDEAL CT index tests weighed 1.150 kg each, while slab specimens for the wheel track test weighed 13.8 kg. The blend was mixed thoroughly for 2 min and then heated to 150°C for 2 h in a temperature-controlled oven. After balancing the bowl, the appropriate amount of asphalt cement, preheated to 150-155°C (to achieve a binder viscosity of 170 ± 20 cSt), was added.

The contents were mixed on a hot plate for 2 min, then placed in the oven at 140°C for 10 min to ensure uniform compaction temperature. The compaction mold, preheated to 100 °C, was prepared. The mixture was then placed in the mold and compacted according to the specific test requirements. A Marshall compactor was put into service for cylindrical specimens, while a roller compactor was utilized for slab specimens. The slab specimens were compacted to a target density of 2.3 g/cm³, matching the corresponding Marshall density for cylindrical specimens.

C. Mix Design

The Marshall mix design method was employed to determine the OAC for the asphalt concrete mixtures with different CR contents. Five different Asphalt Contents (ACs) were tested for each mix type: 4.0%, 4.5%, 5.0%, 5.5%, and 6.0% by weight of the total mix. The OAC was calculated by averaging the three ACs that achieved peak stability, maximum density, and a target AV percentage of 4%. Figure 6 presents the Marshall test results for different percentages of AC and CR. The results in Figure 6 (a) for stability, (b) for AVs, and (e) for density were used to determine the OACs. The calculated OACs are presented in Table VII.



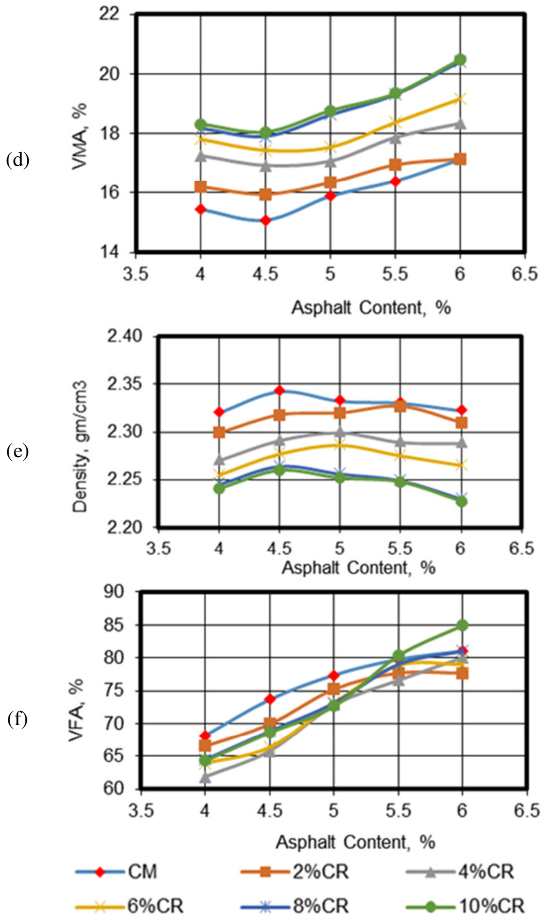


Fig. 6. (a) Stability versus AC, (b) AVs versus AC, (c) flow versus AC, (d) VMA versus AC, (e) density versus AC, and (f) VFA versus AC using the Marshall method.

TABLE VII. OAC FOR MIXES WITH VARIOUS CR CONTENT

CR Content, %	0	2	4	6	8	10
OAC, %	4.7	5.2	5.0	4.9	4.83	4.8

As observed in Table VII, the OAC increased with the addition of CR up to 2%, after which it decreased. This indicates that the presence of CR affects the asphalt mix design, requiring adjustments to achieve optimal properties.

IV. RESULTS AND DISCUSSION

A. Effect of CR on Marshall Properties

The Marshall properties of asphalt concrete mixtures incorporating CR reveal distinctive performance trends as the CR content increases, as evidenced in Figures 7-12. At a 2% CR inclusion level, stability decreases by approximately 8.8% compared to the Control Mix (CM) without CR (Figure 7). This reduction continues with higher CR content, with a 14.7% decrease at 4% CR and a 16.7% decrease at 6% CR, reaching the minimum acceptable limit of 8 kN. Stability reductions of 28.4% and 31.4% occur at 8% and 10% CR, respectively, falling below the SCRB standard. Flow values, indicative of the mix resistance to deformation, increase with CR content (Figure 8). A 2% CR content raises flow by 39.4%, while 4%

CR increases it by 42.4%. At 6% CR, the flow value rises by 60.6%. For 8% and 10% CR, flow values increase by 63.6% and 66.7%, respectively, suggesting improved deformation resistance. Both the stability and flow results comply with the findings of [38].

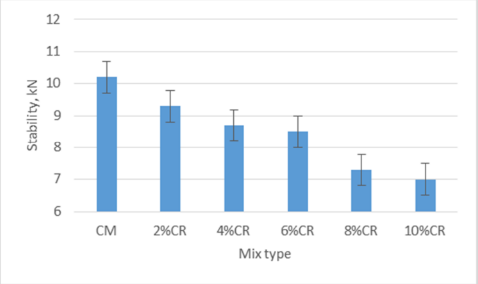


Fig. 7. Effect of CR on Marshall stability.

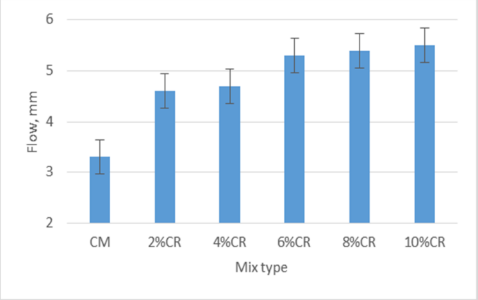


Fig. 8. Effect of CR on Marshall flow.

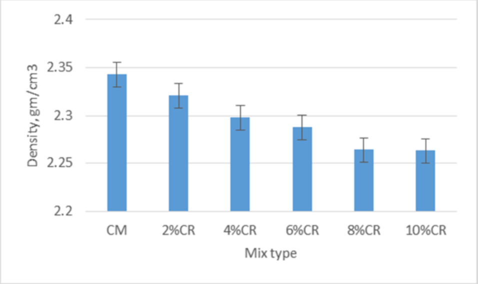


Fig. 9. Effect of CR on mix density.

Density trends move downward for mixtures with CR (Figure 9). The CM has the highest density. With 2% CR, density decreases by 0.9%, with 4% CR by 1.9%, and with 6% CR by 2.3%. At 8% and 10% CR, density decreases by 3.4%. This reduction in density is attributed to CR having less density than the aggregates it replaces; as the percentage of CR increases, the density decreases. AVs increase with higher CR content (Figure 10). The CM has an AV of 3.8%. Adding 2% CR raises AV by 5.3%, 4% CR increases it by 23.7%, and 6% CR raises it by 31.6%. Higher CR contents of 8% and 10% increase AV by 39.5% and 42.1%, respectively, indicating more voids within the mixture. VMA also increase with CR content (Figure 11). The CM has a VMA of 15.4%. A 2% CR inclusion raises VMA by 6.5%, 4% CR increases it by 11.4%, and 6% CR raises it by 13%. Higher CR contents of 8% and 10% raise VMA by 18.8% and 20.1%, respectively, indicating more void space within the aggregate structure. VFAs initially increase with a small amount of CR but decrease with higher contents (Figure 12). The CM has a VFA of 75%. Adding 2% CR increases VFA by 1.3%, but higher CR contents reduce VFA: 4% CR lowers it by 2.7%, 6% CR by 4%, 8% CR by 5.3%, and 10% CR by 6.7%. This trend suggests that while small amounts of CR can enhance binder filling, higher CR contents reduce binder effectiveness.

In summary, the addition of CR affects various Marshall properties of asphalt mixtures. Stability decreases with higher CR content, with acceptable levels up to 6% CR. Flow values increase, indicating improved deformation resistance. Density decreases and AVs increase, suggesting less compactness. VMA increases, indicating more void space within the aggregate structure, while VFA shows that binder effectiveness diminishes with higher CR content. These trends highlight the need for careful optimization of CR content in asphalt mixtures to balance performance and durability.

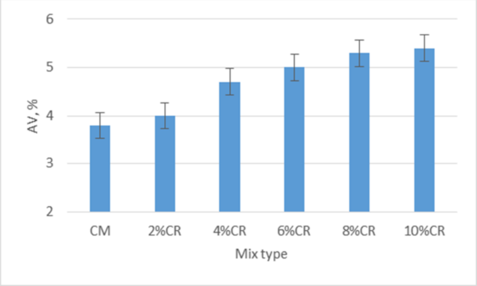


Fig. 10. Effect of CR on AV percentage.

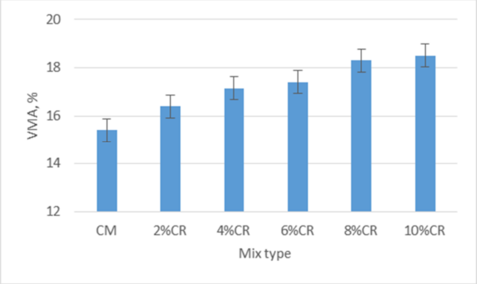


Fig. 11. Effect of CR on VMA percentage.

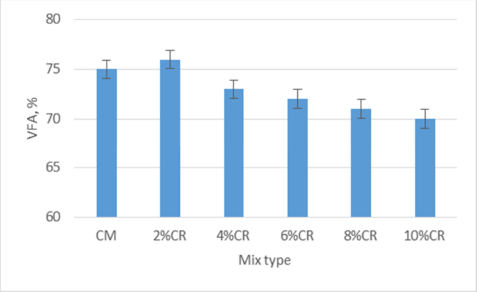


Fig. 12. Effect of CR on VMA percentage.

B. Effect of CR on Fatigue Results

The fatigue resistance of asphalt concrete mixtures incorporating CR was evaluated using the Fracture Energy (Gf) and CT index, obtained from the IDEAL CT index test, as presented in Figures 13 and 14, respectively.

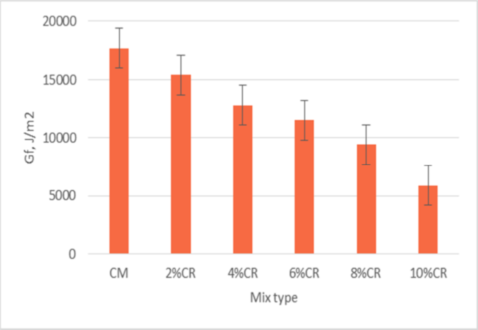


Fig. 13. Effect of CR on fracture energy.

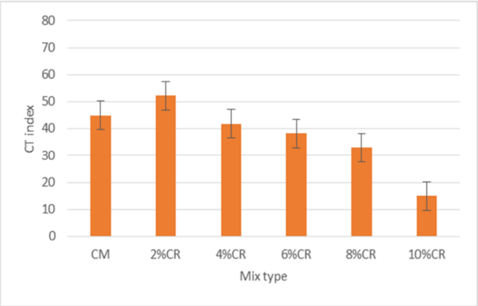


Fig. 14. Effect of CR on CT index.

The Gf, which indicates the material's ability to resist the initiation of cracking, exhibits a notable decline with increasing CR content (Figure 13). The CM without CR demonstrates the highest Gf value of 17700 J/m². Incorporating 2% CR reduces the Gf by approximately 13% to 15400 J/m². This downward trend continues with a 27.6% reduction at 4% CR, reaching 12800 J/m². At 6% CR, the Gf decreases by 34.7% to 11500 J/m². Higher CR contents of 8% and 10% further decrease the Gf to 9400 J/m² and 5900 J/m², respectively, indicating significant reductions in fatigue resistance.

The CT index, which measures the overall resistance to fatigue, follows a similar pattern (Figure 14). The CM achieves a CT index of 44.949. Introducing 2% CR improves the CT index by 16.3% to 52.259, suggesting enhanced resistance to fatigue. These results comply with those presented in [39-41]. However, with 4% CR, the CT index drops slightly by 6.9% to 41.861 compared to the CM. This declining trend continues with 6% CR, exhibiting a reduction of 14.9% to 38.225. At higher CR contents of 8% and 10%, the CT index decreases significantly by 26.5% to 33.029 and by 66.7% to 14.959, respectively, reflecting diminished fatigue performance.

In summary, the results demonstrate that small amounts of CR (2%) can enhance the fatigue resistance of asphalt mixtures, as evidenced by the increased CT index. However, higher CR contents lead to substantial reductions in both Gf and CT index, indicating a decreased ability to resist crack initiation and overall fatigue. This trend suggests that while minor additions of CR can be beneficial, excessive CR content adversely affects the fatigue properties of the asphalt mixtures. These findings stress the importance of optimizing CR content to balance improved fatigue performance with the structural integrity of asphalt concrete mixtures.

C. Effect of CR on Rutting Resistance

The rutting resistance of asphalt concrete mixtures incorporating CR was evaluated using the wheel tracking test, with its results presented in Figures 15 and 16. Figure 15 illustrates the rut depth development over 10,000 wheel passages for different CR contents. The CM without CR shows a consistent increase in rut depth, while the addition of CR impacts the rutting performance. The mix with 4% CR demonstrates the best performance, exhibiting the lowest rut depth throughout the test. Conversely, higher CR contents (8% and 10%) result in increased rut depths, indicating reduced rutting resistance. Figure 16 portrays the change percentage in rut depth compared to the CM for 5000 and 10000 wheel passages. At 2% CR, the rut depth decreases by approximately 7.9% after 5000 passages but increases slightly by 1.3% after 10000 passages. The 4% CR mix shows significant improvements, with a 29.4% reduction after 5000 passages and a 35.9% reduction after 10000 passages. However, 6% CR results in a slight increase in rut depth by 2.4% after 5000 passages and 1.2% after 10000 passages. Higher CR contents of 8% and 10% lead to increased rut depths, with increases of 3.5% and 9.2% after 5000 passages, and 5.6% and 8.5% after 10000 passages, respectively.

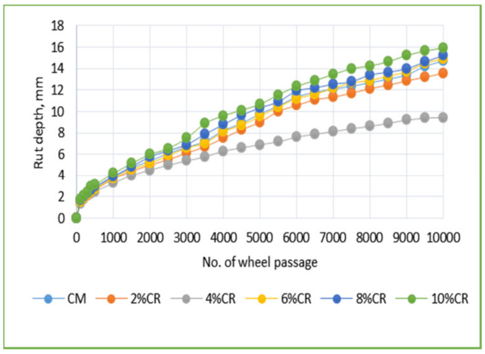


Fig. 15. Effect of CR on rut depth results.

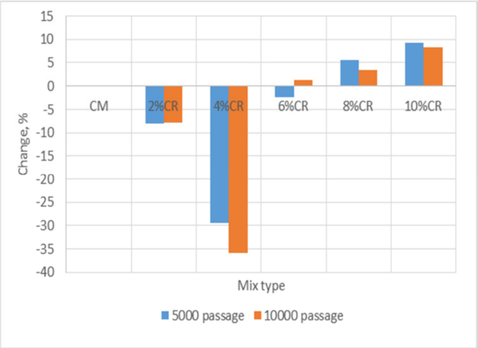


Fig. 16. Percent change in rut depth vs. mix type.

The WTS values (presented in Table VIII) further highlight the deformation resistance of the mixes. Lower WTS values indicate better rutting resistance. The CM has a WTS of 0.986, while the 2% CR mix displays a slight improvement with a WTS of 0.91. The 4% CR mix demonstrates the best performance with a WTS of 0.50. In contrast, higher CR contents result in increased WTS values: 1.068 for 6% CR, 0.978 for 8% CR, and 1.05 for 10% CR, indicating reduced deformation resistance as CR content increases beyond 4%.In summary, the addition of 2% CR improves the rutting resistance of asphalt mixtures, with 4% CR showing the best performance. However, increasing CR content beyond 4% leads to diminished rutting resistance, as evidenced by higher rut depths and WTS values. These findings imply that optimal CR content is crucial for enhancing the rutting resistance of asphalt concrete mixtures.

TABLE VIII. WTS OF DIFFERENT MIXES

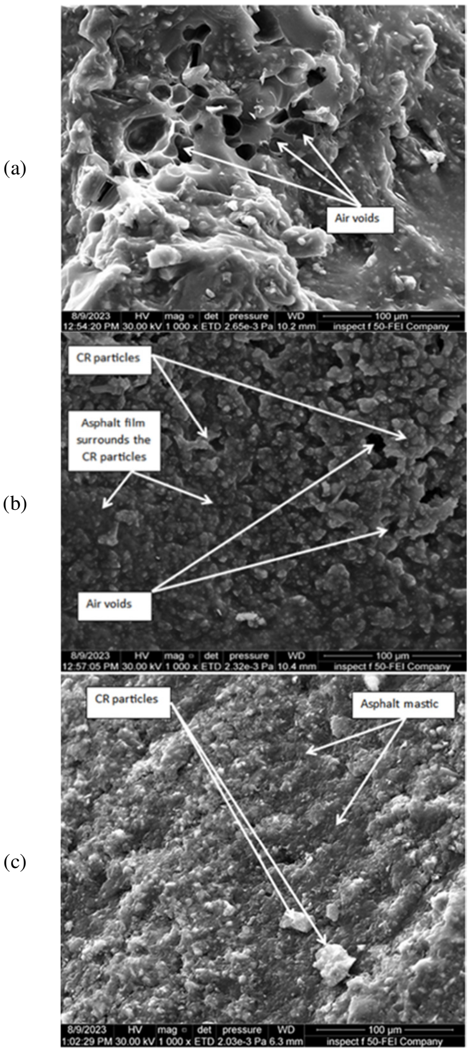
Mix type	WTS
CM	0.986
2% CR	0.91
4% CR	0.50
6% CR	1.068
8% CR	0.978
10% CR	1.05

D. SEM and EDX

This section discusses the results obtained from two tests: SEM and EDX. The tests were conducted using the device spotted in Figure 17. SEM was employed to provide high-resolution close-up images at a magnification level of 1Kx from the original size, and analyze the microscopic structure of different types of asphalt mixtures. EDX was utilized to determine the elemental composition of all the mixes. The SEM photos are presented in Figure 18.

Fig. 17. SEM / EDX device.

The SEM images reveal key microstructural changes in asphalt mixtures with varying CR content. The CM without CR (Figure 18(a)) manifests a dense and homogeneous structure with minimal voids, indicating a well-compacted mix. As CR content increases, the presence of CR particles becomes more pronounced, starting from the 2% CR mix (Figure 18(b)) to the 10% CR mix (Figure 18(f)). The rubber particles are embedded within the asphalt matrix, creating a more heterogeneous surface and increasing surface roughness. Notably, the AVs appear to increase with higher CR content, as observed in the SEM images, particularly from 4% CR (Figure 18(c)) onwards. This trend of increasing AVs with higher CR content aligns with the results obtained from the Marshall tests discussed earlier, where higher CR content led to increased AVs. The images also show that at higher CR contents, the mixture becomes more porous, potentially affecting its durability and mechanical properties. This observation underscores the importance of optimizing CR content to balance performance and durability in asphalt mixtures. The EDX elemental composition analysis further supports these observations by exhibiting significant changes in the mixture's elemental makeup with the addition of CR. The EDX plot for the CR particles is illustrated in Figure 19, and the detailed elemental composition is showcased in Table IX. The EDX results for the different mixes with varying CR content are summarized in Table IX. Based on Figure 19 and the results presented in Table X, it is evident that the main element in CR is carbon, constituting 65.0% atomic percentage with a weight percentage of 47.9%.



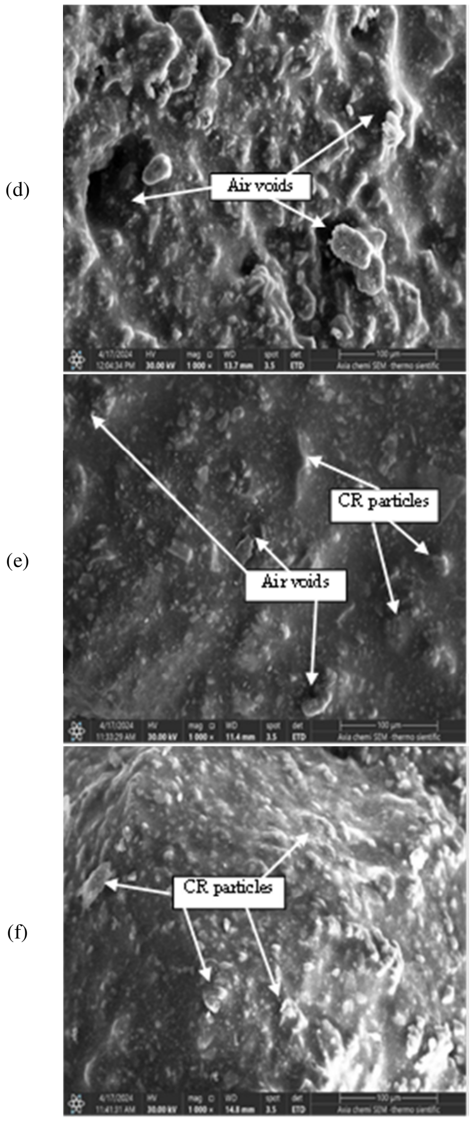


Fig. 18. SEM images for different mixes: (a) CM, (b) 2% CR, (c) 4% CR, (d) 6% CR, (e) 8% CR, (f) 10% CR.

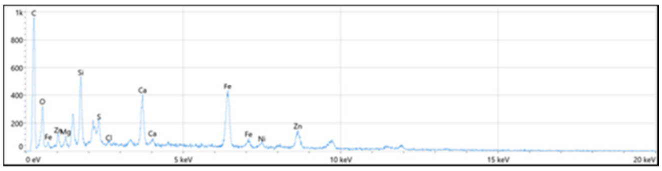


Fig. 19. EDX of the CR.

For the different mixes, the EDX summary in Table X shows that the carbon concentration increases with the rate of CR content in the mixes up to 6%, after which it starts to decrease. Specifically, the carbon content rises from 29.1% in the CM to a peak of 77.4% at 4% CR and then slightly decreases to 74.4% at 6% CR. Beyond this point, the carbon content declines to 65.5% at 8% CR and further to 62.4% at 10% CR. This trend suggests that initially, as CR is added, the carbon content in the mixture increases due to the high carbon content in the rubber. However, beyond 6% CR, the carbon concentration starts to decrease, likely due to the increasing AVs content in the mixes, as observed in the SEM images.

TABLE IX. DETAILED RESULTS FOR THE EDX OF CR

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	65.0	0.8	47.9	0.6
O	24.3	0.5	23.8	0.5
Mg	1.1	0.1	1.6	0.1
Si	2.8	0.1	4.8	0.1
S	0.5	0.0	0.9	0.1
Cl	0.2	0.0	0.3	0.0
K	0.3	0.0	0.6	0.1
Ca	1.6	0.1	3.9	0.1
Fe	2.8	0.1	9.6	0.3
Ni	0.4	0.0	1.3	0.1
Zn	1.3	0.1	5.2	0.4

TABLE X. EDX RESULTS FOR DIFFERENT MIXES

Element	Atomic %					
	CM	2% CR	4% CR	6% CR	8% CR	10% CR
C	29.10	61.60	77.40	74.40	65.50	62.40
O	45.00	25.00	12.00	11.60	20.00	25.30
Mg	0.50	0.40	0.20	0.60	0.40	0.50
Al	1.00	0.80	0.20	0.80	0.40	0.50
Si	20.00	18.00	15.00	12.00	9.00	7.00
S	0.30	0.50	1.30	0.70	1.50	0.90
Ca	17.00	15.00	13.00	12.70	5.40	7.60
Fe	1.20	1.00	0.30	1.30	0.40	0.50

The Oxygen (O) content shows an inverse trend, decreasing from 45.0% in the CM to 11.6% at 6% CR, and then increasing again to 25.3% at 10% CR. Silicon (Si) content, which is a major component of mineral aggregates, consistently decreases with increasing CR content, from 20.0% in the CM to 7.0% at 10% CR. Other elements, such as Magnesium (Mg), Aluminum (Al), Sulfur (S), Calcium (Ca), and Iron (Fe) also exhibit variations. Mg and Al levels remain relatively low and stable, while S content increases with CR addition, indicating the presence of sulfur compounds in the rubber. Ca content decreases significantly from 17.0% in the CM to 5.4% at 8% CR, before a slight increase to 7.6% at 10% CR. Fe content remains low across all mixes but shows a slight decrease with higher CR contents.

In summary, the EDX results demonstrate that incorporating CR into asphalt mixtures significantly alters the elemental composition. The increase in carbon content and the corresponding decrease in O and Si content highlight the substitution of mineral aggregates with organic CR. These compositional changes influence the physical and mechanical properties of the asphalt mixtures, emphasizing the need for optimizing CR content to balance performance and durability.

V. CONCLUSIONS

This study explored the impact of incorporating Crumb Rubber (CR) into asphalt mixtures through an extensive experimental program, including Marshall tests, IDEAL CT index tests and wheel tracking tests alongside Scanning Electron Microscopy (SEM)/Energy-dispersive X-ray spectroscopy (EDX) analysis. The experimental results provided valuable insights into the performance characteristics of CR-modified asphalt. The main conclusions drawn from this research are:

1. The addition of CR impacts the Marshall properties of asphalt mixtures. Stability decreases with higher CR content, remaining acceptable up to 6% CR. Conversely, flow values increase with the addition of CR, suggesting improved deformation.
2. The results indicate that at a 2% CR inclusion level, stability decreases by approximately 8.8% compared to the Control Mix (CM). This reduction continues with higher CR content, with a 14.7% decrease at 4% CR and a 16.7% decrease at 6% CR, reaching the minimum acceptable limit of 8 kN. Stability reductions of 28.4% and 31.4% occur at 8% and 10% CR, respectively. The inclusion of CR reduces the density of asphalt mixtures, while Air Voids (AV) and Voids in Mineral Aggregate (VMA) increase with higher CR content. Voids Filled with Asphalt (VFA) initially increase with small amounts of CR but decrease with higher CR contents, highlighting the need for careful optimization to maintain structural integrity. With 2% CR, the density decreases by 0.9%, with 4% CR the reduction percentage was 1.9%, with 6% CR the reduction percentage was 2.3%, and at 8% and 10%, the density decreased by 3.4%. In this case, it was observed that the best density ratios are 2% CR and 4% CR, at which the mixture has a good density to resist deformation. After that, it starts to decrease. Ratios of 6%, 8%, and 10% are undesirable because they are low.
3. The fatigue resistance, evaluated using the CT index, shows that small amounts of CR (2%) can enhance the fatigue performance of asphalt mixtures. However, higher CR contents lead to substantial reductions in both Fracture Energy (Gf) and CT index, indicating a decreased ability to resist crack initiation and overall fatigue. The control mix achieves a CT index of 44.949. Introducing 2% CR, improves the CT index by 16.3% to 52.259. However, with 4% CR, the CT index drops slightly by 6.9% to 41.861 compared to the CM. This declining trend continues with 6% CR, exhibiting a reduction of 14.9% to 38.225. At higher CR contents of 8% and 10%, the CT index decreases significantly by 26.5% to 33.029 and by 66.7% to 14.959, respectively, reflecting diminished fatigue performance.
4. The addition of 2% CR improves the rutting resistance of asphalt mixtures, with 4% CR demonstrating the best performance. However, increasing CR content beyond 4% leads to diminished rutting resistance, as evidenced by higher rut depths and WTS values.
5. SEM images reveal that air voids increase with higher CR content, which complies with the Marshall test results. EDX analysis shows significant changes in elemental composition with the addition of CR, particularly an increase in carbon content and a decrease in Oxygen (O) and Silicon (Si) content, indicating the substitution of mineral aggregates with organic CR.
6. Based on the experimental results, a 2% CR content is recommended for enhancing asphalt mixture performance. However, these findings are based on laboratory experiments and require field verification to ensure practical applicability and long-term performance.

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