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The Effect of Short-Term Aging on Warm Mix Asphalt Moisture Performance

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Abstract

Warm Mix Asphalt (WMA) is a good pavement option due to its environmental benefits. Short-term aging is one of the critical factors that the WMA should carefully study. This research aims to study the effect of short-term aging on the warm mix asphalt that has different percentages of rubber. In this study, three percentages of rubber (1, 1.5, and 2%) by weight of aggregate are considered to be added to the WMA. By use of the Indirect Tensile Strength test for HMA, WMA unmodified and modified with CR that is exposed to an aging protocol to assess the sensitivity of asphalt mixture to moisture damage. The results show that HMA is less sensitive to moisture than WMA, and the addition of crumb rubber to WMA generally improves the resistance to moisture compared with WMA with 0% of rubber. However, as the rubber content increases to 2%, the resistance starts to decrease. Finally, SEM images were taken of rubber particles, WMA with and without rubber to investigate the changes occurring to the mixtures.

Keywords: WMA; Short-Term Aging; Crumb Rubber; Moisture Damage; SEM Images.

1. Introduction

Asphalt is a hydrocarbon material obtained from crude oil refining. It has solid, semi-solid, and liquid forms according to the conditions exposed to them. Asphalt pavement has properties viscous-elastic to the binder. This characteristic causes a change in the properties of the pavement with the change in the surrounding conditions. In addition to the variation in traffic loads, the pavement is subject to deformations that may be due to the aging of the asphalt binder, which causes an increase in the viscosity of the asphalt binder that makes the pavement brittle and may be fracture [1, 2]. Mixing asphalt binder with aggregates after reducing its viscosity to obtain sufficient viscosity to convert it from a solid to a liquid state with sufficient viscosity to coat the aggregate particles and bond them to obtain cohesive pavement that has satisfactory performance properties, which produces kinds of asphalt pavement such as hot mix asphalt pavement, warm mix asphalt pavement, and cold mix asphalt pavement [3].

Nikolaides [3] HMA produces flexible pavement with high stability and durability compared to CMA. CMA is used in the lower pavement layers of roads with low traffic volumes. After the besieged development in the asphalt pavement industry a mixture was produced that carries the properties of HMA with its functional performance, combining with it the benefits of using CMA with its environmentally friendly properties because it is produced at atmospheric temperature [4]. So, WMA technology was invented. It is produced at a temperature approximately 15–40 °C (59–104 °F) lower than HMA, depending on the type of additives adopted to produce WMA that reduce the viscosity of the asphalt binder [5].

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The warm mix asphalt was produced by reducing the mixing and compaction temperatures compared to the hot mix asphalt. This process is carried out using techniques that reduce the viscosity of the asphalt to obtain satisfactory workability to make the best coating of the asphalt binder around the aggregate particles. These technologies are organic, chemical additives in addition to foamed asphalt [6, 7]. WMA is a technology that began to appear in Germany in the late 1900s and became an important focus of research in 1975. The focus became the production of asphalt pavement with an environmentally friendly production technology with low emissions that cause global warming. Table 1 shows the reduction in gas emissions due to using WMA technology. In 2002, the implementation of the WMA began. Then it entered the United States of America in the same year, after which it found widespread use due to the environmental and economic benefits it provides, as well as comfort and ease during production [8].

Table 1. Emission reduction when implementation of WMA [1]

Air Pollutant Gaseous	Reduction Measured as Compared to HMA
CO_2	15-40%
SO_2	18-35%
NO_X	18-70%
CO	10-30%
Dust	25-55%

Sarsam [9] showed that CMA produced a low bulk density compared to HMA and WMA. The indirect tensile strength was lower with WMA and CMA compared with HMA. CMA was less punching shear strength than WMA and HMA. Abdul Mahdi et al. [10] investigated the effect of moisture damage on the physical properties of the WMA. It showed that with the increase in the asphalt content, the shear strength, indirect tensile strength, and stability decreased. In contrast, the flow increases with the rise in asphalt content, and stiffness increases to the limit of the optimum asphalt content, then decreases. Zhao et al. [11] found that the WMA production technique produced good moisture damage resistance with high proportions of RAP. Abed et al. [12] verified the effect of organic and chemical additives on the properties of WMA. The results showed that both of the used additives delayed the aging of WMA. Rondón-Quintana et al. [13] evaluated the laboratory results of moisture sensitivity and stiffness of WMA and compared them with HMA. This laboratory work produced excellent resistance to moisture damage and service temperature when using asphalt pavement where the air voids were higher in HMA compared to WMA and decreased by increasing the percentage of WMA technology additive. In addition, it reduces cracks and improves fatigue resistance. Moreover, this study showed that the WMA has a lower rutting depth than the HMA. Namaa et al. [14] evaluated the effect of styrene butadiene styrene (SBS) addition on the volumetric and mechanical properties of an asphalt mixture. Indirect tensile strength (ITS), Marshall Stability and flow were evaluated. The results show that the addition of polymer (SBS) leads to improvements in the properties of the modified asphalt mixtures, Marshall and moisture sensitivity. Some studies have used additives to modify the properties of asphalt binder and asphalt mixture and thus improve its resistance to moisture damage that causes failure of asphalt paving such as rutting and fatigue. The materials used were carbon fibres [15], Nano clay with montmorillonite [16], Polypropylene Fibers [17], Steel Fibres [18], Ceramic Fibre and Hydrated Lime [19], and other materials that can improve the moisture resistance of the asphalt mixture.

Polymeric materials can be used to improve the properties of asphalt binder and asphalt mixture. Rubber is a type of polymer because of its elastic properties. In addition, the availability of rubber in large quantities because of the development of traffic led to an increase in vehicle tire waste [20, 21]. Since the middle of the last century, rubber has been used in asphalt pavement at MacDonald's to improve the performance of asphalt pavement [22]. It was used in Sweden and intended to increase the skid resistance and durability of asphalt paving under the name Skega asphalt, or Rubit in northern Europe. Then in 1978, it moved to the United States under the name "Plus Ride," where rubber was used as an elastic aggregate to increase the flexibility of the asphalt pavement under the influence of loads to increase the stiffness of the pavement [23]. Al Qadi et al. [24] have shown that rubber in asphalt pavement enhances durability and resistance to cracking and permanent deformation and reduces moisture sensitivity in addition to its ability to absorb noise. It was used in China as a micro-surface to reduce noise resulting from the movement of vehicles. Preparing rubber crumbs from scrap rubber tires includes cutting the outside of the tire frame into small parts using a sharp knife, washing them with water, and then exposing them to air to dry. They are grinded, crushed into small pieces and even obtained crumb rubber of the required sizes [24]. There are two standard methods available to prepare rubberized asphalt binder and crumb rubber asphalt mixtures: dry and wet. The dry method means using crumb rubber as part of the aggregate in the asphalt mixture to produce aggregate rubber [25]. The wet process combines the crumb rubber with the asphalt binder in the mixing containers and allows them to react at a set temperature of 175 to 210 °C (350 to 400 °F) for a set time of 45 to 60 min to produce rubberized asphalt [26].

Arya & Prakash [21] and Baumgardner et al. [27]: these studies show the effect of crumb rubber on the performance characteristics of HMA, as they show that an increase in the proportion of crumb rubber increases the viscosity of the asphalt at 135 °C and improves the properties of rutting and fatigue. It also showed that an increase in the percentage might lead to an increase in the softening point and a decrease in durability and penetration at 25 °C (77 °F). Qadir Ismael [28] evaluated the role of crumb rubber modified for the properties of the asphalt binder and asphalt mixture. It also produced an increase in the viscosity of the asphalt binder based on the decrease in penetration at a temperature of 25 °C (77 °F) and an increase in the softening point, in addition to improving the resistance to crack fatigue. Hashimi et al. [20] demonstrated the effect of the percent of rubber crumbs added to modify the properties of the asphalt mixture to resist crack fatigue at low and medium temperatures. It was found that increasing the percentage of rubber improved the fracture resistance of the asphalt mixture before cracks occurred at low and medium temperatures. Gibreil & Feng [29] investigated the effect of adding high-density polyethylene and crumb rubber on the performance of asphalt pavement. It shows decreased penetration at a temperature of 25 °C (77 °F) with an increase in the content of crumb rubber and high-density polyethylene crumbs. At the same time, there was an increase in the softening point that indicates an increase in deformation resistance between moderate and high temperatures with an increase in the content of the used additive. Abdul Hassan et al. [30] proved that using crumb rubber as an effective additive to modify the properties of the asphalt mixture. Laboratory tests were carried out to evaluate the properties of the modified rubber crumbs added to the asphalt mixture using the dry method by adding coarse and fine rubber with a percentage of 0, 1.5, and 2.5% of the aggregate weight. The results of the volumetric property and Marshall Test showed that fine crumb rubber have a better effect on the asphalt mixture than the other mixtures.

2. Materials

To prepare asphalt samples, locally available materials will be used, which are asphalt, aggregate, and mineral fillers, as materials conforming to the Iraqi specification SCRB (R/9, 2003) [31].

2.1. Asphalt Cement

The asphalt cement was obtained from Al-Daurah refinery, located southwest of Baghdad, and had a penetration grade of (40-50). Table 2 shows the physical properties and tests of the asphalt cement used in this work.

Table 2. Physical Properties of Asphalt Cement

Property	ASTM Designation	Test result	SCRB specification [31]
Penetration at 25 °C, 100 gm, 5 sec. (0.1 mm)	D-5 [32]	47	(40-50)
Ductility at 25 °C, 5 cm/min. (cm)	D-113 [33]	145	>100
Flash point (Cleveland open cup), (°C)	D-92 [34]	321	Min.232
Softening point, (°C)	D-36 [35]	56	-
Viscosity @ 135 °C, c.p	D-4402 [36]	450	Min.400
Viscosity @ 165 °C, c.p	D-4402 [36]	145	-
Specific gravity at 25 °C	D-70 [38]	1.03	-

2.2. Aggregate

The aggregate used in this research is a crushed aggregate that has been produced at the Al-Nibaie quarry, which is located north of Baghdad. The used aggregates satisfy the specifications for fine and coarse aggregates to meet binder course gradation as required by State Corporation for Roads and Bridges (SCRB) specifications (R9/2003) [31]. Table 3 shows the physical properties and tests of aggregate that were used in this work.

Table 3. The physical properties of the coarse aggregate

Property	ASTM Designation	Coarse aggregate	Fine aggregate	Specification
Bulk Specific Gravity	C-127, [38] C-128 [39]	2.61	2.62	-
Apparent Specific Gravity	C-127 [38], C-128 [39]	2.67	2.68	-
Percent Water Absorption	C-127 [38], C-128 [39]	0.94	0.91	-
Toughness, by (Los Angeles Abrasion)	C-131 [40]	20.80%	-	Max. 30%
Soundness loss by sodium sulfate solution%	C-88 [41]	4.10%	-	Max 12 %

2.2.1. Coarse Aggregate

The coarse aggregate (crushed) was brought from Al-Nibaie quarry. The gradation of coarse aggregate for binder course ranges between 1 in. (25.0 mm) and No.4 sieve (4.75 mm) according to SCRB R/9 (2003) specification [31]. The physical properties of the coarse aggregate shown in Table 3.

2.2.2. Fine Aggregate

The fine aggregate was brought from the Al-Nibaie quarry. The gradation of fine aggregates ranges between passing 4.75 mm (No.4) sieve and retaining on 0.075 mm (No.200) sieve. The physical properties of the fine aggregate are shown in Table 3.

2.3. Mineral Filler

Portland cement, available locally, used as a filler in this work. It was obtained from Al-Mas Company-Iraq. Table 4 shows the physical properties of Portland cement that passed through sieve No. 200 (0.075 mm).

Table 4. The physical properties of Portland cement

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

2.4. Aspha-Min (Zeolite)

Zeolite (shown in Figure 1) is a white powdery substance that is added in proportions of 0.3 of the total mass of the asphalt mixture as an additive to produce warm asphalt mixes. The imported zeolite has physical and chemical properties according to the information attached to it from the manufacturer (as shown in Table 5).

Figure 1. Aspha-min (Zeolite) powder

Table 5. Physical and chemical properties of WMA additive, zeolite

Property	Results
Ingredients	**Na_2O. Al_2O_3.2 SiO_2 (sodium aluminosilicate)**
SiO_2	32.80%
Al_2O_3	29.10%
Na_2O	16.10%
LOl	21.20%
Physical state	Granular powder
Color	White
Odor	Odorless
Specific gravity	2.03

2.5. Crumb Rubber

The rubber crumbs used in this research were brought from Al-Kut Towers Company (Al-Diwaniyah Tires Factory) affiliated to the Iraqi Ministry of Industry and Minerals. Where the ratios 1, 1.5, and 2% of the total weight of the asphalt mixture used, the fine aggregate replaced with a size NO.8 and NO.50 as shown in Figure 2, the Table 6 shows the properties of the rubber crumbs used.

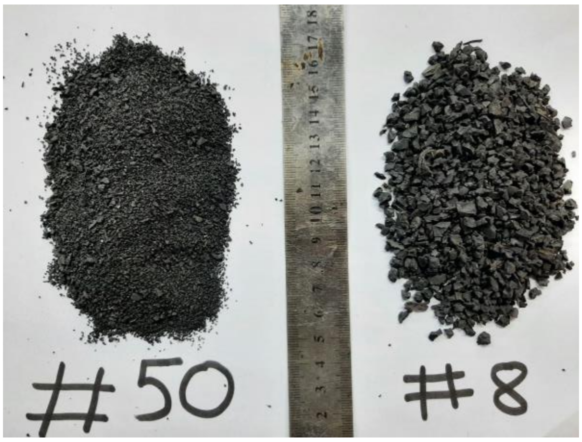


Figure 2. Sizes of crumb rubber used in this work

Table 6. The properties of the rubber crumbs

Property	Test results
Specific gravity	1.15
color	black

3. Selection of Aggregates Gradation

According to the Iraqi State Corporation for Roads and Bridges [31], the maximum size of the aggregate selected for the aggregate gradation used in asphalt concrete mix for the laboratory specimens for binder course was 25.0 mm, as shown and Figure 3.

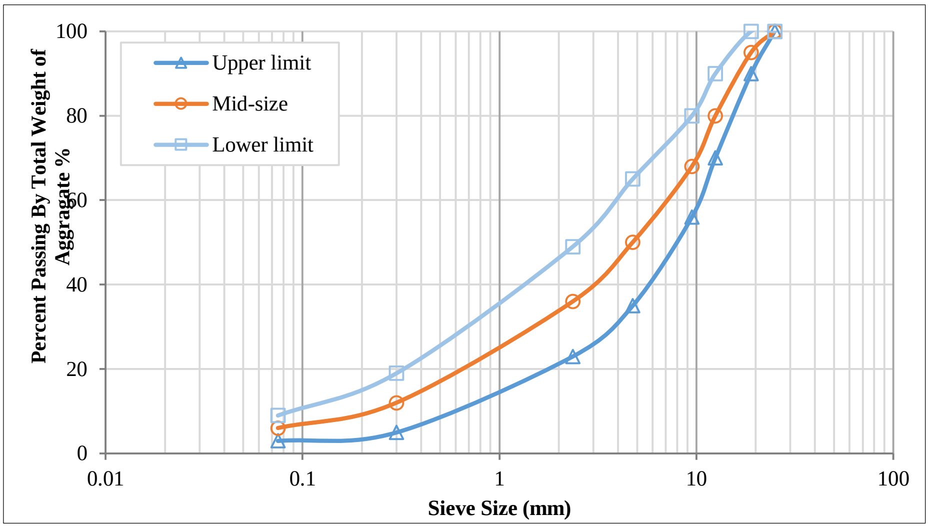


Figure 3. Gradation curves of an aggregate for binder coarse

4. Mix Design

The asphalt mixtures used in this research were designed according to Marshall's method [42] and in compliance with the Iraqi specifications for the binder layer with asphalt paving (Iraqi General Standards SCRB R9/2003) [31]. The HMA was heated at a temperature appropriate for mixing viscosity of 170 ± 20 cP (0.17 ± 0.02 Pa.s) and compaction viscosity of 280 ± 30 cP (0.28 ± 0.03 Pa.s), respectively, and in accordance with Figure 4 [36]. The WMA was prepared at a production temperature of 120 °C (248 °F) using 0.3% of the total weight of the mixture of synthetic zeolite. In addition to the WMA modified with rubber crumbs, 1, 1.5, and 2% of the total weight of aggregate. Adding crumbs of rubber to WMA in a dry way is shown in Figure 5. After heating the aggregate to the required temperature, rubber was added, and the mixture was well mixed until it was homogeneous. The synthetic zeolite is added and mixed well, and the asphalt binder is added. After obtaining the asphalt mixture, it is returned in the loss state to the furnace to get the curing period in which the rubber is swelled after absorbing the lightweight components of asphalt. For this reason, the proportions of asphalt used to design mixtures containing rubber crumbs have been increased. The optimum asphalt percents were 4.5, 4.45, 5, 5.4, and 5.6% that sequentially produced Marshall and volumetric properties as shown in Table 7. After designing the asphalt mixture, the samples are prepared to be exposed to the short-term aging conditions shown in Figure 6 to prepare the samples for testing their sensitivity to moisture.

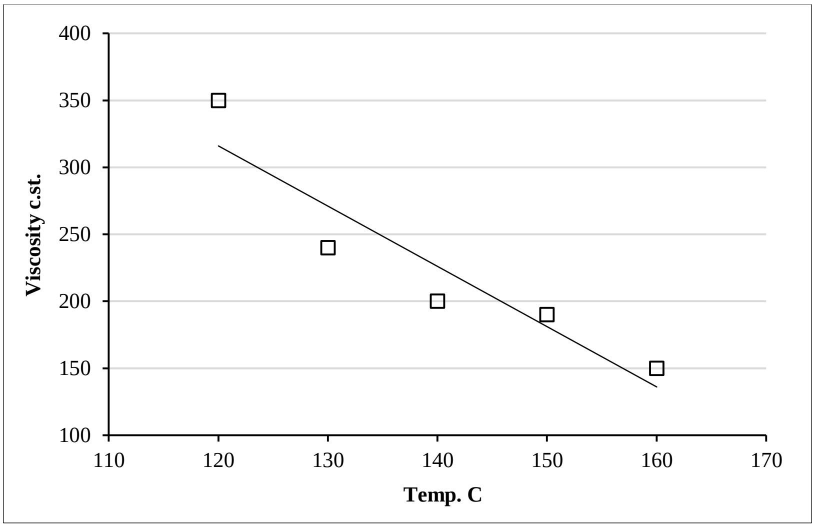


Figure 4. Viscosity-Temperature Chart for Asphalt Cement (40-50)

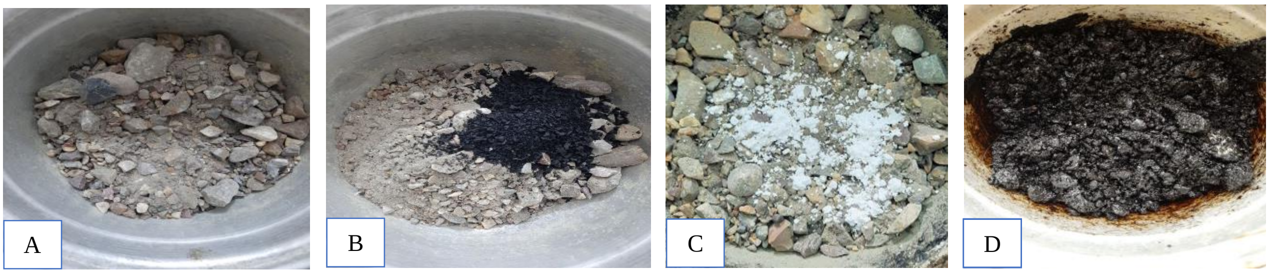


Figure 5. The work stage of WMA modified by CR: A: hot aggregate. B: addition of CR on heated aggregate. C: speared zeolite on dry materials. D: adding asphalt cement

Table 7. Marshall and volumetric properties

Type	AC%	Stability (KN)	Flow (mm)	Density	AV%	VMA%	V.F.A.%
HMA	4.5	10.5	3.2	2.325	4.2	16.5	75
WMA	4.45	9	3.2	2.32	4.5	16.6	72
1% Rubber	5	10	3.7	2.3439	3.7	15.8	77
1.5% Rubber	5.4	8.2	3.9	2.327	3.8	15.4	75
2% Rubber	5.6	8.1	4.5	2.315	4.7	16.3	71
SCRB	(4-6)	Min. 7.0	(2-4)	-	(3-5)	Min.13	-

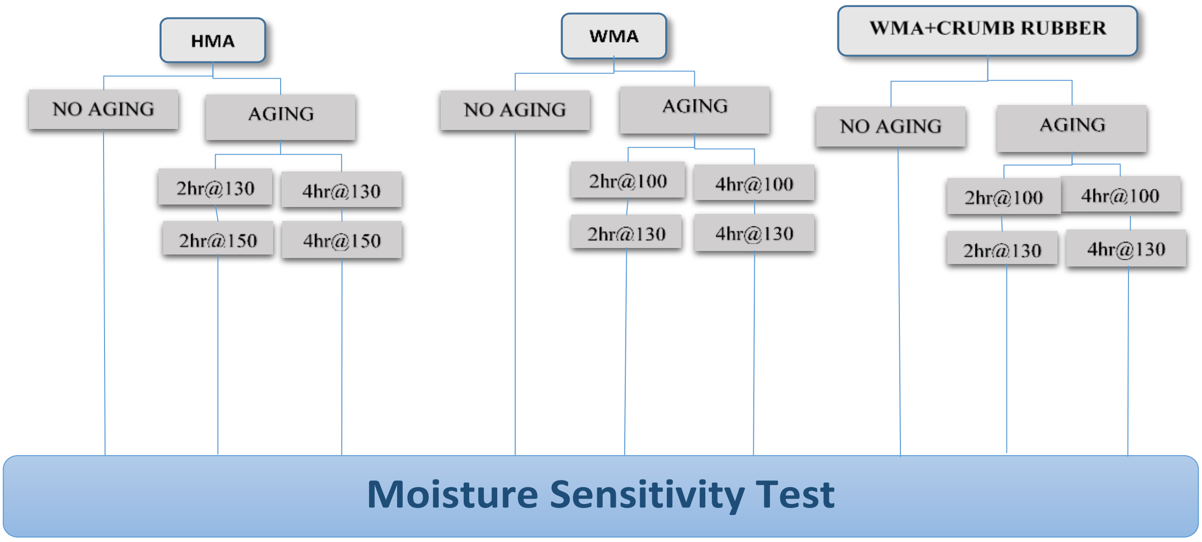


Figure 6. Short-term aging conditions

5. Indirect tensile strength Test

An indirect tensile strength test is used to assess the potential for moisture impact on mixtures [43]. The test method was performed using an indirect tensile strength test procedure [44]. The standard Marshall specimens of 101.6 mm in diameter and 63.5 mm in height were prepared. Two subsets of specimens are prepared for each asphalt mix. Every subset consists of three specimens; one of the subsets is dry and the other is wet. All specimens were compacted to reach (7±1)% air voids, equivalent to void levels in the field typically within 6–8% of air voids, which was achieved by several experiments with different compaction blows, as shown in Figure 7. The number of blows needed for the test specimens corresponding to the air voids at a percentage of (7±1)% was (47±10) blows calculated from this figure, and after conducting several trials with the number of different compaction blows. For the conditioned subset, the three specimens were prepared with distilled water at room temperature using a vacuum chamber to achieve 55–80% of saturation degree. Then, the partially saturated specimens were soaked in distilled water for a period of 24 hours at a temperature of (60 ± 1) °C. Finally, the temperature was adjusted for soaked specimens at (25±1) °C for a period of 1 hour in another water path before the test has begun. In the dry condition, the temperature of the three specimens has been changed to (25±1) °C by soaking them in a water bath for a period of 20 minutes before being tested. All samples were subjected to an indirect tensile strength (IDT) test at a constant loading rate of 50 mm/min at 25 °C (77 °F) before they failed due to vertical deformation (Figure 8). According to Equation 1 [44], the maximum load was recorded for determining the tensile strength of all specimens tested. To compare the moisture sensitivity of all mixtures, the tensile strength ratio (TSR) was determined, which is a ratio of the indirect tensile strength of wet specimens to the indirect tensile strength of dry specimens. The TSR value was determined using Equation 2, as shown below. According to ASTM D4867 (2014) [43], the TSR value should be greater than or equal to 80%, which indicates adequate moisture resistance.

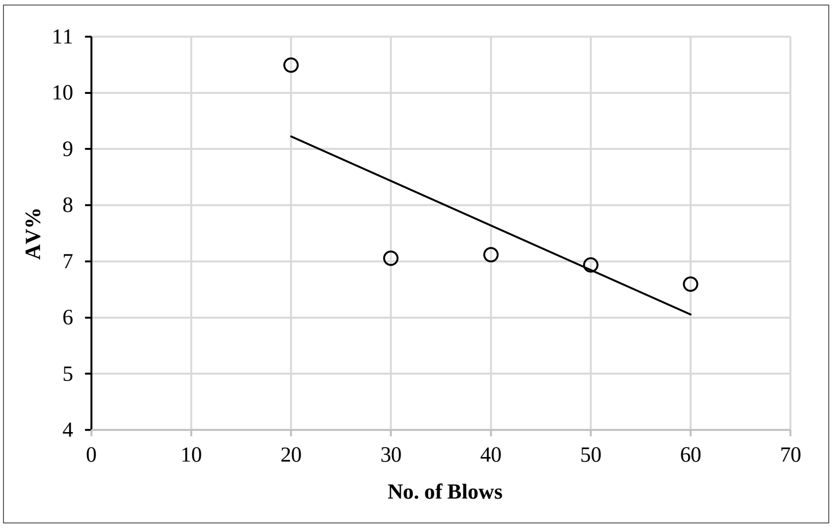


Figure 7. Relationship between No. of blows and Air Voids Percentage

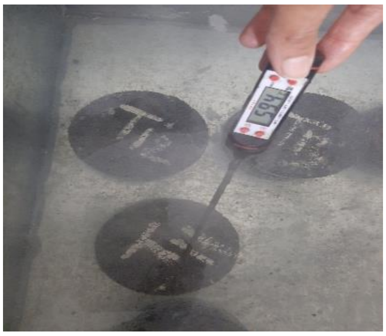
$$St = \frac{2000 \times p}{\pi \times D \times T} \quad (1)$$

Where St is Tensile strength (KPa), P is Maximum load (N), and T is height of specimen immediately before test (mm).

$$TSR = \frac{Stm}{Std} \times 100 \quad (2)$$

where TSR is Tensile strength ratio, Stm is average tensile strength of the wet condition, KPa, and Std is average tensile strength of the dry condition, KPa.

(a)



(b)

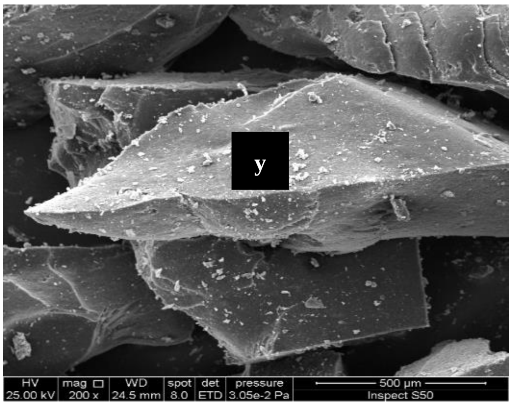
(c) (d)

Figure 8. Indirect tensile test: a) Freezing cycle at -18°C for a period of 16 hr, b) thawing cycle with distilled water at a temperature of 60 °C and for a period of 24 hr, c) Water bath at 25 °C, d) Under splitting load

6. Results and Discussion

6.1. SEM Analysis

SEM provides extra information about the chemical composition and physical configuration of materials. The analysis was carried out for the particles of rubber crumbs, the image was shown in Figures 9-a and 9-b, where it appeared that the particles were cubic in shape with a rough surface. As for the WMA and WMA modified with 1% rubber crumbs, the surface of the mixture appears to be clear weaves, as in Figures 10-a and 11-a, respectively. In addition to that, conducting SEM has the advantage of chemical analysis of the constituent elements of materials using EDX mode, where an energy spectrum is shed on the gold-covered sample shown in Figure 12. After that, the energy reflected from the surface of the sample is analyzed to reveal the chemical composition as shown in the Figures 9-c, 10-b and 11-b which show the analysis as the percent of elements against the energy of those elements. It can be clearly seen in Figure 11-a that the rubber disperses uniformly among the WMA mixture particles and the image has a darker color than that in Figure 10-a which refers to a denser mixture

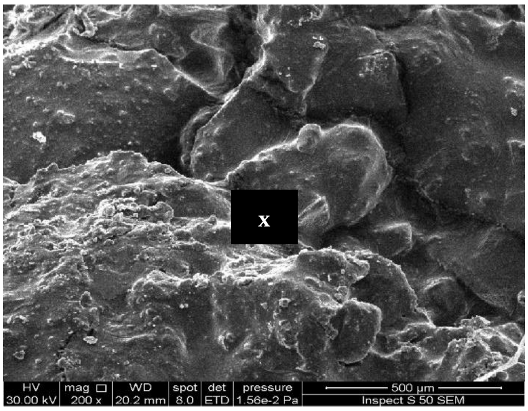


(a)

Element	Weight %	Weight % Error
Carbon	63.8	`8.377583
Sulfur	11.65	0.262804
Zinc	8.08	0.209166
Iron	5.95	0.117731
Silicon	5.3	0.073557
Calcium	5.19	0.078294

(b)

Figure 9. SEM images of rubber particles: (a) rubber particles with magnification×200 and scale bar 500 µm. (b) Element composition of rubber at point y in the image (a)

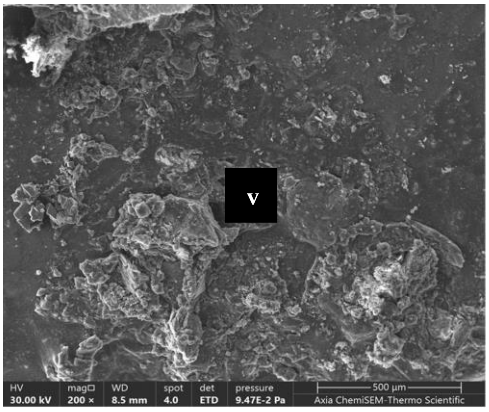


(a)

Element	Weight %	Weight % Error
Carbon	34.854	10.39993
Calcium	18.91	0.634054
Silicon	18.33	0.715891
Sulfur	12.14	0.442909
Aluminium	8.65	0.365871
Magnesium	7.11	0.303229

(b)

Figure 10. SEM images of WMA with 0%CR: (a) WMA with magnification×200 and scale bar 500 µm. (b) Element composition of WMA at point x in the image (a)



(a)

Element	Weight %	Weight % Error
Carbon	46.18	0.5
Calcium	20.28	0.2
Silicon	15.08	0.1
Sulfur	6.78	0.1
Iron	6.58	0.2
Aluminium	4.98	0.1

(b)

Figure 11. SEM images of WMA with 1%CR: (a) WMA with 1%CR with magnification×200 and scale bar 500 µm. (b) Element composition of WMA with 1%CR at point v in the image (a)

Figure 12. Testing sample covered with gold film

6.2. Indirect Tensile Test

150 Marshall Samples were prepared with dimensions (4×2.5) in with the optimum asphalt content of HMA, WMA, and WMA modified with 1, 1.5, and 2% of crumb rubber. As shown in Figures 13 to 17, an increase in temperature and time of aging lead to an increase in the value of TSR. The reason for this is the HMA that is most commonly used in Iraq. The aggregate was heated to a high temperature so that all moisture in its pores of the aggregate was removed. In addition, the asphalt was heated to a high temperature so that the viscosity of the asphalt decreased and the workability of the mixture increased. The thickness of the asphalt film surrounding the aggregate particles increases, and thus the adhesion force between the components of this structure increases. Notice that at WMA, with 0% of the additional crumb rubber, with an increase in short-term aging conditions of temperature and time, the values of TSR increase but remain less than the TSR values of HMA. The reason is that the WMA contains zeolite, which is a chemical compound that contains in its composition a percentage of water.

Table 7 shows that AV%, VMA% in WMA is higher than HMA, and VFA% in WMA is less than HMA. This indicates that the WMA contains more spaces that allow moisture to penetrate the asphalt pavement, which decreases the value of TSR% and thus becomes susceptible to moisture damage. This is consistent with the studies by Albayati & Abduljabbar [45], Lolly [46], and Mogawer et al. [47]. As for WMA modified with crumb rubber, it was observed that with the increase in the short-term aging conditions of temperature and time, the values of TSR increased, which indicates the reason for decreasing the sensitivity of WMA by increasing the short-term aging conditions. However, with the increase in the percentage of rubber crumbs, AV% and VMA% increase and VFA% decrease due to the ability of the rubber crumbs to swell [30]. When crumb rubber is exposed to heat, it absorbs lightweight materials that constitute asphalt, and therefore, the materials remain with a high specific weight so that the asphalt mixture becomes more viscous. It means it is difficult to obtain a perfect coating of asphalt film around aggregate particles and makes the asphalt mixture more exposed to a water attack. That causes a decrease in the values of TSR%.

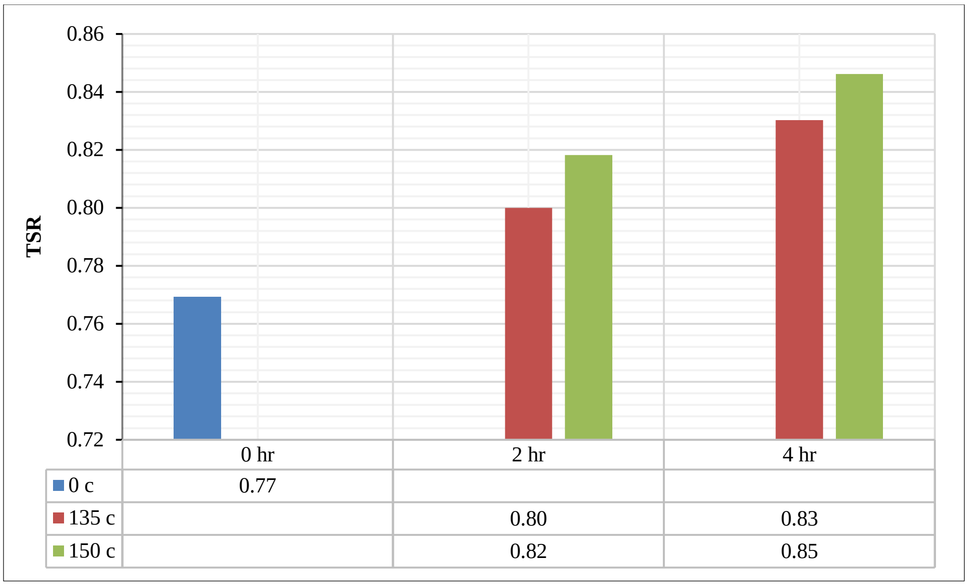


Figure 13. The TSR values for HMA

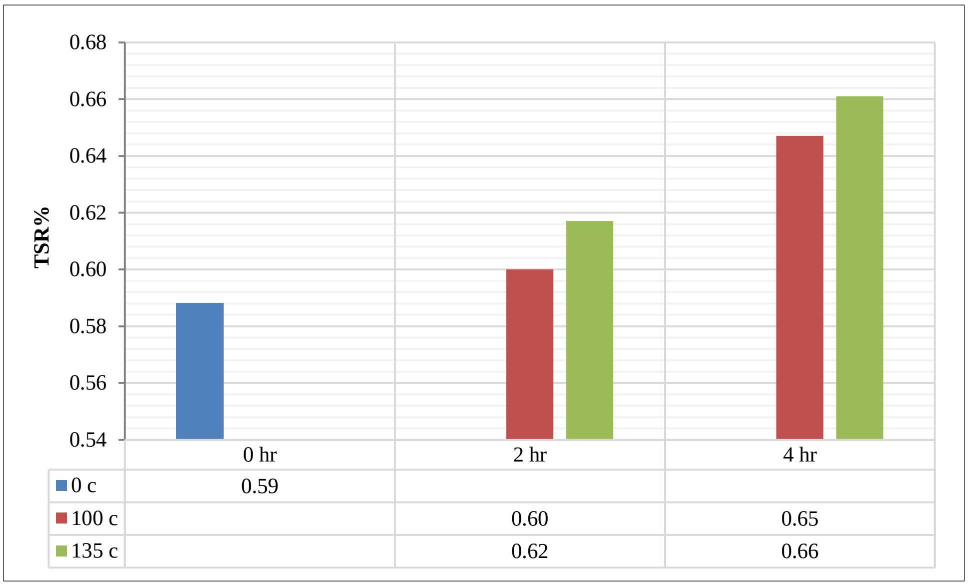


Figure 14. The TSR values for WMA+0%CR

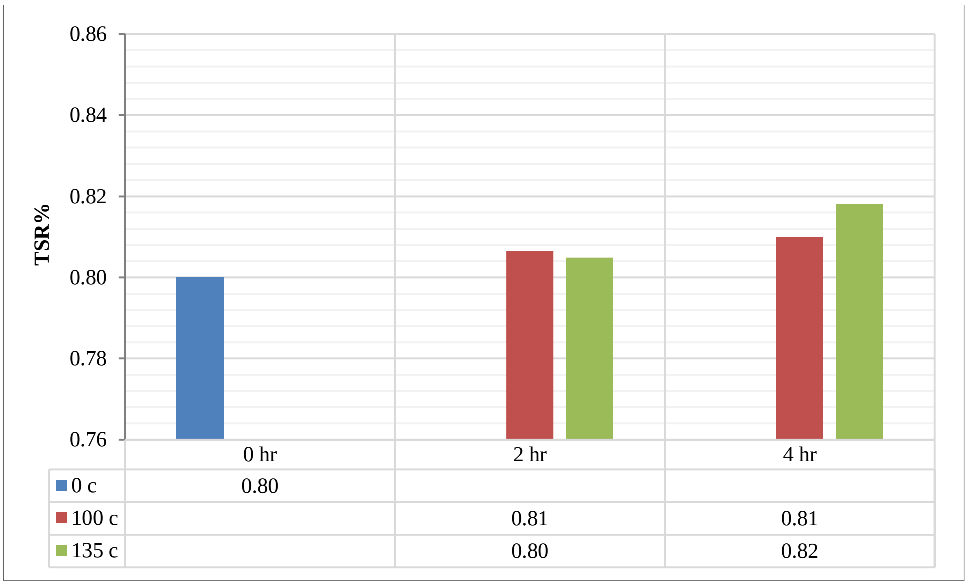


Figure 15. The TSR values for WMA+1% CR

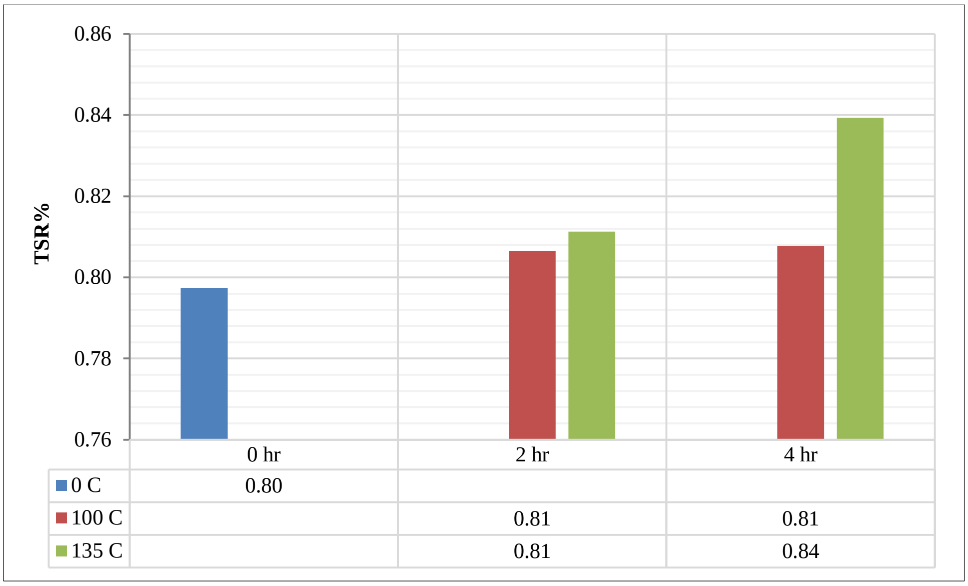


Figure 16. The TSR values for WMA+ 1.5%CR

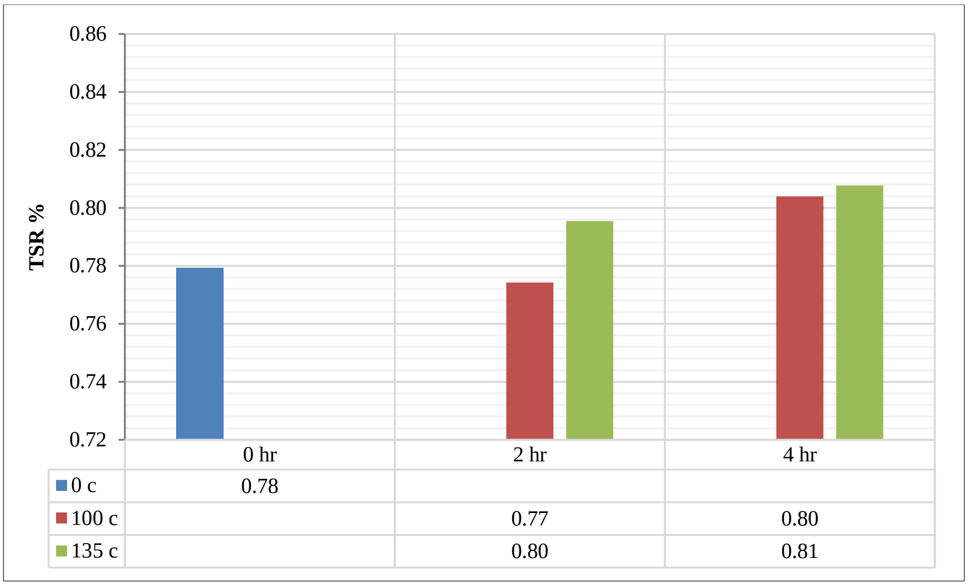


Figure 17. The TSR values for WMA+ 2%CR

7. Statistical Analysis to Simulate Short-Term Aging of Asphalt Mixtures based on Indirect Tensile Strength

In this section of the research, Minitab computer software v.16 was used to complete it. Linear regression analysis was used for the data obtained from the indirect tensile strength test, considering the dependent variable TSR values and the independent variable expressing the short-term aging conditions, as well as the percent of rubber crumbs in the warm mixture. A statistical model was obtained that predicted TSR values in different conditions of STA limited to (0-4) hours and (0-150) Celsius for the hot asphalt mixture and (0–135) Celsius for the warm asphalt mixture. The R-square values are used, which indicate the strength of the relationship between the dependent variable and the independent variable (shown in Equations 3 and 4).

$$\text{HMA. TSR} = 0.759 + 0.0116\,t + 0.000240\,T \quad \text{R-Sq.} = 96.5\% \tag{3}$$

$$\text{WMA. TSR} = 0.610 + 0.00420\,t + 0.000455\,T + 0.0885\,CR \quad \text{R-Sq.} = 88.3\% \tag{4}$$

Where, t is short-term aging period in hour, T is short-term aging temperature in Celsius, and CR is percent of crumb rubber replacement.

8. Conclusions

In this research, the effect of adding rubber to warm mix asphalt (WMA) was studied. Three percentages of rubber were added, which are 1, 1.5, and 2% by weight of aggregate. The research can be concluded as:

- A WMA prepared with 0.3% synthetic zeolite has a moisture sensitivity of about 43% more than a HMA;
- The use of tire rubber waste has a positive effect on improving the moisture sensitivity of warm asphalt paving, as well as reducing the risk of this waste to the environment;
- The excess amount of rubber 2% caused a reduction in moisture susceptibility due to the high void content in the mixture;
- It was determined that the optimum rubber crumb present was based on the Marshall test and the indirect tensile test at 1%, which produced an increase in Marshall stability and an improvement in moisture sensitivity compared with the control WMA;
- The aging duration of the samples has a significant impact on the TSR values; mostly, the TSR values increased as the duration increased. This could be due to the increase in bonds between the aggregate and rubber particles;
- The aging temperature has also played an important role in the resistance to moisture susceptibility;
- SEM images were taken for the rubber particles and mixtures modified with rubber and it was found that the mixtures that contain rubber have a more homogenous blend.

9. Declarations

9.1. Author Contributions

Conceptualization, H.M.M.; methodology, Z.T.F.; software, H.M.M. and Z.T.F.; formal analysis, Z.T.F.; data curation, Z.T.F.; writing—original draft preparation, Z.T.F.; writing—review and editing, H.M.M.; supervision, Z.T.F.; funding acquisition, H.M.M. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are available in the article.

9.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

9.4. Conflicts of Interest

The authors declare no conflict of interest.

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