

Experimental Study of the Effect of Crumb Rubber on Properties of Asphalt Mix by Wet Process

Kawther Y. H. Al-Soudany^{1,a*}, Humam H. Mohammed^{1,b}, Luay Y. Hussein^{1,c} and
Zaynab I. Qasim^{1,d}

¹Civil Engineering Department, University of Technology, Baghdad, Iraq

^ak.y.alsoudany@gmail.com, ^b40328@uotechnology.edu.iq, ^cbce.20.70@grad.uotechnology.edu.iq and
^d40322@uotechnology.edu.iq

*Corresponding author

Abstract. The increase in the number of vehicles during the past twenty years has dramatically increased the traffic density and axial loading. In addition to the construction failures and lack of periodic maintenance, rapid deterioration of the road condition happens. So, it was necessary to find solutions to these problems that have been growing for years. One of these solutions is to improve the asphalt mixture to resist excessive loads and weather fluctuations. This research aims to investigate the addition of crumb rubber derived from recycled tires; to the asphalt mixture for improving performance characteristics and to compare the improved and unimproved samples. It is worth mentioning that crumb rubber addition to the asphalt mixture is considered one of the smart solutions for sustainability that the world is heading towards today, considering that the crumb rubber comes from waste tires, which is difficult to eliminate and pollute the environment. Four different proportions of crumb rubber have been added in this research (6, 9, 12, and 15%); by weight of bitumen to (60-70) asphalt binder, with a particle size passing from sieve no.50 (0.3 mm). The aggregate gradation is designed according to the Marshall method with a (12.5 mm NMAS) wearing course to obtain the optimum asphalt content and to prepare laboratory samples to perform various laboratory tests. Marshall Stability and flow, indirect tensile strength (ITS), moisture susceptibility, and permanent deformation of asphaltic mixes with different contents of crumb rubber were investigated. The results of the tested samples were compared with the original samples. It is shown that the asphaltic mixes performance has been improved when adding a certain amount of crumb rubber. Marshall Stability is increased by 29.2% when adding 9% CR by the weight of bitumen. However, the addition of crumb rubber can increase the stiffness of the asphalt mixture resulting in a more rigid pavement structure that is less prone to moisture damage and rutting under traffic load.

Keywords: Bitumen; crumb rubber; rubberized bitumen; Marshall Stability; volumetric properties; rutting.

1. INTRODUCTION

The road structure has been deteriorating rapidly over the years because of increasing traffic density, axle loading, and low maintenance services [1-4]. Therefore, the asphalt mixture must be improved to reduce pavement surface deterioration and increase durability [5-7]. During the past years, researchers have improved the asphalt binder concerning performance-related properties, such as resistance to permanent deformation (rutting) and fatigue cracking [8-10]. Several asphalt modifiers and additives are used in the world today, such as styrene butadiene rubber (SBR), styrene butadiene styrene (SBS), and crumb rubber modifier (CRM) [11-12]. The ideal asphalt at high temperatures must have strength enough to resist permanent deformations and softening enough to resist excessive thermal stresses at low temperature and fatigue cracks at medium temperature [13]. Also, the polymer improving effectiveness of linear rheology depends on the polymer nature, its concentration, and the testing temperature [14].

It is worth mentioning that the use of chemicals such as (SBR) and (SBS) leads to an increase in the cost of road construction despite their effectiveness due to their high cost [11]. However, the use of crumb rubber in the asphalt mixture and its advantages, such as low cost, improvement of durability, and reducing environmental pollution, must be considered [11]. There is a real problem at the present time represented by the increasing number of waste tire disposal in the world [15]. Where the functional life of millions of tires ends and ends now in landfills [16,17]. The efficient reutilization of waste tires includes processing them into new materials, e.g., rubber powder [18]. According to environmental and economic considerations, the use of crumb rubber as a modifier should be considered to solve the waste disposal problems as well as to improve the quality of the road's pavement.

Using crumb rubber CR to enhance the asphaltic mix performance is not new, as it has been applied for several years [19]. Usually, it is added to asphaltic mixtures in two ways, the dry and wet processes [20]. In the wet process, the crumb rubber is added to the bitumen first, so the bitumen will be improved before its addition to the mix, which in return will improve the properties of the asphalt mixture, and usually, the crumb rubber is mixed with asphalt at a temperature of 191 to 218 degrees Celsius for 1 to 2 hours [19]. While in the dry process, the crumb rubber is combined with the aggregates before it is blended with asphalt. In the dry process, the amount of CR is about 2 to 4 times that used in the wet process [21]. The dry process is not very common due to the weakness of the results shown by previous studies [22]. On this basis, the researchers relied on the wet process in this research. Depending on that, the interaction between the crumb rubber and bitumen will play a major role in the results of the asphaltic mixes properties. During the crumb rubber interaction with the bitumen, the crumb rubber causes part of the aromatic fraction of the bitumen to be

absorbed, resulting in swelling in the crumb rubber particles [19]. Temperature effectively influences the particle size of crumb rubber [21]. Reducing the oily portion of bitumen leads to an increase in viscosity [19]. However, asphalt cement of 60-70 penetration grades was used in this research because its viscosity is slightly higher than that of asphalt 40-50 commonly used in Iraq's road works.

The research problem is the deterioration of some road surfaces because of the increasing number of vehicles and axle loading, lack of maintenance, and some shortcomings in construction work. Although several studies have been conducted in the field of asphalt mixes enhanced by crumb rubber, there is little sufficient knowledge in Iraq. The main objective of this research was to investigate the effectiveness of crumb rubber as a sustainable and cost-effective alternative to the properties of asphalt mixture. The following objectives have been assumed:

- a) Effect of crumb rubber on the asphalt physical properties, such as asphalt penetration, viscosity, ductility, etc.
- b) The effect of crumb rubber on the mechanical properties of asphalt mixture such as Marshall Stability and flow.
- c) The effect of adding crumb rubber to the moisture-related properties as the indirect tensile test and tensile strength ratio.
- d) Effect of crumb rubber addition on the permanent deformation resistance (rutting test).

2. METHODOLOGY AND EXPERIMENTAL WORK

To evaluate the effect of adding crumb rubber on the performance of the asphalt mixture, different percentages of crumb rubber were added to the bitumen grade 60-70 at a rate of (6, 9, 12, and 15%) by weight of bitumen with a particle size passing from sieve no.50 (0.3 mm) depending on the wet method in the mixing process. The total air voids (VTM) and stability were investigated using a theoretical maximum density test, Marshall Stability, and flow test. Furthermore, the mechanical properties of conventional and improved samples, such as Marshall Stability and flow, were evaluated. The moisture susceptibility was also investigated by using the indirect tensile test to assess the resistance of asphalt mixtures to moisture damage. Moreover, the wheel tracking machine test is used for investigating the original and modified asphalt samples resistance to permanent deformations (rutting). The materials used in this research include aggregate, bitumen, filler, and crumb rubber.

2.1 Aggregates

The aggregate used in this research contains coarse aggregate, fine aggregate, and filler. Laboratory tests such as sieve analysis according to the specifications of SCRB R-9 [23] and AASHTO [24]. Ordinary Portland cement was used as filler with a bulk specific gravity of 3.2, and the percentage of passing sieve No. 200 is 97%. A dense graded for surface wearing course of asphaltic pavement was used in this study according to the specifications of SCRB R9 [23]. Table 1 presents the physical properties of crushed aggregates.

2.2 Bitumen

An asphalt cement of 60-70 penetration grades was used in the study. It is used in road works in the northern regions of Iraq, but it has been prepared from the Dora refinery in Baghdad. The physical properties of the used asphalt were identical to the Iraqi standards specifications for roads and bridges SCRB-R9 [23].

Table 1: Physical characteristics of crushed aggregates.

Properties	ASTM Specification Coarse Aggregate	Results			
		Sieve size (mm)	G _{sb}	G _{sa}	Abso. %
Specific Gravity	(ASTM C127,128-15)	12.5	2.651	2.674	0.32
		9.5	2.585	2.591	0.09
		4.75	2.57	2.582	0.18
Los Angeles Abrasion, 30% Max	ASTM (C131-14)	19.18			
Fractured Pieces, 95% Min	ASTM (D5821-13)	97			
Fine Aggregate					
Specific Gravity	(ASTM C127,128-15)	2.36, 0.075	2.588	2.774	2.6
Clay Content by Sand Equivalent% 45 min	ASTM (D2419-14)	49			

2.3 Crumb Rubber

The crumb rubber powder, used as an additive to the asphalt, has been prepared by shredding and sieving the recycled tires. It was brought from local manufacturing plants in Baghdad. The particle size of crumb rubber powder passing from sieve no. 50 (0.3 mm), with the percentage passing from sieve no. 200 (0.075 mm) 3% - 0.7%. The rubber shape and hardness are essential as they are part of aggregates; their impact is significant on the stability of the asphalt mixtures. The standard specifications of the crumb rubber powder used in asphalt mixtures depend on the country or region. However, In the United States, the standard specifications for physical properties of crumb rubber used in asphalt mixtures are typically governed by the American Society for Testing and Materials (ASTM). For example, standards specify the distribution of particle sizes; it should normally have a particle size ranging from 0.075 mm (No. 200 sieve) to 4.75 mm (No. 4 sieve). Also, the specification may limit the content of steel wires and fibers in the crumb rubber derived from recycled tires to

ensure proper performance and avoid potential issues. In this research, ASTM D5603 [25] and ASTM D-6270 [26], which specify the physical characteristics of crumb rubber, including particle size distribution, bulk density, and specific gravity, are followed. Table 2 shows some properties of used crumb rubber.

Table 2: Test results of crumb rubber and performance requirements.*

Properties	Value	Requirement [25]
Hardness (N)	70	≥55
Density (g/cm ³)	1.3	-
Carbon black content (%)	30	25–38
Impurity content (%)	0.38	<0.75
Slender flat content (%)	7.5	≤10

* Results are taken from State Company for Rubber and Tires Industries

2.4 Asphalt mixture proportions

The wet process was used as a mixing technique in this research, where a specific quantity of crumb rubber was added and mixed with bitumen before being added to the aggregate. The crumb rubber is combined, mixed thoroughly with bitumen, and digested for 60 minutes at a minimum temperature that does not exceed 190°C in compliance with standard specifications [27]. In this research, one selected blend of aggregate gradation of (12.5 mm NMAS) was employed following SCR-B-R9 [23] and ASTM D6926-20 [28], as given in Figure 1. Then the mixed material samples were tested. Asphalt mixture specimens of CR (3, 6, 9, and 12% of the binder weight) were prepared with a diameter of 101.6mm of Marshall Moulds. The standard specifications of the Marshall samples, such as the optimum bitumen contents, density, and Marshall Stability, are presented in Table 3 [29]. Then Marshall Samples with different contents of crumb rubbers are subjected to 75 compaction blows on each side of the specimen. The optimum asphalt content is found to be 5.0%.

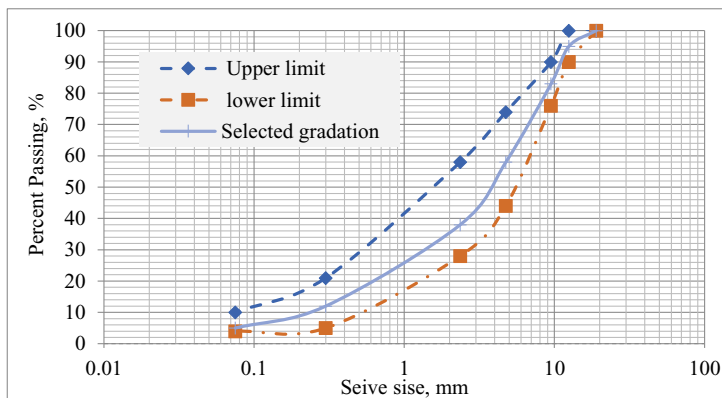


Figure 1: Gradation of aggregates.

Table 3: Criteria for asphalt institute for Marshall Mix design [29].

Compaction (Blows)	Traffic Level					
	Light		Medium		Heavy	
	35		50		75	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Stability, kN (lb)	3.34 (750)		5.34 (1200)		8.01 (1800)	
Flow, 0.25 mm (0.01 in.)	8	18	8	16	8	14
Air Voids, %	3	5	3	5	3	5
VFA, %	70	80	65	78	65	75

3. EXPERIMENTAL RESULTS AND DISCUSSION

The effect of adding crumb rubber powder with different contents in bitumen was assessed. Marshall Stability and flow were investigated with different crumb rubber percentages to determine the maximum load carried by the compacted sample at a temperature of 60°C. As well as the effect of adding various proportions of crumb rubber to bitumen. The moisture susceptibility test was used to examine the effect of moisture on rubberized asphalt mixtures. Also, the resistance of various rubberized asphalt mixtures to rutting are evaluated using the wheel tracking test.

3.1 Physical Properties of Rubberized Bitumen

Results of the physical properties of original and modified asphalt with different contents of crumb rubber are presented in Table 4. Based on the results obtained, it was concluded that crumb rubber significantly affects the bitumen stiffness and elastic properties. Penetration of studied specimens was reduced by

increasing crumb rubber content. It is decreased by (6.25, 12.5, 18.75, and 25%) for adding crumb rubber of (3, 6, 9, and 12%) by the binder weight, respectively. The reason is back to the interaction between rubber and asphalt binder. In addition, the adsorption of the maltene phase by crumb rubber particles increases the asphaltene part of the bitumen and causes swelling through the blending process. Furthermore, the crumb rubber particles stiffness is more than bitumen. Hence, increasing the crumb rubber content leads to increased stiffness.

It was also observed through the results an increase in bitumen viscosity, representing a measure of flow resistance at a temperature of 135°C. It is increased by (12.5, 46.8, 65.6, and 71.8%) when adding (3, 6, 9, and 12%) of crumb rubber powder, respectively. The reason is that the crumb rubber absorbed the light oily components of bitumen through the interaction process, which caused the decrease in viscosity. Also, an increase in the softening point, which represents the temperature at which asphalt reaches softening, was observed. It is increased by (3.9, 5.8, 11.7, and 19.6%) when adding (3, 6, 9, and 12%) crumb rubber powder by wt. of bitumen, respectively. It is found a consistent relationship between the viscosity and softening point of rubberized bitumen; it is concluded that increasing rubber content leads to increasing both viscosity and softening point, indicating that rubberized bitumen would be less sensitive to high-temperature change and more resistance to rutting. The increase in the penetration index also proves this. As presented in Table 4, the penetration index increased with crumb rubber content. Therefore, the temperature susceptibility of rubberized asphalt is reduced by CR increasing. Asphalt with low-temperature susceptibility is more resistant to rutting and thermal cracks.

Table 4: Effect of crumb rubber contents on asphalt binder's physical properties.

Test	Origin value	SCRB -R9 specification	Test Results of CR Binder				Stand. Req. for modified binder
			3% CR	6% CR	9% CR	12%CR	
Penetration @25°C,100 gm, 5 Sec	64	(40-50)	60	56	52	48	Min. 20
Viscosity @135°C, (Pa.s)	0.32	-	0.36	0.47	0.53	0.55	-
Softening Point (4±1) °C /min, (°C)	51.0	-	53	54	57	61	-
Penetration Index	-0.5	-	+0.25	+0.3	+0.6	+1.2	-3 to +3
Flash Point (°C)	263	>232	270	275	278	280	>232
Ductility @25 °C, 5 cm/min, (cm)	151	>100	140	127	121	115	>100
Specific Gravity	1.03	(1.01-1.05)	1.03	1.03	1.03	1.03	>1.0

Moreover, the ductility of the rubberized asphalt samples decreased with the increase in the crumb rubber powder percentage. It is decreased by (7.28, 15.8, 19.8, and 23.8%) when adding (3, 6, 9, and 12%) crumb rubber powder by weight of bitumen, respectively. The reason may be the reduction of oily materials in bitumen because of their absorption by the fine rubber particles leading to a toughness increase resulting in less ductility with an increase of rubber content, in addition to an increase in the mass of the rubber particles. Accordingly, increasing the asphalt binder mass can increase the binder flexibility, toughness, and resistance to cracking. It is worth noting that the rubberized asphalt becomes thicker than the original asphalt sample.

3.2 Check for Marshall Stability and Flow

Results show that Marshall's stability increased slightly with increased crumb rubber content. Stability represents the maximum load required to produce specimen's failure when load is applied at a constant rate. It is noted that it is increased by (5.8, 17.6, 29.4, and 25%) when CR is added by (3, 6, 9, and 12%), respectively, as shown in Figure 2-a. However, the values of Marshall's stability at the different ratios of crumb rubber satisfy the specifications for the maximum stability value [30]. The increase is due to the increase in the viscosity of rubberized asphalt, which consequently increases the bonding force between the aggregates and asphalt at high temperatures. Since the stability is primarily affected by the internal friction of aggregates and the viscosity of bitumen, the addition of crumb rubber powder will improve the mechanical properties of the asphalt mixture.

It was also observed that the stability value gradually decreased when the rubber content exceeded 9%. It is believed that the reason is due to the low resistance of the fine rubber particles, which will affect the strength of the total mixture if it exceeds a certain percentage. Figure 2-b illustrates the results of adding crumb rubber on Marshall Flow which refers to the vertical deformation of the sample (measured from the start of loading to the point at which stability begins to decrease in 0.25 mm). It is observed that flow decreased slightly with increasing crumb rubber content. However, all flow values are more significant than the local standard specification's minimum value (2 mm) . This decrease indicates that the asphalt mix will resist deformation under exposed traffic because the crumb rubber increases the cohesion of bitumen material. It maintains the fine materials that would increase the mixture's hardness, increase the asphalt mixture's stability, and reduce the flow.

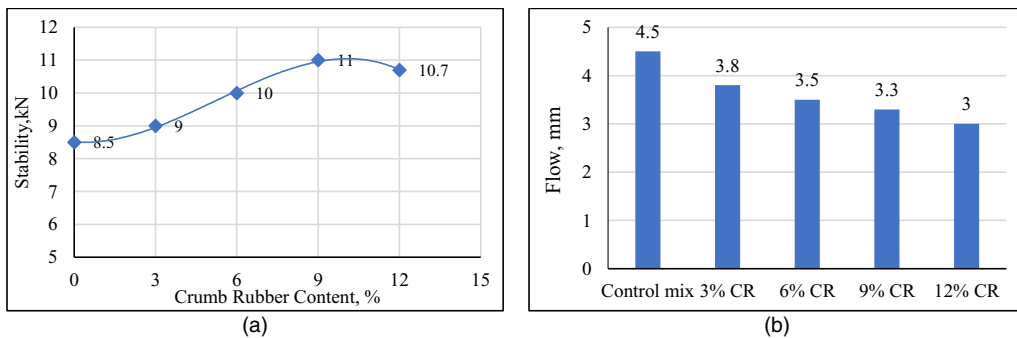


Figure 2: Effect of the crumb rubber on (a) Marshall Stability (b) Marshall Flow.

3.3 Check for Indirect Tensile Strength and Moisture Susceptibility

The moisture susceptibility test was applied in compliance with AASHTO T283 to investigate the moisture damage potential of asphaltic mixes, as well as to measure the indirect tensile strength at two temperatures, 25°C and 60°C, through apply of diametric load to a cylindrical specimen at deformation speed of 50 mm/minute. Figure 3-a) shows the result of indirect tensile strengths of the original and rubberized asphalt mixture. It is observed that adding crumb rubber powder to the asphalt mix causes an enhancement in the indirect tensile strength. It was concluded that it is increased with increasing of the crumb rubber content. ITS was increased by (7.4, 10.5, 20.4, and 29.3%) for adding (3, 6, 9, and 12%) of crumb rubber, respectively, at 25°C (77°F). At the same time, ITS increased by (4, 13.7, 21, and 27) for adding (3, 6, 9, and 12%) of crumb rubber, respectively, at 60°C (140°F).

Figure (3-b) shows that rubberized samples have higher TSR values than original asphalt mixtures. It is noted that TSR increased with CR content increasing, which means that the rubberized asphalt mixtures have less susceptibility to moisture damage. It is increased by (2.7, 6.1, 8.6, and 9.7%) by adding (3, 6, 9, and 12%) of crumb rubber, respectively. The reason may be the chemical modification of the bitumen adhesion leading to capacity improvement of binder absorption. Moreover, crumb rubber particles have hydrophobic properties, meaning they repel water. When added to asphalt, they can form a barrier that helps reduce water penetration into the asphalt binder. By enhancing moisture resistance, adding crumb rubber to asphalt can help extend the service life of asphalt pavements and reduce maintenance needs.

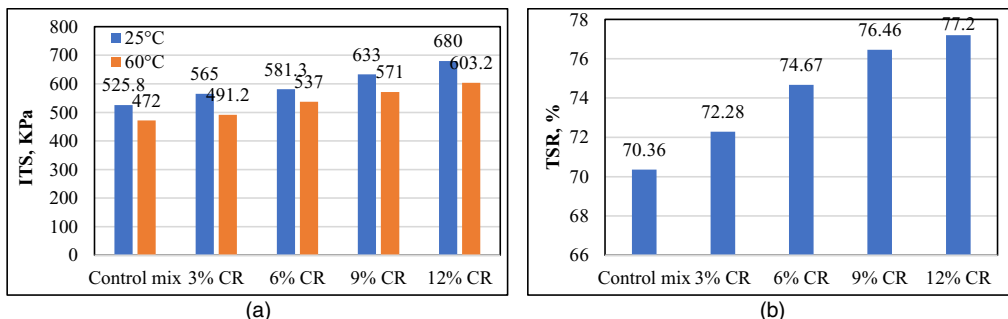


Figure 3: Effect of the crumb rubber on (a) ITS (b) %TSR.

3.4 Check for Permanent Deformation (Rutting Resistance)

Rutting test is performed on control and rubberized asphalt slabs using a wheel tracking test according to AASHTO: TP-63 [31], to evaluate the compacted specimen's resistance to rutting under loading through passing a loaded wheel over the sample. The test temperature was 50°C, and the rutting depth values are recorded at successive 2000, 3000, 4000, and 10000 cycles. Figure 4 shows the effect of crumb rubber powder on the rutting depth of asphalt compacted samples. It is observed that rubberized asphalt samples have better resistance to rutting than control samples. Furthermore, the permanent deformation resistance increased as the percentage of crumb rubber content increased. It is also noted that rubberized asphalt samples with 12% crumb rubber addition showed higher rutting resistance than other samples. The reason may be that the crumb rubber particles have rubber-like properties, including higher elasticity than conventional aggregate materials. The rubber particles can absorb and dissipate stress, reducing the pavement's magnitude and extent of permanent deformation. This enhanced elasticity can help minimize rutting in the asphalt mixture. In addition, crumb rubber is blended with the asphalt binder, resulting in a modified binder with improved resistance to high-temperature deformation. The rubber particles act as reinforcement within the binder matrix, reducing the

flow and deformation characteristics of the asphalt mixture at elevated temperatures. This can mitigate rutting by providing a more stable and resilient binder.

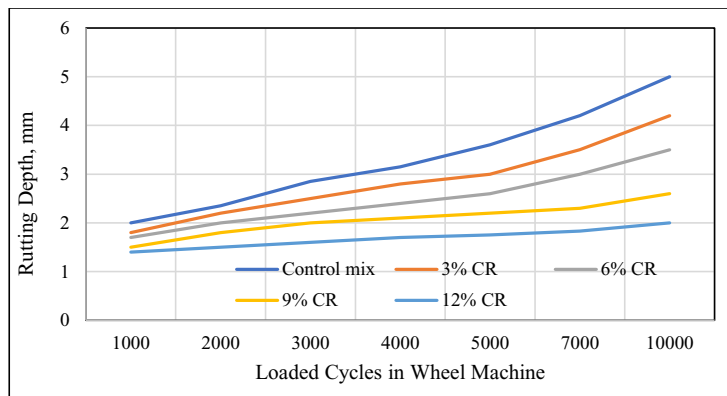


Figure 4: Effect of crumb rubber content on samples rutting depth.

4. CONCLUSIONS

Based on laboratory results related to the addition of rubber powder with four ratios (3, 6, 9, and 12%) by the weight of bitumen using the wet process and its effect on the asphalt mixture properties, the following conclusions can be drawn:

- The crumb rubber addition to bitumen modifies asphalt binder properties, making it more flexible and elastic. This increased flexibility can help the mixture withstand traffic loads and reduce the formation of cracks.
- Marshall's stability increased with the increase of crumb rubber content. The rubber particles act as reinforcement, reducing the flow and increasing the resistance of the asphalt mixture to deformation under traffic loading, in addition to increasing the elasticity and flexibility of the asphaltic mixture. Modified asphalt samples with 9% CR yielded the highest value of Marshall's stability.
- Crumb rubber enhanced the moisture resistance of the asphaltic mixture. The rubber particles repel water and can help reduce moisture damage, such as stripping or moisture-induced cracking. Modified asphalt samples with 12% CR yielded the highest tensile strength ratio TSR value and had the best moisture damage resistance.
- The mixture resistance to permanent deformation or rutting is enhanced when crumb rubber is added to asphalt. It is increased as crumb rubber contents increase. That means that rubber particles can absorb and distribute the applied load more effectively, reducing the potential for rut formation under high temperature.
- Using crumb rubber in asphalt mixtures offers environmental benefits through recycled materials that would otherwise end up in landfills. This helps to reduce waste and conserve natural resources.

REFERENCES

- [1] Q. Liu, J. Xie, and Z. Zhang. A vehicle fuel consumption model on reconstructed roads based on the roughness and its measurement method. *Advances in Civil Engineering*. 2021.
- [2] H. H. Joni, A. A. Mohammed, A. A. Shakir. Classification of Traffic Accidents datasets between 2003 - 2017 in Iraq. *Data in Brief*. 2019; 28(1):104902. DOI: 10.1016/j.dib.2019.104902.
- [3] H. H. Joni. Most Distresses Causes in Flexible Pavement for Baghdad Streets at Last Years. *Engineering and Technology Journal*. 2010; 28(18): 894-906.
- [4] S. A. Sultan. Damaging Effect of Armoured Vehicles with Rubber Tires on Flexible Pavement. *Engineering and Technology Journal*. 2010; 28(17): 5568-5580.
- [5] Mashaan N. S., Ali A. H., Karim M. R. and Abdelaziz M. An overview of crumb rubber modified asphalt. *International Journal of the Physical Sciences*. 2012; 7(2): 166 – 170. DOI: 10.5897/IJPSX11.007
- [6] H. H. Joni, H. H. Zghair, A. A. Mohammed. Rutting Parameters of Modified Asphalt Binder with Micro and Nano-Size of Metakaolin Powder. *Journal of Engineering Science and Technology*. 2020; 15(5): 3465 - 3480.
- [7] Abdelgalil, A. and H. Nor. The Influence of Block Thickness on the Performance of Asphalt Paving Blocks. *Research Journal of Applied Sciences, Engineering and Technology*. 2014; 7(10): 2129-2134.
- [8] Mashaan NS, Ali AH, Karim MR, Mahrez A. Effect of crumb rubber concentration on the physical and rheological properties of rubberised bitumen binders. *Int. J. Phys. Sci*. 2011; 6(4): 684-690.
- [9] A. H. Abed, Z. I. Qasim, H. M. Al-Mosawe, and H. H. Norri. The Effect of Hybrid Anti-Stripping Agent with Polymer on the Moisture Resistance of Hot Mix Asphalt Mixtures. *Cogent Engineering*. 2019; 6 (1). DOI: 10.1080/23311916.2019.1659125.

- [10] H. H. Joni and A. Hussein, Evaluation The Moisture Sensitivity of Asphalt Mixtures Modified with Waste Tire Rubber. IOP Conference Series Earth and Environmental Science. 2022; 961(1):012029. DOI:10.1088/1755-1315/961/1/012029
- [11] Hamed FK. Evaluation of fatigue resistance for modified asphalt concrete mixture based on dissipate energy concept. Ph.D. Thesis, Technische University Darmstadt, Germany. 2010.
- [12] Al-Azawee E.T, Qasim Z. I. The influence of crumb rubber modifier (CRM) on the properties of asphalt concrete mixtures. Int. Journal of Civil Eng. and Technology. 2018; 9(10): 201-212.
- [13] F. M. Nejad, P.A., A. Modarres, H. Firoozifar. Investigating the properties of crumb rubber modified bitumen using classic and SHRP testing methods. Construction and Building Materials. 2012 26 (1): 481-489.
- [14] Navarro, FJ, Partal P, Garcia MM, Martin-Alfonso MJ, Martinez BF, Gallegos C, et al. Bitumen modification with reactive and non-reactive (virgin and recycled) polymers: a comparative analysis. J. Ind. Eng. Chem. 2009; 15(4):458–464.
- [15] Adhikari B, De D, Maiti S. Reclamation and recycling of waste rubber. Progress in Polymer Science. 2000; 25(1): 909- 948.
- [16] Nea.gov.sg, Waste Statistics and Overall Recycling, (2016).<http://www.nea.gov.sg/energy-waste/waste-management/waste-statistics-and-overall-recycling>
- [17] Abdul R. Kamel; Ahmed H. Ali; Nahedh Mahmood; Mohammed M. Kadhum. Effect of the Waste Rubber Tires Aggregate on Some Properties of Normal Concrete. Engineering and Technology Journal. 2022; 40(1): 275-281.
- [18] Ariyapijati R H, Hadiwardoyo S P, Sumabrata R J. Skid resistance of gap graded hot-mix asphalt with added crumb rubber. Conf. Series: Journal of Physics. 2018; 1376(1). doi:10.1088/1742-6596/1376/1/012010.
- [19] H. Takallou, J. McQuillen, and R. Hicks. Effect of Mix Ingredients on Performance of Rubber-Modified Asphalt Mixtures. Alaska DOT and Public Facilities, Fairbanks, AK. 1985.
- [20] F. Navarro, P. Partal, F. Martinez-Boza, and C. Gallegos. Thermo-rheological behaviour and storage stability of ground tire rubber-modified bitumens. Fuel. 2004; 83(14): 2041-2049.
- [21] F. L. Roberts, P. S. Kandhal, E. R. Brown, and R. L. Dunning. Investigation and evaluation of ground tire rubber in hot mix asphalt. National Center for Asphalt Technology. 1989.
- [22] M. S. Buncher. Evaluating the Effects of the Wet and Dry Processes for Including Crumb Rubber Modifier in Hot Mix Asphalt. DTIC Document. 1995.
- [23] SCRB/R9. General Specification for Roads and Bridges, Section R/9, Hot-Mix Asphalt Concrete Pavement, Revised Edition. State Corporation of Roads and Bridges, Ministry of Housing and Construction, Republic of Iraq. 2003.
- [24] AASHTO Guide for Design of Pavement Structures. The American Association of State Highway and Transportation Officials, Washington, D. C., USA. 2010.
- [25] ASTM- D6270. Standard Practice for Use of Scrap Tires in Civil Engineering Applications, Annual Book of ASTM Standards: 7. 2020.
- [26] ASTM D5603. Standard Classification for Rubber Compounding Materials—Recycled Vulcanizate Rubber, Annual Book of ASTM Standards: 7. 2019.
- [27] Specification 516, Crumb Rubber Open Graded Asphalt, Main roads of western Australia, vol. 20/3018. 2020.
- [28] ASTM D-6926. Standard Practice for Preparation of Asphalt Mixture Specimens Using Marshall Apparatus, Annual Book of ASTM Standards: 7. 2020.
- [29] Asphalt Institute. The Asphalt handbook, 2001 ed. (Manual series, no. no 4 (MS-4)). College Park, Md., USA: Asphalt Institute. 2001.
- [30] ASTM-D 6927. Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures, Annual Book of ASTM Standards: 7. 2015.
- [31] AASHTO-TP63. Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) using the Asphalt Pavement Analyzer (APA), USA. 2007.