Tikrit Journal of Engineering Sciences (2025); 32(1): 1189
DOI: http://doi.org/10.25130/tjes.32.1.3

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)
Tikrit Journal of Engineering Sciences
available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Design and Evaluation of Asphalt Mixtures Containing Crumb Rubber as Aggregates Replacement

Abdullah M. Rashed [a], **A. I. Al-Hadidy** [*b]
a Highways and Bridges Engineering, Technical College of Engineering, DPU, Kurdistan Region, Iraq.
b Department of Civil Engineering, Mosul University, Mosul, Iraq.

Keywords:
Crump rubber; Deformation strength; Kim test; Mechanical characteristics; Static creep compliance.

Highlights:

- *The durability and mechanical attributes of CR/AC mixtures were investigated and compared with AC mixtures.*
- *Different CR contents, i.e., 0.5%, 1.0%, 1.5%, and 2.0% wt. of aggregates were used as aggregates replacement.*
- *The AC mixture with 0.5-1.0% CR content shows similar Marshall stability, moisture resistance, deformation strength, and static creep compliance to those of AC mixture without CR.*
- *A design methodology for crumb rubber-asphalt mixtures was introduced to determine the appropriate amount of CR by considering the durability and mechanical properties.*

ARTICLE INFO
Article history:

Received	12 June	2023
Received in revised form	06 Sep.	2023
Accepted	28 Nov.	2023
Final Proofreading	02 Aug.	2024
Available online	22 Feb.	2025

Citation: Rashed AM, Al-Hadidy AI. **Design and Evaluation of Asphalt Mixtures Containing Crumb Rubber as Aggregates Replacement**. *Tikrit Journal of Engineering Sciences* 2025; **32**(1): 1189.
http://doi.org/10.25130/tjes.32.1.3

*Corresponding author:

A. I. Al-Hadidy
Department of Civil Engineering, Mosul University, Mosul, Iraq.

Abstract: Crumb rubber (CR) as a modifier has been used by many for asphalt binders and asphalt concrete (AC) mixtures production. Nevertheless, the engineering properties of AC mixtures containing CR as aggregate replacement still need to be determined. Nevertheless, it is essential to ascertain the engineering qualities of AC mixtures that incorporate CR as a replacement for aggregates. This study investigates the durability and mechanical attributes of conventional AC mixtures and CR/AC mixtures. The assessment involves analyzing various properties, such as Marshall stability, static creep compliance, indirect tensile strength (ITS), tensile strength ratio (TSR), and deformation strength in the Kim test. One AC control mixture and four CR combinations were created. The CR contents of four CRAC mixes were 0.5%, 1.0%, 1.5%, and 2.0% wt. of aggregates. Optimum asphalt content increased and bulk specific gravity decreased with increasing crumb rubber content. The AC mixture with 0.5% CR content showed approximately similar Marshall stability, moisture resistance, deformation strength, and static creep compliance to those of the AC mixture without CR. Whereas, AC mixture with 1.0% CR content showed higher plastic flow. The stability and TSR values remained higher than the ASTM specification's minimum values, which cap CR up to 1.0%. This study introduces a design methodology for crumb rubber-asphalt mixtures, which determines the appropriate amount of CR by considering the durability and mechanical properties of the asphalt mixture. According to this study, 0.5–1.0% of the CR by weight of aggregates can be replaced as aggregates for paving applications.

تصميم وتقييم مزجات الأسفلت التي تحتوي على فتات المطاط كبديل للركام

عبدالله محمود رشيد[١] ، عبد الرحيم إبراهيم الحديدي[٢]
[١] هندسة الطرق والجسور/ الكلية التقنية الهندسية/ إقليم كردستان – العراق.
[٢] قسم الهندسة المدنية/ جامعة الموصل/ الموصل – العراق.

الخلاصة
فتات المطاط (CR) كمحسن قد استُخدم من قبل العديد من الأشخاص للمادة الأسفلتية وإنتاج مزجات الأسفلت الخرساني (AC). ومع ذلك، لا يزال من الضروري تحديد الخصائص الهندسية لمزجات AC التي تحتوي على CR كبديل للركام. ومع ذلك، فمن الضروري التأكد من الصفات الهندسية لمزجات الأسفلت الخرساني (AC) التي تدمج CR كبديل للركام. تتناول هذه الدراسة الخصائص الميكانيكية ومتانة كل من المزجات التقليدية للأسفلت الخرساني ومزجات CR/AC. يشتمل التقييم على تحليل معلمات مختلفة مثل ثباتية المارشال، وقوة الشد غير المباشرة عند درجة حرارة ٢٥ درجة مئوية و ٦٠ درجة مئوية، ومعامل قوة الشد، والانضغاط الثابت عند ٤٠ درجة مئوية، وقوة الانفعال في اختبار كيم عند ٦٠ درجة مئوية. لهذا الغرض، تم إنشاء خليط أسفلت خرساني مرجعي ومجموعة من أربعة مزجات CR. تراوحت محتويات CR في مزجات CRACالأربعة بين ٠,٥٪ و١,٠٪ و١,٥٪ و٢,٠٪ من وزن الركام. يزداد محتوى الأسفلت الأمثل في حين تقل الكثافة النوعية العامة عند زيادة محتوى المطاط الحبيبي. يُظهر المزيج AC بنسبة ٠,٥٪ من CR استقرار مارشال مشابهًا تقريبًا ومقاومة للرطوبة والانضغاط الثابت للمزيج ACبدونCR ، بينما يُظهر مزيج AC بنسبة ١,٠٪ من محتوى CR انسيابًا أعلى للمادة البلاستيكية. قيم الثباتية ونسبة قوة الشد لا تزال أعلى من القيم الدنيا لمواصفات ASTM، التي تحد من استخدام CR حتى نسبة ١,٠٪. تقدم هذه الدراسة منهجية تصميم لمزجات الأسفلت الخرساني بفتات المطاط ، تحدد الكمية المناسبة من فتات المطاط من خلال النظر في الخصائص الميكانيكية والمتانة للمزيج الأسفلتي. وفقًا لهذه الدراسة، يمكن إعادة تدوير نسبة ٠,٥-١,٠٪ من CR بوزن الركام واستخدامها كبديل للركام في تطبيقات الرصف.

الكلمات الدالة: فتات المطاط، الخصائص الميكانيكية، مقاومة التشوه، الانضغاط الساكن، اختبار كيم.

1.INTRODUCTION

Over the last few decades, several experiments have been conducted to develop Asphalt Concrete (AC) mixes by incorporating crumb rubber (CR) to enhance pavement performance [1-3]. Because of its beneficial economic and environmental impacts, along with the desirable physical and rheological characteristics of asphalt binder and mixtures, CR modifier is considered one of the most extensively employed asphalt cement modifiers [4-6]. Specifically, the number of trucks on road networks has swiftly risen with time, with registrations now exceeding one million [7]. Future traffic volume increases are anticipated to cause increased cumulative vehicle loads and accelerated rutting failure, which is a prevalent kind of deterioration detected in Iraq's road networks being tackled. Rutting, a significant type of road damage, significantly reduces traffic safety. Road safety becomes compromised once rut depth reaches 13 mm, leading to a decrease of 0.35 points on the Present Serviceability Index (PSI) [8]. Moreover, with the increasing vehicles number on the roads, the proper disposal of waste tire rubber becomes increasingly crucial to safeguard the environment. One efficient method of tire disposal involves shredding and grinding discarded tires to produce scrap rubber of different sizes, which can then be further processed and utilized. Another widely adopted technique, developed and extensively employed over the last three decades, is called Crumb Rubber-Modified (CRM), which aims to enhance the effectiveness of AC. Utilizing CRM-AC offers several advantages, including reduced fatigue and thermal cracking of the mixture. Moreover, there is a rise in tensile strength when exposed to elevated temperatures and enhanced material resilience at moderate temperatures, showing a regenerative effect [8]. Various test results indicated that pavement constructions utilizing CRM-AC were notably superior to those constructed with traditional AC in diverse real-life scenarios [9-11]. Even though it comes at a higher cost and requires more intricate construction techniques, utilizing CRM-enhanced AC can be financially rewarding due to its numerous engineering benefits [12]. CRM-AC can facilitate longer road service life at a reduced maintenance cost [13]. The initial applications of used auto tires in AC occurred in the 1960s, and the processes were known as dry and wet processes to reflect adding CR [14]. The primary methods employed to integrate CR into asphalt mixes are wet and dry [15]. In the wet method, the CR and bitumen are mixed for 1-2 hrs. at a temperature ranging between 191°C and 218°C [16]. In this method, bitumen is altered before being added to a mixture, as a result altering the properties of the mixture. The CR and aggregates are mixed before being blended with the bitumen, as opposed to the dry procedure [17]. The dry method typically involves using approximately 2-4 times more CR than the wet method [18]. The wet method is more widely favored between these two methods. Conversely, the dry method is less commonly employed due to previous studies indicating inferior outcomes [19]. According to the authors' knowledge, developing and accessing asphalt mixtures that substitute traditional aggregates with crumb rubber focus on examining their mechanical and durability properties have been yet to be investigated in terms of moisture damage, deformation strength in Kim tests at 60°C, and static creep compliance at 40°C. Hence, there remains a need for additional research that specifically targets this subject matter.

2.RESEARCH OBJECTIVES AND METHODOLOGY

The main objective of this research is to design and assess asphalt mixtures that utilize CR as a substitution for traditional aggregates, focusing on their mechanical and durability properties. The present study aims to investigate the performance of asphalt mixtures using CR as aggregate replacements in the direction of long-term, sustainable growth of road substructure. Figure 1 shows the approaches working to complete the study aim of this study. Using tests such as the Marshall stability, ITS in dry and wet conditions, moisture sensitivity, deformation strength by Kim test at 60 °C, and static creep compliance at forty °C, the effect of the crumb rubber was introduced in the form of granules. The outcomes were compared with the control mixtures.

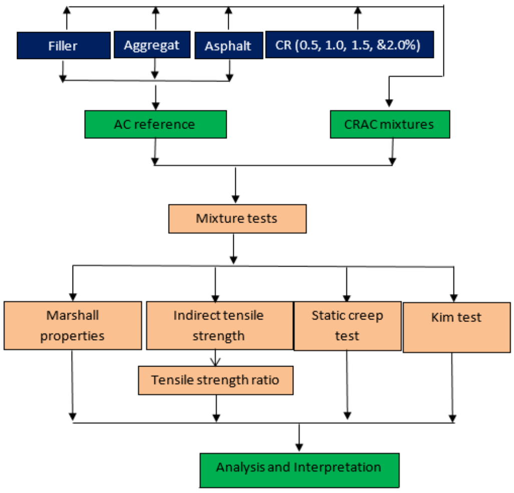


Fig. 1 Flowchart Depicting the Experimental Procedures Conducted in the Present Study.

3.MATERIALS

In the present investigation, fine and coarse aggregates were obtained from an asphalt plant in Mosul in northern Iraq. The gradation chosen for this study falls within the recommended limits set by ASTM (D3515), positioned at the center of the suggested range [20] for dense graded asphalt mixtures. A maximum size of aggregate of 19 mm was used (Fig. 2). The aggregate utilized in this study is characterized by several fundamental engineering parameters, as outlined in Table 1. Limestone filler ($CaCO_3$) served as the mineral filler in this research. The filler underwent sieving using sieve No. 200 and exhibited a specific gravity of 2.731, in accordance with ASTM-D854 [21]. In this study, the binder used was asphalt binder with a penetration grade ranging from 40 to 50, obtained from the Dora refinery in Baghdad. The engineering properties of this asphalt binder are outlined in Table 2. The CR used in this research was sourced from discarded tires and divided into two particle size categories. The present research investigates replacement percentages ranging from 0.5% to 2% by the aggregate weight, increasing in increments of 0.5%. The results of the sieve analysis are provided in Table 3. Figure 3 depicts the particle sizes of the crumb rubber utilized in this study.

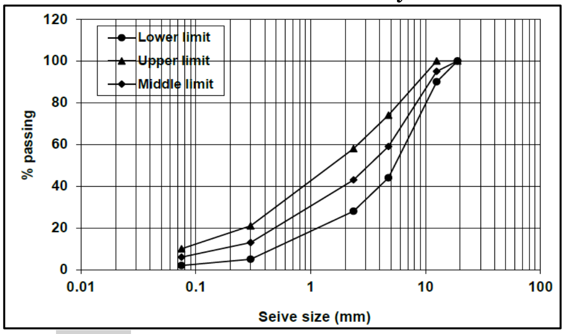


Fig. 2 Gradation Limits of Aggregate.

Table 1 Physical Characteristics of the Chosen Aggregate.

Properties	Aggregate		ASTM	NCCL
	Course	Fine	Designation	limits
Bulk sp. gr.	2.653	2.542	C – 127	----
Apparent sp. gr.	2.692	2.591	C – 128	----
Absorption %	0.763	1.42		----
Toughness, %	20	----	C – 131	≤ 30
Angularity, %	98		D – 5821	≥ 95

Table 2 Asphalt Binder Properties.

Properties	Results	ASTM limits	NCCL limits
Penetration (25 °C, 100gm, 0.1mm)	47	40-50	40-50
Ductility (25°C, cm)	150+	> 100	>100
R and B softening point, °C	52.0	50-58	51-62
Flashpoint, deg. C	267	> 230	> 232
Thin film oven loss, %	0.18	< 1.0	< 0.75
Sp. gr.	1.036	1.010-1.060	----
Rotational Viscosity	565 @ 135°C 142 @ 165°C		----
Solubility in CCl_4, %	99.70	> 99	> 99.0
Aged penetration after TFOT, % of original	67	----	> 55
Residue ductility (25°C, 5cm/min)	62	----	> 50
Aged softening point after TFOT, °C	6	----	< 10.0

Table 3 Crumb Rubber Sieve Analysis.

Sieve No. (#)	Passing %
4	100
8	69
50	31
200	0.0

Fig. 3 Crumb Rubber Particle Sizes.

4.EXPERIMENTAL PROCEDURES

4.1.Preparation of Sample

Asphalt concrete modified and unmodified mixtures were devised utilizing the Marshall process. Before adding the asphalt binder to the mixture, a dry method was employed to incorporate CR into the asphalt mixture. Various CR ratios, i.e., 0.5%, 1%, 1.5%, and 2%, were substituted by the weight of aggregates. In this study, aggregate was heated at 160 °C for 3 hours to prepare CR mixtures. Additionally, the bitumen was heated to 150°C before being mixed with the aggregate. As for the dry process method, the aggregate was heated, and CR was added directly to the aggregates and mixed for 30 sec. Then, the mixture was combined with asphalt in a mixing vessel. For 2-3 minutes until the surface of the aggregates was sufficiently coated by asphalt. The mixing temperature was maintained within the range of 160°C to 165°C. Each specimen underwent compaction using a Marshall Hammer, with 75 blows applied on every side of the sample at a temperature of 145°C. The optimum binder content for each type of mixture, i.e., control, CR0.5%, CR1.0%, CR1.5%, and CR2.0%, was determined and found to be 5.1%, 5.25%, 5.40%, 5.60%, and 5.72%, respectively. Then, all mixtures were subjected to the following tests:

4.2.Marshall Stability and Flow Tests

Stability and flow value tests were conducted on compacted samples containing different proportions of CR, following the guidelines outlined in ASTM D6927 [22]. Following submersion in heated water at 60°C for 30-40 minutes, cylindrical compacted samples with dimensions of one hundred millimeters in diameter and sixty-three and a half millimeters in height were subjected to failure by loading them with curved steel plates along their diameters. The loading process was performed at a constant compression rate of fifty-one millimeters per minute. The Marshall Stability test determines the maximum compressive force a material can endure, measured in Kilonewtons (kN). The flow value, measured in millimeters (mm), indicates the maximum amount of plastic deformation the material can undergo when subjected to the maximum force. Marshall rigidity, expressed in kN/mm, is determined by dividing the stability (kN) by the flow and serves as the measure of stiffness. Three samples were examined, and the results were summarized in the form of an average, which was then utilized in the investigation.

4.3.Tensile Properties and Moisture Susceptibility Tests

Asphalt mixtures susceptible to moisture-induced deterioration are at a higher risk of experiencing bitumen stripping. This phenomenon is marked by the detachment of asphalt binder from the aggregate. Asphalt mixtures characterized by little void percent and a sturdy structure are less susceptible to this phenomenon. Nevertheless, even materials with relatively high density yet permeable to water pose a risk of stripping, potentially leading to weakened adhesion between particles and even surface disintegration. Even in highly compact water-permeable materials, this hazard remains. The probability of bitumen stripping correlates directly with the bond strength between the aggregate and asphalt binder and the aggregate's resistance to the detrimental impacts of water. During mechanical testing under immersion conditions, the primary objective is to examine the efficiency of a compressed paving mixture when it is submerged in water. One indirect method of quantifying stripping involves calculating the ratio of a specific characteristic after immersion to the characteristic beforehand immersion. Following the guidelines drawn in ASTM D6931, the tension strength ratio (TSR) is a ratio that compares the performance of wet-conditioned samples of bituminous material to that of specimens of the same material without experiencing the conditioning process. The comparison is quantified as a percentage [23]. To measure the tensile characteristics of the control and CR-mixes and examine their susceptibility to moisture, the ITS test was utilized, as illustrated in Fig 4. The mixes maintained a typical air-void content of 7% of the total volume. The ITS test was conducted in two groups for the control and CR samples, followed by recombination (C). The samples were divided into two groups. The first was immersed in water at 60°C for 24 hours, while the second group remained at the laboratory temperature. After 24 hours, both groups were immersed in water for another 2 hours at 25°C. Finally, the samples were subjected to a sequence of tests on the Marshall apparatus till failure occurred, utilizing a loading rate of 51 millimeters per minute. ITS has been determined using Eq. (1) [24], which was calculated using the maximum load at sample failure.

$$ITS = \frac{2P}{\pi d t} \quad (1)$$

where P represents the maximum load in (N), d represents the sample diameter (mm), and t represents the depth of the sample (mm). The ITS test conducted at 25°C determined the tensile strength ratio of conditioned (C) to the unconditioned (U), denoted as TSR, as indicated in Eq. (2).[24].

$$TSR\ (\%) = \frac{ITSC}{ITSU} \times 100 \quad (2)$$

where ITSC and ITSU represent the indirect tensile strength (N/mm^2) of conditioned and unconditioned samples, respectively. The stiffness modulus of the base course and road base layers is widely acknowledged as an essential performance metric. It measures the capacity of the bituminous layers to distribute loads and assesses the degree to which tensile strains induced by traffic at the base of the road foundation result in fatigue cracking. Additionally, it regulates the potential for permanent deformation caused by compressive strains in the subgrade. The stiffness modulus of a material is defined as the ratio between its ultimate stress and ultimate strain when subjected to uniaxial loading. The term "complex modulus" is commonly used to refer to this property when discussing viscoelastic materials, such as bituminous composites. The time between applying the stress and measuring the strain is called the phase angle. Bituminous materials include a viscous component that causes the strain to lag behind the stress. The TSM (Tensile Strength Modulus) in N/mm² was determined at 25°C and 60°C. This calculation involved utilizing the maximum vertical load applied and the average horizontal deformation value derived from Eq. (3). [25].

$$TSM = \frac{P\,(\mu+0.27)}{D\,t} \qquad (3)$$

where P represents the maximum applied load in (N), μ represents the Poisson's ratio (typically assumed as 0.35), D represents the mean horizontal displacement in (mm), and t represents the sample thickness in (mm).

4.4.Deformation Strength Test (SD)

When analyzing the effectiveness of asphalt mixtures, it can be quite helpful to have the ability to analyze the rutting damage using rapid and simple tests. Given the relevance of rutting damage in asphalt mixes, particularly in blends involving (CRMA), its consideration becomes essential. A static test is led to estimate the susceptibility of asphalt to rutting, and the mix demonstrating greater resistance to rutting is characterized by having higher deformation strength [26, 27]. The asphalt mixture rutting can be assessed through a straightforward test called deformation strength. According to Fakhri et al., it is recommended to utilize static deformation strength due to its test simplicity and convenience [28]. This recommendation resulted from the substantial correlation between rutting resistance and static deformation strength when the Wheel Track test was performed. This test can be done by heating the specimens to 60°C using the Marshall method for half an hour. After the surface had been dried, the sample was positioned within the loading frame (Fig. 5). Then, a loading head was utilized to administer a vertical static load directed towards sample compaction at a rate of 2 in/min to the top of the specimen. This load is naturally vertical. A loading head with a circular edge and a flat bottom, having a diameter of 30 millimeters and a curvature radius of 7.5 millimeters, was utilized. The final step was recording the force applied to the specimen versus its displacement. During this particular test, the deformation strength was determined using the following formula:

$$SD = \frac{0.32\,P}{\left(10\,P + \sqrt{20\,y - y^2}\right)^2} \qquad (4)$$

where SD represents the deformation strength measured in (MPa), P represents the maximum failure load in (N), and y represents the vertical deformation in (mm).

4.5.Static Creep Compliance

This guideline delineates the procedure required to assess a material's tensile creep and tensile strength utilizing a single specimen, which is essential for conducting thermal cracking examinations. Evaluating tensile creep involves applying a consistent static load along the diametral axis of the sample. When determining the tensile creep compliance of the specimen as a function of time, the vertical deformations of the specimen are considered. According to AASHTO specifications [29], the test was conducted using Marshall specimens at 40°C. The samples were placed in a water bath at the test temperature for 2 hrs. A load of 100 kPa was applied, and readings were recorded every minute for 60 minutes. Subsequently, the load was removed, and the readings were recorded for the next 30 minutes.

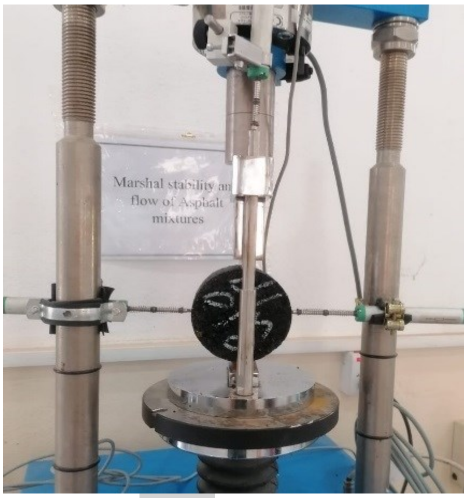


Fig. 4 ITS Test.

(a)

(b)

Fig. 5 Kim test (a- Mold, b- Testing).

Fig. 6 Mix type.

5.RESULTS AND DISCUSSIONS

5.1.Statistical Considerations

In this investigation, AC and CR mixes were compared using the null hypothesis (H0=0) and a significance level of 0.05 (ANOVA) [30]. The least significant difference (LSD) was supplied to evaluate whether a notable distinction between the two averages exists. If the variance between the two means equals or surpasses the LSDV, it is considered statistically significant; otherwise, it is insignificantly considered. The mean discrepancies are represented by alphabetical letters in Table 4. Means with the same letter are considered statistically insignificant.

5.2.Bulk Specific Gravity

Specimens of asphalt binder containing various contents of CR, i.e., 0.5%, 1%, 1.5%, and 2%, and a control mix (without CR) were subjected to Marshall technique test. The Marshall results are illustrated in Fig. 7. Adding CR clearly influenced the optimal bitumen contents (OBC) in the different specimens. The results indicated that the mixture lacking crumb rubber (CR) displayed a lower OBC of 5.1%. Conversely, with the incorporation of 2% crumb rubber content replacing aggregates in the asphalt mixture, the OBC increased to 5.72%, marking a 12.2% rise, as illustrated in Fig. 7, demonstrating that the OBC value rises with the inclusion of CR, which possesses a low specific gravity. A higher content of CR results in an elevation of the lighter constituents of asphalt absorbed by the CR, consequently increasing void space among the aggregate particles, resulting in a decline in the mixture density.

5.3.Marshall Stability, Flow, and Marshall Quotient

Figure 8 (a) demonstrates the influence of CR substitutional on mixture stability. Moreover, the figure visually represents the standard error (SE), calculated by dividing the standard deviation by the square root of the specimen. As anticipated, due to the higher compressibility of CR compared to fine and coarse aggregates, it is evident that the stability of AC mixtures declined with the escalating CR concentration. Mixtures with a 0.5%, 1.0%, 1.5%, and 2.0% CR content displayed lower stability values than the AC mixture. Specifically, stability decreased by 6.7%, 14.08%, 35.3%, and 44.2% for mixtures using CR0.5%, CR1.0%, CR1.5%, and CR2.0%, respectively, relative to the AC mixture. This finding highlights the significant effect of CR as an aggregate replacement on stability, which has an adverse effect on the stability of AC mixtures. Moreover, no statistically significant distinction was observed in stability between the AC and CR 0.5% mixes and the CR 0.5% and CR 1.0% mixes. However, a significant disparity was observed between the AC mixture and other CR mixtures, i.e., CR1.0%, CR1.5%, and CR2.0%. This information can be found in Table 4. For instance, there was a stability change of 0.824kN (12.357kN for AC and 11.533kN for CR0.5%) and 0.916kN (11.533kN for CR0.5% and 10.617kN for CR1.0%), meaning that the AC and CR0.5% mixtures and CR0.5% and CR1.0% mixtures depicted similar stability. Similar to stability, the flow values, as depicted in Fig. 8 (b), exhibit a consistent trend, with CR0.5%, CR1.0%, CR1.5%, and CR2.0% samples showing higher values than the AC mixture. Specifically, flow decreased by 5.9%, 33.7%, 70.7%, and 76.5% for mixtures using CR0.5%, CR1.0%, CR1.5%, and CR2.0%, respectively, relative to the AC-mixture. However, it is noteworthy that the flow value of the CR0.5% mixture lies within the designated span of 2-4 mm, deemed suitable for high-volume traffic situations [22]. The rise in flow values indicates that the CR specimens demonstrate enhanced resistance against the initiation and spread of cracking compared to the control mixture. Figure 8 (c) demonstrates the AC and CR samples' Marshall quotient (MQ). The incorporation of CR into the AC mixture decreased the MQ values. More precisely, relative to the AC mixture, CR0.5%, CR1.0%, CR1.5%, and CR2.0% mixtures set at their Optimum Binder Content (OBC) displayed 11.7%, 34.9%, 62%, and 68.2% lower MQ values, respectively. The comparatively minor reduction in the MQ values for CR mixtures may be ascribed to their increased flow and reduced stability. Nishant et al. confirmed that paving mixes with the values of MQ falling within the range of 2-5 kN/mm generally exhibit acceptable resistance against rutting and creep deformation. Mixes with very high stiffness levels demand meticulous handling, as they are more susceptible to cracking, especially when laid on weak foundations. Nevertheless, it is notable that AC-mixtures containing up to 1.5% CR content still maintain MQ exceeding 2.0 kN/mm, representing their suitability for pavement applications [31], suggesting that these mixtures possess the ability to endure rutting and creep deformation comparable to the AC mixture, despite displaying lower Marshall stability values than the control mixtures. The results suggest that the amount of binder used impacts the compaction properties of dense graded (DG) mixtures, resulting in a notable effect on the mixture density. Figure 8 (d) demonstrates that the specific gravity of the compacted mix decreases gradually as the CR content of the mix increases because the specific gravity of CR is considerably lower than the aggregate density [32], reducing the bulk density (Gmb) of the mix. Due to CR's elastic properties, mixtures behave more elastically as their CR level rises. Consequently, introducing CR lowers the Gmb of the asphalt mixture at the same compaction intensity (75 blows on each side of the Marshall specimen). Hence, more compaction efforts than the usual mixture would be required to improve the Gmb in the field construction. All CR mixtures except CR2.0% meet the minimum standards ASTM [33] and NCCL [21], specifying that an optimal binder concentration should achieve stability of 8 kN (Fig. 8 (a)).

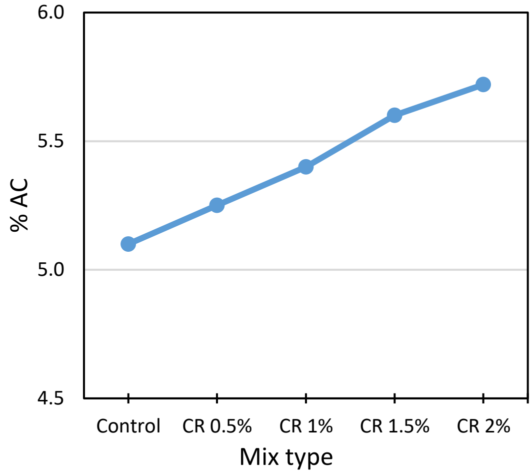


Fig. 7 Effect of Crumb Rubber Percentages on Optimum Bitumen Content in the Mix.

Table 4 Statistical Examination of Marshall Properties, ITS, and SD of AC and CR Mixtures.

Property	**AC**	**CR 0.5%**	**CR 1.0%**	**CR 1.5%**	**CR 2.0%**
Marshall stability at 60°C, kN	12.36±0.35A	11.54±0.52AB	10.62±0.36B	8.0±0.37C	6.9±0.27D
ITS at 25°C, MPa	0.947±0.0.072A	0.737±0.037B	0.67±0.129BC	0.533±0.043CD	0.471±0.029D
ITS at 60°C, MPa	0.816±0.0517A	0.519±0.0165B	0.435±0.0096C	0.316±0.0163D	0.216±0.02E
SD at 60°C, MPa	4.228±0.271A	4.201±0.25A	3.329±0.132B	2.303±0.198C	2.222±0.24C

N.B.: Means labeled with distinct letters vertically indicate a notable distinction observed at a predetermined significance level of $p<0.05$, as determined by the Fisher LSD Method.

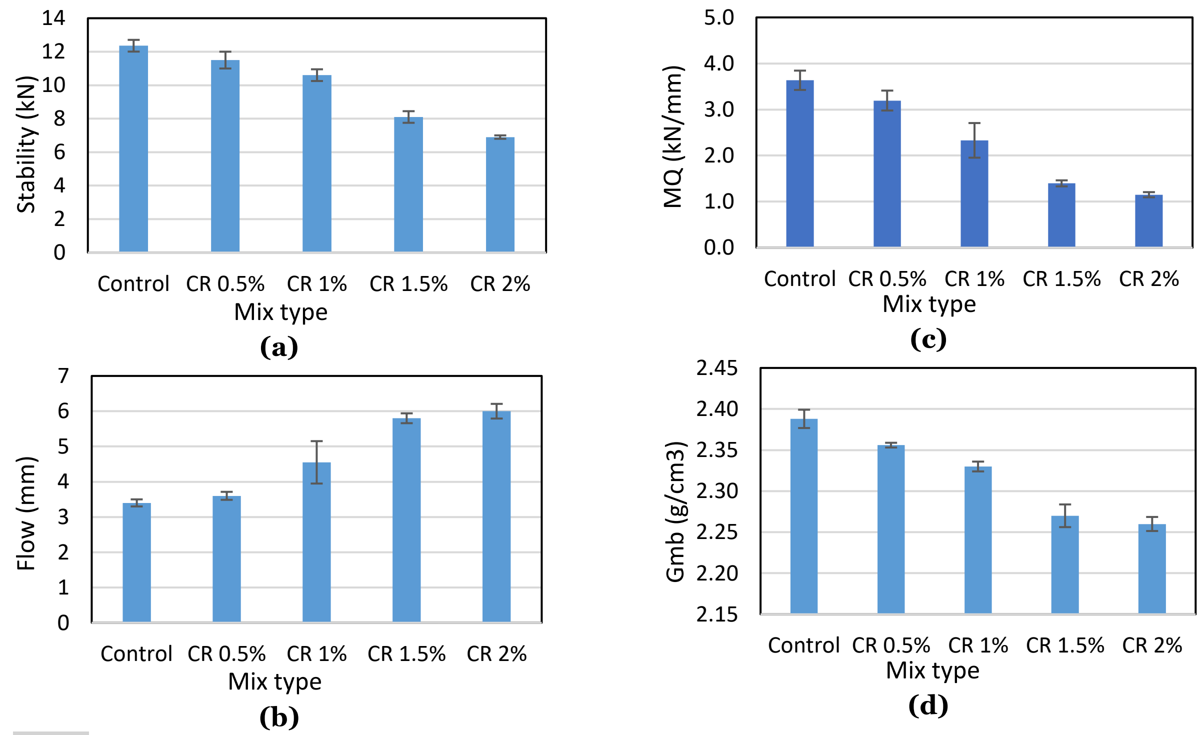
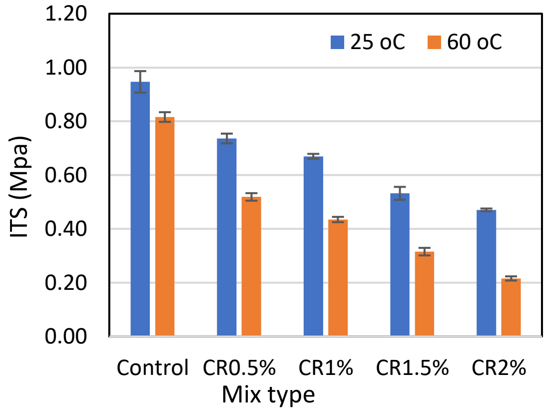


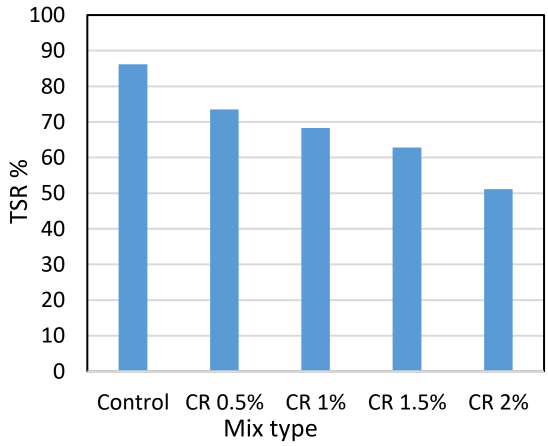
Fig. 8 Marshall Characteristics of AC and CR-Mixtures (a) Stability, (b) Flow, (c) Marshall Quotient, and (d) Bulk Density).

5.4.Indirect Tensile Strength (ITS)

To study the impact of temperature and moisture content on the tensile strength of CR mixes, the ITS test was performed. Figure 9 (a) illustrates the different blends' conditioned and unconditioned tensile strengths, providing a comprehensive view of the results. The figure illustrates that the conditioned and unconditioned CR samples exhibit lower ITS values than the control AC specimens, regardless of whether the CR samples were conditioned or not. When CR was utilized as aggregate replacement in asphalt mixtures, the unconditioned specimens' ITS values decreased, as expected. It is possible that the CR used in manufacturing the mixtures negatively impacted the elasticity of the asphalt cement at temperatures in the intermediate range. Comparable to the reference mixture, the ITS value of unconditioned samples was reduced by 22%, 29 %, 44 %, and 50%, respectively, when CR0.5%, CR1.0%, and CR1.5% and CR2.0% combinations were used. Similarly, the average values of ITS-conditioned samples with combinations of CR contents of 0.5%, 1.0%, 1.5%, and 2.0% decreased by 36.5%, 46%, 61%, and 73%, respectively. To assess the statistical significance of the disparity in ITS between the conditioned and unconditioned states, a one-way analysis of variance was also utilized. Table 4 presents the outcomes. While there was a statistically negligible difference in unconditioned ITS between CR0.5% and CR1.0%, CR1.0% and CR1.5%, and CR1.5% and CR2.0% mixtures, there was a statistically significant change in unconditioned and conditioned ITS between AC and CR-mixtures (Table 4). Nonetheless, there was statistically significant variation in conditioned ITS across all CR-mixtures. For example, the change in unconditioned ITS was relatively smaller, measuring 210 kPa. (947kPa for AC and 737kPa for CR0.5%), 67kPa (737kPa for CR0.5% and 670kPa for CR1.0%), 204kPa (737kPa for CR1.0% and 533kPa for CR1.5%), and 62kPa (533kPa for CR1.5% and 471kPa for CR2.0%), meaning that the CR0.5% and CR1.0%, CR1.0% and CR1.5%, and CR1.5% and CR2.0% mixtures had similar unconditioned ITS values. Figure 9 (b) illustrates the TSR of the treated group compared to the untreated group. This comparison was conducted so that the AC and CR combination moisture susceptibility could be further evaluated. Because the TSR of every CR mixture was less than the AC mixture, it may be deduced that these mixtures were less resistant to moisture damage. It has been discovered by other researchers that including CR in a mixture results in a reduction in the tensile strength ratio [34, 35]. Compared to the AC reference combination, the mixtures incorporating CR at 0.5%, 1.0%, 1.5%, and 2.0% exhibit TSR values decreased by 18.2%, 24.7%, 31.2%, and 46.8%, respectively. This finding suggests a significant influence of CR on moisture damage, adversely impacting the tensile properties of AC mixes. To globally identify CR mixtures that exhibit satisfactory resistance to moisture susceptibility, a commonly recommended lowest TSR value of 0.7 is often utilized. It is worth noting that this minimum value is also appropriate for selection purposes in Iraq [21]. Notably, the TSR of AC mixes containing up to 1.0% CR content was more than 0.7, indicating resistance to moisture damage, while the TSR of AC-mixture with 1.5% and 2.0% CR replacement was lower than 0.7, indicating moisture susceptible mixture. Comprehensively, these comparisons demonstrate that all CR mixtures (except 1.5% and 2.0% CR) provide moisture resistance. The explanation for the TSR reduction of the AC mixture with 1.5% and 2.0% CR replacement was that when CR content reached 1.5%, the stiffness of the asphalt mixture decreased sharply.



(a)



(b)

Fig. 9 Properties ITS of AC and CR-Mixes (a-ITS and b- TSR).

5.5.Tensile Stiffness Modulus (TSM)

Figure 10 presents the TSM values obtained under two different conditions: 25°C and 60°C. Three measurements average was calculated for each type of mixture. The findings revealed that the TSM values of the CR mixtures were less than the reference mixtures at testing temperatures of 25°C and 60°C. The TSM values with CR0.5%, CR1.0%, CR1.5%, and CR2.0% mixes evaluated at 25°C were 46.4%, 60%, 68.5%, and 77.6% less than the control AC mix, as depicted in the figure. The values TSM at CR0.5%, CR1.0%, CR1.5%, and CR2.0% combinations decreased by 58%, 74.4%, 82%, and 88.5%, respectively. This finding at 60°C is reliable with the results found from the ITS test. The MQ values supported these observations, but the TSM values of the crumb rubber samples were considerably less than those of the control mixture, indicating that the CR mixtures exhibit lower tensile strength at failure in the ITS test and are less stiff than the control mix, consequently, suggesting proportionally higher values of stresses in the CR mixtures.

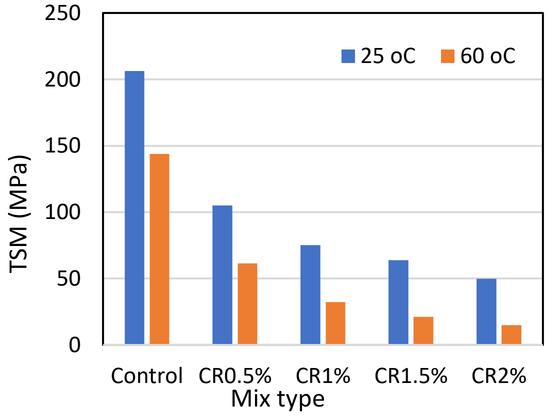
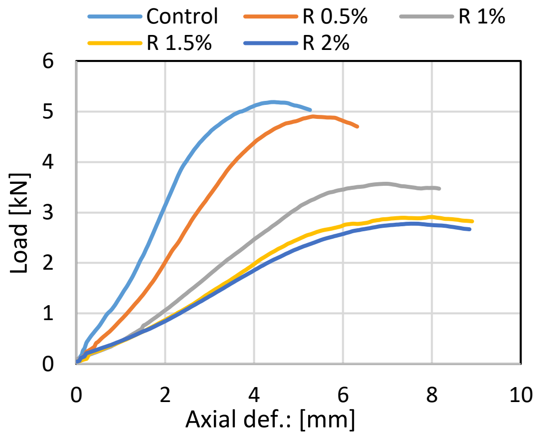


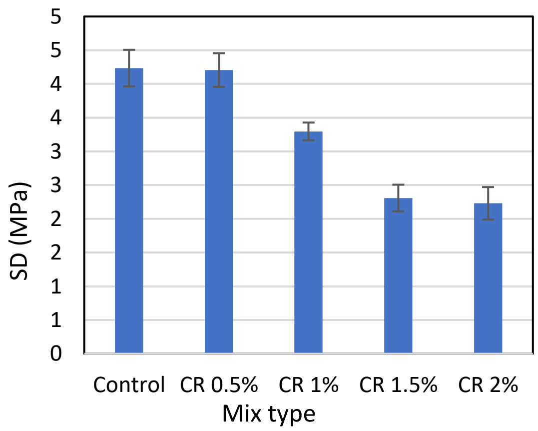
Fig. 10 TSM of AC and CR-Mixtures.

5.6.Deformation strength (SD)

Figure 11 illustrates the outcomes of the Kim test executed on the AC and CR mixes. Figure 11 (a) presents load-displacement curves. According to the findings, the peak load of every CR mixture (except CR 0.5%) was much less than that of the control mixture. Additionally, it is evident from the same figure that the control mixtures are more brittle than CR mixtures. The viscosity phase is lower in CR specimens. These observations may be drawn from the data presented in the figure. In addition, the control mixes are superior to CR in terms of their capacity to dissipate energy and absorb load, which translates to a greater ability to maintain tensile strength. It is possible that the behavior of the mixture can be explained by the fact that no microcracks were initiated or detected while the experimental work was being done until the peak load was reached. Figure 11 (b) displays the outcomes of the deformation test, which indicate the CR mixtures' resistance to rutting. Additionally, one-way analysis of variance (ANOVA) was used to examine the statistical significance of the variation in SD, with the results in Table 4. A significant statistical difference was observed between CR1.0% and AC and other CR-mixes, but not between CR1.0% and CR0.5%, CR1.5% and CR2.0%, or the remaining mixtures (Table 4). As an example, the change in SD was relatively minor, measuring 27 kPa (4228kPa for AC and 4201kPa for CR 0.5%), whereas the SD change between CR 0.5% and CR 1.0% mixtures was 872kPa (4201kPa for CR 0.5% and 3329kPa for CR 1.0%). Based on Fig. 11, it can be inferred that containing 0.5% CR does not have a notable impact on deformation strength compared to the control mixtures. While the effect of using CR was very significant on the deformation strength at 1% and more, resulting in a reduction in deformation by 22 %, 45%, and 45.6% for CR 1%, CR 1.5%, and CR 2% mixtures, respectively. These results imply that asphalt mixtures incorporating CR0.5% demonstrate a capability to withstand rutting and creep deformation at 60°C comparable to that of the AC mixture, as evidenced by the MQ values recorded at 60°C.



(a)



(b)

Fig. 11 Properties of Kim Test for Control and CR Mixes (a) Load-Deformation & (b) Deformation Strength.

5.7.Static Creep Compliance

The rise in traffic volume over the years has exacerbated the issue of permanent deformation on Iraqi roads, a critical concern. This deformation accumulates within the layers of asphalt pavements. Asphalt mixtures typically exhibit viscoelastic behavior, meaning their durability hinges on two crucial components: flexibility and viscosity. The proportions of these components are primarily influenced by many factors, such as loading duration and temperature. Figure 12 illustrates the creep test results, indicating that the CR mixtures exhibited higher deformation than the control mixtures. Specifically, specimens with CR content of 1.0%, 1.5%, and 2.0% failed after 1560, 1440, and 1140 seconds, respectively, showing similar trends. In contrast, the CR 0.5% mixture exhibited a trend similar to that of the AC mixture. Notably, the permanent deformation values for AC and CR 0.5% mixtures were measured at 0.415mm and 0.931mm, respectively, implying that the permanent deformation of the AC mixture increased by approximately 1.24 times with 0.5% CR content. This increase is attributed to the lower stiffness of the CR 0.5% mixture at 40°C. Indeed, it is customary to establish a maximum allowable permanent deformation value of 20 mm to ascertain which AC mixtures exhibit satisfactory resistance to rutting. This minimum threshold holds relevance for implementation in Iraq [21], suggesting that the CR 0.5% mixture can withstand rutting and creep deformation akin to the AC mixture, as evidenced by the MQ and SD values recorded at 60°C.

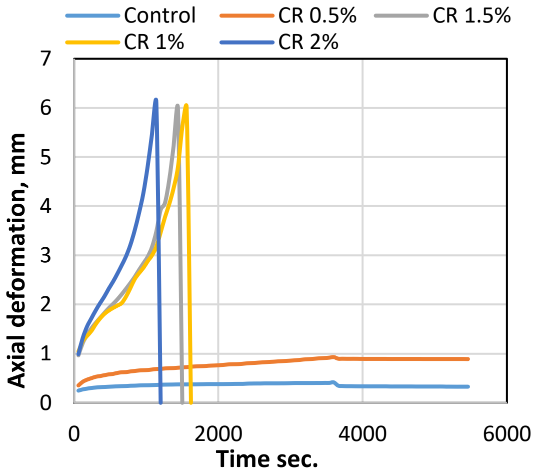


Fig. 12 Static Creep of AC and CR Mixtures.

6.CONCLUSIONS

The present study evaluates the mechanical and durability characteristics of AC mixes containing CR as aggregate replacement. The moisture damage was evaluated in terms of TSR, the cracking resistance was examined in terms of semi-circular bending (SCB), and the rutting resistance was examined in terms of deformation strength (SD) in the Kim test and static creep compliance. Based on the test results presented in this research, the following conclusions are drawn:

1- Due to CR absorbing asphalt, the optimal asphalt content of the asphalt mixture increased after CR was replaced. In contrast, bulk-specific gravity decreased after replacing CR or adding more crumb rubber to the asphalt mixture.
2- Compared to the control mix, the CR mixes showed slightly reduced stability and Marshall quotient values, along with high flow values. However, the mixtures containing 1.0% CR and 1.5% CR still met the minimum quality requirements set by ASTM and exhibited sufficient stability.
3- The CR mixes displayed lower tensile strength, TSM, and TSR than the reference mixture. Furthermore, the 0.5% and 1.0% CR mixes meet the minimum TSR criteria of 70%.
4- The CR mixtures with a CR 0.5% content demonstrated a greater capacity to resist rutting at 60°C and creep deformation at 40°C than the asphalt mixture.

Based on these findings, it can be concluded that the asphalt mixture containing 0.5–1.0% crumb rubber as aggregate replacement is a viable option for utilization in pavement construction and maintenance. These percentages depend on the total weight of the aggregates. The properties of Marshall, moisture susceptibility, and resistance to rutting all met the requirements. Moreover, the incorporation of CR in asphalt mixtures holds the potential to be more cost-effective while simultaneously conserving valuable landfill space.

ACKNOWLEDGMENTS

The author would like to thank the Duhok Construction Laboratories in Duhok, Iraq, for their invaluable technical support and the Dora refinery (located in Baghdad, Iraq) for supplying the materials utilized in this study.

DECLARATIONS

The authors have stated that they do not have any conflicts of interest.

REFERENCES

[1] Talib NB. **Use of Scrap Tires as a Substitute for Fine Aggregates in Asphalt Pavement**. B.Sc. Thesis. *National Seminar on Civil Engineering Research*; 2006.

[2] Cao W. **Study on Properties of Recycled Tire Rubber Modified Asphalt Mixtures Using Dry Process**. *Construction and Building Materials* 2007;**21**(5):1011-1015.

[3] Hernández-Olivares F, Witoszek-Schultz B, Alonso-Fernández M, Benito-Moro C. **Rubber-Modified Hot-Mix Asphalt Pavement by Dry Process**. *International Journal of Pavement Engineering* 2009; **10**(4):277-288.

[4] Shafabakhsh G, Sadeghnejad M, Sajed Y. **Case Study of Rutting Performance of Hma Modified with Waste Rubber Powder**. *Case Studies in Construction Materials* 2014; **1**:69-76.

[5] Khalili M, Jadidi K, Karakouzian M, Amirkhanian S. **Rheological**

Properties of Modified Crumb Rubber Asphalt Binder and Selecting the Best Modified Binder Using Ahp Method. *Case Studies in Construction Materials* 2019; **11**:e00276, (1-20).

[6] Radeef HR, Hassan NA, Katman HY, Mahmud MZH, Abidin ARZ, Ismail CR. **The Mechanical Response of Dry-Process Polymer Wastes Modified Asphalt under Ageing and Moisture Damage**. *Case Studies in Construction Materials* 2022; **16**:e00913, (1-15).

[7] Jomnonkwao S, Uttra S, Ratanavaraha V. **Forecasting Road Traffic Deaths in Thailand: Applications of Time-Series, Curve Estimation, Multiple Linear Regression, and Path Analysis Models**. *Sustainability* 2020; **12**(1):395, (1-17).

[8] Roberts FL, Kandhal PS, Brown ER, Lee DY, Kennedy TW. **Hot Mix Asphalt Materials, Mixture Design and Construction**. 2nd ed., New York: The National Academies of Sciences, Engineering, and Medicine; 1996.

[9] Heitzman MA. State of the Practice: Design and Construction of Asphalt Paving Materials with Crumb-Rubber Modifier. Final Report. Federal Highway Administration, Washington, DC (United States); 1992.

[10] Hicks R, Lundy J, Leahy R, Hanson D, Epps J. Crumb Rubber Modifier (Crm) in Asphalt Pavements: Summary of Practices in Arizona, California, and Florida. Interim Report. 1995: pp.

[11] Unsiwilai S, Sangpetngam B. **Influences of Particle Size and Content on Deformation Resistance of Crumb Rubber Modified Asphalt Using Dry Process Mix**. *Engineering Journal* 2018; **22**(3):181-193.

[12] Papagiannakis A, Lougheed T. **A Review of Crumb-Rubber Modified Asphalt Concrete Technology**. Research Report. 1995.

[13] Wang T, Xiao F, Zhu X, Huang B, Wang J, Amirkhanian S. **Energy Consumption and Environmental Impact of Rubberized Asphalt Pavement**. *Journal of Cleaner Production* 2018; **180**:139-158.

[14] Nguyen HT, Tran TN. **Effects of Crumb Rubber Content and Curing Time on the Properties of Asphalt Concrete and Stone Mastic Asphalt Using Dry Process**. *International Journal of Pavement Research and Technology* 2018; **11**(3):236-244.

[15] Navarro F, Partal P, Martınez-Boza F, Gallegos C. **Thermo-Rheological Behaviour and Storage Stability of Ground Tire Rubber-Modified Bitumens**. *Fuel* 2004; **83**(14-15):2041-2049.

[16] Hicks R, Takallou H, McQuillen Jr J. **Effect of Mix Ingredients on Performance of Rubber Modified Asphalt Mixtures**. B.Sc. Thesis. Alaska Department of Transportation and Public Facilities; 1985.

[17] Eltwati AS, Saad I, Elsaiti A. **The Effect of Crumb Rubber on Properties of Asphalt Mix by Dry Process**. *The International Journal of Engineering and Information Technology* 2019; **5**(1): 86-89.

[18] Roberts FL, Kandhal PS, Brown ER, Dunning RL. **Investigation and Evaluation of Ground Tire Rubber in Hot Mix Asphalt**. NCAT Report: Carolina; 1989: pp. 89-83.

[19] Buncher MS. **Evaluating the Effects of the Wet and Dry Processes for Including Crumb Rubber Modifier in Hot Mix Asphalt**. Ph.D. Thesis. Auburn University; Auburn, Alabama, USA: 1995.

[20] American Society for Testing and Materials; 2015.

[21] National Center for Construction Laboratories (NCCL) (2018) Materials and construction works specification, Ministry of Housing and Construction and Public Works. Directorate of Research and Technical Affairs, January, 2018, Baghdad-Iraq.

[22] ASTM-D6927. **Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures**. West Conshohocken, USA: Annual Book of ASTM Standards; 2015.

[23] ASTM (American Society for Testing and Materials). Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures, D6931, 2012.

[24] Al-Hadidy A. **Sustainable Recycling of Sulfur Waste through Utilization in Asphalt Paving Applications**. *International Journal of Pavement Research and Technology* 2022; **16**(2): 474-486.

[25] Al-Hadidy A, Khalid SA. **Effect of Long-Term Aging on the Tensile Strength, Flexural Strength and Creep Behaviour of Asphalt Mixtures Containing Different Wma Additives**. *International Journal of Pavement Research and Technology* 2022; **17**(2):435-445.

[26] Kim KW, Doh YS, Amrikhanian SN. **Feasibility of Deformation Strength for Estimation of Rut Resistance of**

Asphalt Concrete. *Road Materials and Pavement Design* 2004; **5**(3):303-322.

[27] Doh YS, Yun KK, Amirkhanian SN, Kim KW. **Framework for Developing a Static Strength Test for Measuring Deformation Resistance of Asphalt Concrete Mixtures**. *Construction and Building Materials* 2007; **21**(12):2047-2058.

[28] Fakhri M, Maleki H, Hosseini SA. **Investigation of Different Test Methods to Quantify Rutting Resistance and Moisture Damage of Gfm-Wma Mixtures**. *Construction and Building Materials* 2017; **152**:1027-1040.

[29] AASHTO-T322. **Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device**. American Association of State and Highway Transportation Official; 2007.

[30] SPSS. **Statistical Package for the Social Sciences**. Version 16. Chicago, Illinois, USA; 2016.

[31] Internet Source: Bhargava N, Das BP, Siddagangaiah AK. **Synergistic Influence of Aging and Moisture on Performance of Warm Mix Asphalt**. International Journal of Pavement Research and Technology 2018.

[32] Al-Ani T, Ahmed TY, Mahmood W, Al-Ani S. **Using Crumb of Tyres in Hot Asphalt Mixture as Part of Aggregate**. *Al-Rafidain Engineering Journal* 2011; **19**(2):29-39.

[33] Júnior JCDC, de Souza Campelo N, Vieira AK, Júnior JLF, Souza ES. **Dosage of Dry Mixed Rubberized Sma by Bailey Method**. *International Journal of Modern Engineering Research* 2020; **10**(1): 25-38.

[34] Ma F, Dai J, Fu Z, Liu J, Dong W, Huang Z. **A New Type of Crumb Rubber Asphalt Mixture: A Dry Process Design and Performance Evaluation**. *Applied Sciences* 2020; **10**(1): 372, (1-20).