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Properties of Modified Warm-Mix Asphalt Mixtures Containing Different Percentages of Reclaimed Asphalt Pavement

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Abstract: The Rapid reduction of energy resources and the escalated effects of global warming have created a strong motivation to find some new techniques in the field of paving construction. Adopting new technologies, such as warm-mix asphalt (WMA) or the recycling process of asphalt can be very helpful for the economy and have a significant impact on the environmental footprint. Thus, this research aimed to study the mechanical and durable characteristics of modified WMA mixtures using (1.0%, 1.5%, and 2.0%) Sasobit REDUX®, (0.3%, 0.4%, and 0.5%) Aspha-Min®, and (0.07%, 0.1%, and 0.125) ZycoTherm® additives corresponding to three percentages of reclaimed asphalt pavement (RAP) (20%, 40%, and 60%). Three mixing temperatures have been conducted in this study to generate WMA mixtures at (135 °C, 125 °C, and 115 °C) corresponding to three compacting temperatures (125 °C, 115 °C, and 105 °C). The mechanical properties of the developed WMA mixtures have been evaluated using the Superpave volumetric properties (air voids, voids filled with asphalt, and voids in mineral aggregate), while the durable properties have been investigated using the resilient modulus test (M_R) at 25 °C, resilient modulus ratio (RM_R), and Hamburg wheel-track test in terms of permanent deformation, moisture susceptibility, and rutting resistance. To make the WMA mixtures accept high quantities of RAP (>25%), an insignificant increase in the amounts of WMA additives was needed to produce mixtures carrying sustainability labels. Results indicated that all the used additives had pushed the WMA mixtures to achieve considerable mechanical properties, whereas the best properties for the WMA mixtures containing 0%, 20%, 40%, and 60% of RAP have been achieved by mixing with (1.0% Sasobit REDUX® @ 125 °C), (1.0% Sasobit REDUX® or 0.3% Aspha-Min® @ 135 °C), (1.5% Sasobit REDUX® @ 125 °C), and (2.0% Sasobit REDUX® or 0.5% Aspha-Min® @ 135 °C), respectively. On another hand, the best durable properties have been achieved by mixing the mentioned WMA mixtures containing 0%, 20%, 40%, and 60% of RAP with 0.07%, 0.07%, 0.1%, and 0.125% of ZycoTherm® at 153 °C, respectively. Using such additives in the recycled WMA mixtures made it possible to activate waste recycling in the paving industry.

Keywords: WMA; RAP; rutting resistance; moisture susceptibility; waste recycling

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1. Introduction

During the proposed life of a highway, pavement layers will be subject to several distresses, which affect the strength and reduce the durability of the highway. Such damage can be caused by moisture, which is the most common type due to its significant effects on adhesion and cohesion forces. Moisture might also lead to various problems, such as aggregate degradation, bleeding, potholes, and rutting issues [1].

The moisture susceptibility of asphalt mixtures mainly depends on several factors, such as environmental conditions, the quality of mixtures' materials, types and sources of aggregate, and traffic volume [2]. As a result, moisture resistance must be considered in the design and construction of any paving structures. Moisture damage can be reduced or even prevented through good mix design and modifications of asphalt mixtures using anti-stripping additive (ASA) materials [3]. Several studies have investigated the effects of ASA materials, such as hydrated lime, Portland cement, fly ash, polymers, nano-sized materials, and waste plastic on the moisture resistance of asphalt mixtures. The results that came up from previous studies aid the role of ASA materials in increasing the resistance of pavement to moisture damage [4].

In recent years, to reduce the side effects of the paving industry on the environment, energy cost, and materials consumption, several solutions have been suggested to deal with these issues by many paving technologists [5].

Warm mix asphalt (WMA) mixtures and reclaimed asphalt pavement (RAP) are considered to be among the major solutions that have been used in different places around the world. By far, WMA mixtures are considered the most suitable alternative to hot-mix asphalt (HMA) mixtures in the asphalt pavement industry due to the obvious reduction in mixing and compacting temperatures caused by lowering the viscosity of the binder or by improving the workability [6]. The normal mixing temperature for conventional hot-mix asphalt mixtures is (140–160 °C), while for WMA mixtures it is (110–135 °C). The WMA method uses little energy, whereas it can be installed in a fast way and transported for long distances in comparison to HMA mixtures. It is significantly safer and healthier for the workers, more cost-effective and has a good impact on the environment [7].

WMA additives can be classified into foamed, chemical, and organic additives. Many studies have been conducted to evaluate the performance of asphalt mixtures containing WMA additives. Some of these refer to better performance, while others refer to the opposite [8]. Owing to the lower mixing temperature of WMA mixtures in comparison to the HMA mixtures, the mixed aggregate will never be completely dry, and that leads to an increase in the moisture susceptibility of the WMA mixtures [9]. The reduction in the moisture susceptibility of WMA mixtures is caused by a lack of adhesion power between the aggregate and the binder. However, this issue has been solved by using specific materials to improve the bonding between the components of WMA mixtures, such as ASA or polymers [10]. Based on previous and current studies, it has been found that using reclaimed asphalt pavement (RAP) within asphalt mixtures, especially HMA mixtures, can be implemented in different ways and methods according to the adopted mixing standards. The benefits of using RAP can be summarized by minimizing the consumption of raw materials and improving the overall performance of the mix [11].

As mentioned before, HMA mixtures tend to use high mixing temperatures, and that means using RAP within those kinds of mixtures leads to additional aging of the RAP's binder.

Since the WMA mixtures can be mixed at a lower temperature, they become more compatible with RAP than the HMA mixtures. It has been proven that the combination of RAP with WMA improves the performance of WMA and allows for the use of a high content of RAP [12].

Oner J. et al. [13] examined the use of RAP within WMA mixtures by using three additives (chemical, organic, and watery) and proved that using RAP up to 30% is acceptable in regard to the used additives. It has also been concluded that using RAP within WMA mixtures can reduce the total cost compared to HMA and WMA mixtures. On the other hand, Yousefi A. et al. [8] studied the performance of WMA at mechanical and durable levels by incorporating RAP within the WMA mixtures up to 50%, using various types of additives. Furthermore, adding RAP materials into asphalt mixtures improved their moisture damage resistance.

Shu X. et al. [14] evaluated the moisture susceptibility of foamed RAP-WMA mixtures and proved that foamed WMA mixtures incorporating RAP can perform similarly to HMA mixtures. In addition, Fakhri M. et al. [15] investigated the performance of RAP-WMA mixtures in terms of permanent deformation and moisture susceptibility. Their results proved that by increasing the RAP content, the moisture susceptibility is decreased. Furthermore, Saleh M. et al. [16] checked out the use of rejuvenators in the production of WMA mixtures containing different percentages of RAP. The results showed adding the rejuvenator directly to the RAP leads to a significant increase in the moisture resistance of the mixture.

The performance of warm-mix asphalt mixtures containing different percentages of reclaimed asphalt pavement (WMA–RAP) depends on the type and amount of WMA and RAP content.

Therefore, this study tries to evaluate the effect of WMA additives on the performance of recycled asphalt mixtures; two types of WMA additives are used (Sasobit REDUX the organic additive and Aspha-min the foamed one), and three percentages of RAP (20%, 40%, and 60%) are used, in addition to one type of ASA which is (ZycoTherm).

The novelty of this study is revealed by investigating the performance of organic, foamed, and anti-stripping additives within the WMA-RAP mixtures in terms of permanent deformation, moisture susceptibility and rutting resistance in order to find the optimum percentages of the used additives for the virgin and recycled WMA mixtures at different levels of mixing temperatures.

All the generated mixtures are tested in terms of permanent deformation using the resilient modulus test (MR), moisture susceptibility using the resilient modulus ratio (RMR), and rutting resistance using the Hamburg wheel-track test, to produce WMA mixtures with a high amount of RAP used as an equal alternative to HMA mixtures or even better.

2. Experimental Program

2.1. The Used Materials

2.1.1. Asphalt Binder

The binder used in this study has a penetration of (40–50), which is the most common type of binder used in flexible pavement construction in Iraq. Table 1 lists the most required properties for this type in accordance with ASTM standards and Iraqi specifications (SCRB, R/9).

Table 1. Mechanical properties of the used (40–50) binder.

Test	Penetration (1/10 mm)	Kinematic Viscosity (Poise)	Specific Gravity	Flashpoint (°C)	Ductility (cm)
Results	47	3.7	1.04	238	145
Standards	ASTM D244	ASTM D2170	ASTM D70	ASTM D92	ASTM D113
(S.C.R.B) Specification	(40–50)	(3.36–3.98)	(1.01–1.05)	Min. 232	>100

2.1.2. The Aggregate

The virgin coarse and fine aggregates are normally local materials that can be obtained from different places in Iraq. Tables 2 and 3 present the physical and chemical properties of the used aggregate. The adopted gradation for the virgin aggregate is selected for the wearing (IIIA) surface layer, as presented in Table 3. In accordance with ASTM standards and Iraqi specifications (SCRB, R/9).

Table 2. The physical properties of the virgin aggregate and RAP.

Test	Bulk Specific Gravity		Los Angles Abrasion (%)	Soundness (%)	Water Absorption (%)		Angularity (Coarse) (%)
	Coarse Agg.	Fine Agg.			Coarse Agg.	Fine Agg.	
Virgin Aggregate	2.38	2.36	21	1.3	1.2	2.8	89.6
RAP	2.35	2.33	19.8	0.9	0.8	0.9	93.2
Standards	ASTM C-127/ C-128		ASTM C-131	ASTM C88/C88M	ASTM C-127/ C-128		ASTM D 5821

Table 3. The chemical properties of the virgin aggregate and the RAP.

Chemical Component (%)	SiO_2	CaO	MgO	SO_3	Al_2O_3	Fe_2O_3
Virgin aggregate	80.53	10.36	0.71	2.8	0.45	0.72
RAP aggregate	72.41	11.31	3.02	6.12	2.18	0.67

2.1.3. Reclaimed Asphalt Pavement (PAP)

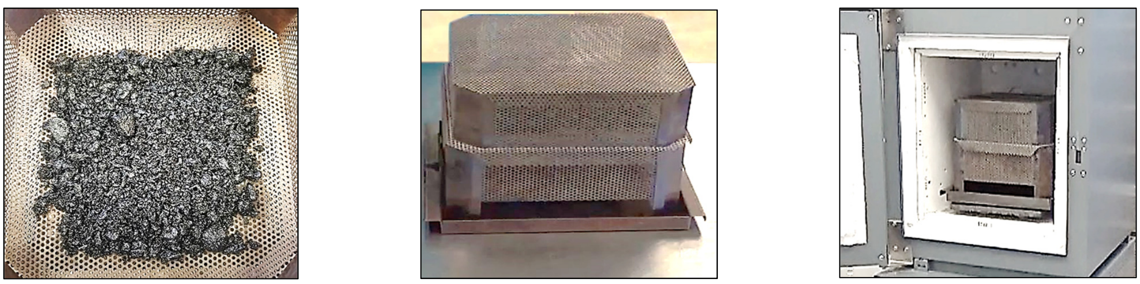
RAP materials are obtained from a stockpile of materials reclaimed during maintenance works on the freeway linking Baghdad and Hilla cities, as shown in Figure 1, Tables 2 and 3 present the physical and chemical properties of the used RAP.

Figure 1. A stockpile of RAP.

The aggregate gradation of RAP after the extraction test is presented in Table 4. The binder content in the RAP has been recovered using the ignition method according to AASHTO T 308 [17] and found to be (3.5%) as shown below in Figure 2.

Table 4. The gradation of virgin aggregate, RAP, and combined aggregate.

Sieve Size	Specification Limit	Wearing (IIIA) Gradation	RAP Gradation	Combined Agg. of 20% RAP	Combined Agg. of 40% RAP	Combined Agg. of 60% RAP
$\frac{3}{4}$	100	100	93	98.6	97.2	95.8
$\frac{1}{2}$	100–90	93	95.3	93.46	93.92	94.38
3/8	90–76	85	79.6	83.92	82.84	81.76
No.4	74–44	50	58	51.6	53.2	54.8
No.8	58–28	40	41.6	40.32	40.64	40.96
No.50	21–5	12	13.7	12.34	12.68	13.02
No.200	10–4	7	5.7	6.74	6.48	6.22



(**A**) (**B**) (**C**)

Figure 2. The ignition method according to AASHTO T 308. (**A**) Spreading the RAP; (**B**) Covering the RAP; (**C**) Heating the RAP.

2.1.4. Sasobit REDUX® WMA Organic Additive

It is an organic additive made by Sasol Wax in South Africa. A synthetic Fischer-Tropsch product contains other waxes related to petroleum, as shown in Figure 3. The Sasobit additive increases the stability of the asphalt binder but, at the same time, reduces its viscosity [18]. Therefore, it is well known as a compaction aid and viscosity reducer additive. The physical characteristics of the intended additive are presented below in Table 5.

Figure 3. Flakes of Sasobit REDUX.

Table 5. The physical properties of Sasobit REDUX.

Property	Sasobit REDUX
Components	Hydrocarbons
Shape State	Flakes
Colour	Off- white
Content of Oil	0.9%
Molecular Mass	620 Dalton
Density	580 kg/m^3
Congealing Point	72–83 °C
Penetration at 25 °C	16–30 dmm
Kinematic Viscosity at 100 °C	9.0 cSt
Distribution of Carbon	1.3%
Dosage	1–1.5% by weight of binder (as recommended by Sasol Wax company) [18]

2.1.5. Aspha-Min® WMA foamed Additive

It is a fine powdered product, as shown in Figure 4. Manufactured in Germany by Eurovia Services from hydrothermally crystallized zeolite as a WAM additive. The utilized synthetic zeolite is composed of sodium aluminum silicate hydrate [19]. It has been considered one of the foaming additives due to its effect on releasing water in the mixtures and increasing their workability. The physical characteristics of the intended additive are presented below in Table 6.

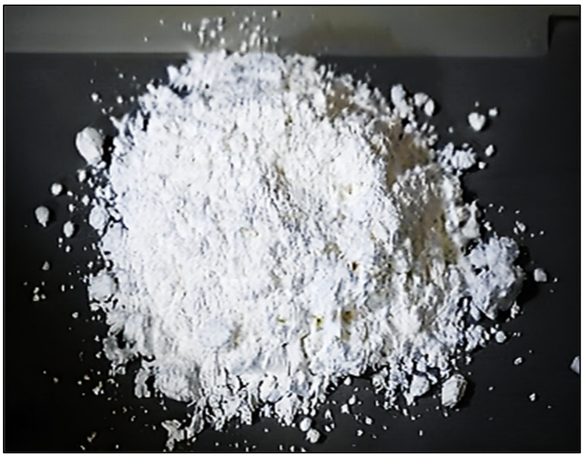


Figure 4. Granulated powder of Aspha-Min.

Table 6. The physical properties of Aspha-Min.

Property	Aspha-Min
Components	Sodium Alumino-Silicate
Shape State	Granulated Powder
Colour	White
Size of Particles	380 µm
Specific Gravity	2.05
Density	524 kg/m^3
Dosage	0.3% by weight of total mix (as recommended by Eurovia manufacturer) [19]

2.1.6. The Ordinary Filler

Normal Portland cement has been used with normal physical and chemical properties, as demonstrated below in Tables 7 and 8.

Table 7. The Physical properties of the ordinary filler.

Physical Properties	Specific Gravity	Fineness by (cm^2/gm)	% Passing Sieve No. 200
The Result	3.14	3044	94

Table 8. The chemical properties of the ordinary filler.

Chemical Component (%)	SiO_2	CaO	MgO	SO_3	Al_2O_3	Fe_2O_3	S	C	Loss of Ignition
The Result	0.01	65.20	0.51	2.8	0.01	0.12	0.12	4.55	33.15

2.1.7. ZycoTherm® (ASA)

It is a polymer-based additive produced by Zydex Industries in India, for WMA mixtures, as shown in Figure 5. ZycoTherm is a liquid reactive additive that works to increase the resistance of the mixture to moisture susceptibility by enhancing the strength of the binder [20]. The physical characteristics of the intended additive are presented below in Table 9.

Figure 5. ZycoTherm additive.

Table 9. The physical properties of ZycoTherm.

Physical Properties	Its Form	Color	Specific Gravity	Viscosity at 25 °C (Pas)	Flash Point (°C)	Dosage
The Result	liquid	Pale yellow or colorless	0.98	1–5	>80	(0.03–0.1%) by weight of binder (as recommended by Zydex Industries) [20]

2.2. Asphalt Mixtures Design

All the prepared samples are implemented in accordance with the Superpave mix design method (NCHRP-752, 2013) [21], whereas the compaction process has been made under the (AASHTO T 312, 2015) [22] employing the gyratory compactor of Superpave (SGR) as in Figure 6.

Figure 6. SGR apparatus.

The Max. Theor. density of the prepared samples was found depending on the common practice and the levels of gyration as set in three levels N_{design}, $N_{initial,}$ and $N_{maximum}$, whereas:

- N_{design} is the design number of gyrations
- $N_{initial}$ is the initial number of gyrations
- $N_{maximum}$ is the maximum number of gyrations

The value of N_{design} = 100 was selected at medium to high traffic levels ((3 to <10) $\times 10^6$ Traffic level) as shown in Table 10. (NCHRP-714, 2012) [23]. Additionally, it is the recommended level by (SHRP-A-407) [24] for the state of the climate and traffic in Babylon-Iraq.

Table 10. Levels of N_{design} according to NCHRP-714.

Design Traffic (ESALs) × 10^6	**N_{design}**
<0.3	50
0.3 to <3	75
3 to <10	100
10 to <30	100
≥30	125

After selecting the design structure of the aggregate, the trial mixtures are prepared to conduct the estimated binder content of the designed mixture. According to the asphalt institute manual (2014) [25], a trial binder normally depends on the nominal maximum size of the adopted aggregate, which is (12.5 mm) for the wearing (IIIA) layer, corresponding to 5% binder content, to begin with. The whole point of the process is to figure out the percentage of binder needed to obtain a 4% air content in the compacted mixtures. Superpave samples are compacted normally to 4790 gm at the select binder content for trials in order to determine the maximum theoretical and bulk-specific gravity (G_{mm} and G_{mb}) in accordance with the (AASHTO T 209) [26] and (AASHTO T 166) [27], respectively.

The trial mixture at 5% binder content showed a diversion in the air content from the 4% or 96% G_{mm} as has been stated in the Superpave design process. Consequently, after several trials, the goal has been achieved at 4.8% estimated binder content which corresponds to the requested air content as below in Table 11. All the related design equations to predict the estimated binder content were implemented according to (AASHTO R 35) [28].

Table 11. The estimated volumetric properties of the trial mixture.

Property	**Estimated Binder (Pb)**	**Estimated Voids of Mineral Aggregate (VMA)**	**Estimated Voids Filled with Asphalt (VFA)**	**Estimated Effective Binder (Pbe)**	**Proportion of Dust**	**Estimated G_{mm} at $N_{initial}$**
Result	4.8%	14.50	72.17	4.82%	1.23	86
AASHTO M323 Standards [29]	——	Min. 14%	(65–75)%	——	0.6–1.2	<89%

The optimum binder content is found by compacting four types of mixtures, each one containing a specific amount of binder as below:

- The first mix compacted at the estimated binder content
- The second mix compacted at the estimated binder content − 0.5%
- The third mix compacted at the estimated binder content + 0.5%
- The fourth mix compacted at the estimated binder content + 1.0%

Then, the generated mixtures have to be evaluated in terms of volumetric properties (air voids, VFA, and VMA) and the percentage of G_{mm} at $N_{initial,}$ and N_{design} in accordance with (NCHRP-673, 2011) [30].

After determining the optimum content for the HMA mixture, All the generated WMA mixtures are implemented using the same design procedure of HMA mixtures following the (AASHTO R35), whereas the adopted optimum binder content for the WMA mixtures is the same as HMA.

The procedure for handling the RAP within the HMA mixtures is based on AASHTO M 323. For mixtures containing a high percentage of RAP, more than 25%, special blending charts are required depending on the viscosity and the penetration of the recovered RAP binder to select the right grade of the virgin binder. This scenario does not work very well with WMA mixtures, as the used additive will soften the virgin binder by lowering its viscosity; therefore, the combined blend between the modified binder of WMA and the aged binder of RAP has a lower viscosity than the combined blend of the recycled HMA mixtures.

Consequently, the RAP percentage within the WMA mixture is related to the quantity of the used additive in the mix; in other words, the selected additive can be considered as a rejuvenator or recycling agent for the aged RAP binder within the recycled WMA mixtures [16]. According to previous studies, the RAP needs to be preheated and mixed at a specific range of temperatures (120–180 °C) in order to activate the RAP binder and make it effective in combining with the virgin one [31]. Depending on the RAP percentages within the mixtures, mixing and compaction temperatures have to be selected on that basis. The percentage of the virgin binder to be added to the recycled WMA mixture is restricted depending on the amount of RAP within the mixture and by employing the equation below, which has been developed and used by the Asphalt Institute and AASHTO M 323 [32].

$$P_{nb} = \frac{P_b \times \left(100^2 - P_{sb} \times r\right)}{\left(100 - P_{sb}\right) \times 100} - \frac{P_{sb} \times (100 - r)}{100 - P_{sb}} \quad (1)$$

Whereas,

P_{nb}: the percentage of the newly added virgin binder.
r: the percentage of new aggregate in the recycled mixture.
P_{sb}: the percentage of binder content in the RAP.
P_b: the estimated percentage of binder content in the recycled mixtures, which is assumed to be equal to the binder content of a new mixture with 100% new materials.

2.3. Mixing Process of the Additives

2.3.1. Mixing of Sasobit REDUX Additive

The used additive is composed on a cellular level of a long chain length with 40–115 atoms of carbon, creating a high melting point. This type of additive works to reduce the viscosity of the mixing binder at 100 °C and above, leading to a reduced overall temperature of the WMA mixture by 15–55 °C. In this study, the adopted dosage of the additive was 1.0% by weight of the binder as recommended by the Sasol company under hard waxing additive products. For WMA mixtures containing RAP, three percentages of Sasobit REDUX are selected, as shown below in Table 12.

Table 12. Sasobit REDUX dosage within the recycled WMA mixtures.

Mixture Type	Recycled WMA Mixtures		
	20% RAP	40% RAP	60% RAP
Sasobit REDUX dosage by weight of the binder	1.0%	1.5%	2.0%

The mixing process of this kind of additive is the wet method, which is implemented in accordance with the manufacturer's recommendations, by adding the sasobit to the binder in a specific blender, as shown below in Figure 7 and applying a 125 °C mixing temperature for 30 min of mixing. The blender is continuously running at 2500 rpm as instructed by the mixing procedure of the Sasol Wax Company in order to provide an efficient, uniform, and homogeneous blend [18].

Figure 7. Asphalt binder blender.

2.3.2. Mixing of Aspha-Min Additive

This kind of additive can decrease the production temperature of the asphaltic mix and also aid the compaction process by changing the viscosity of the used binder. The selected dosage of Aspha-min is 0.3% by weight of the total mix as recommended by Eurovia Services GmbH.

For WMA mixtures containing RAP, three percentages of Aspha-min are selected, as shown below in Table 13. Both Aspha-min and the selected binder can be added at the same time to the mix in order to create the foaming process [19].

Table 13. Aspha-min dosage within the recycled WMA mixtures.

Mixture Type	Recycled WMA Mixtures		
	20% RAP	40% RAP	60% RAP
Aspha-Min dosage by weight of the total mix	0.3%	0.4%	0.5%

2.3.3. Mixing of ZycoTherm (ASA)

This type of ASA works to improve and increase the powers of adhesion between the binder and the aggregate by forming a strong and permanent chemical bond between them, as shown below in Figure 8. As a result of that bond, the moisture resistance and the durability of the pavement will be significantly improved. The dosage of the additive is (0.03–0.1%) by weight of the binder as recommended by Zydex Industries. Therefore 0.07% is the adopted percent of the additive in this study. For the mixture containing RAP, Zydex recommended using (0.07–0.125%) of ZycoTherm for better workability of the generated mix. The blending process between the additive and the binder was implemented by adding the adopted percentages of ZycoTherm (0.07% for virgin WMA mixture) to the binder in the blender, as shown previously in Figure 7 for 30 min at 125 °C under 2500 rpm and the selected dosages for mixtures containing RAP [20] are shown below in Table 14.

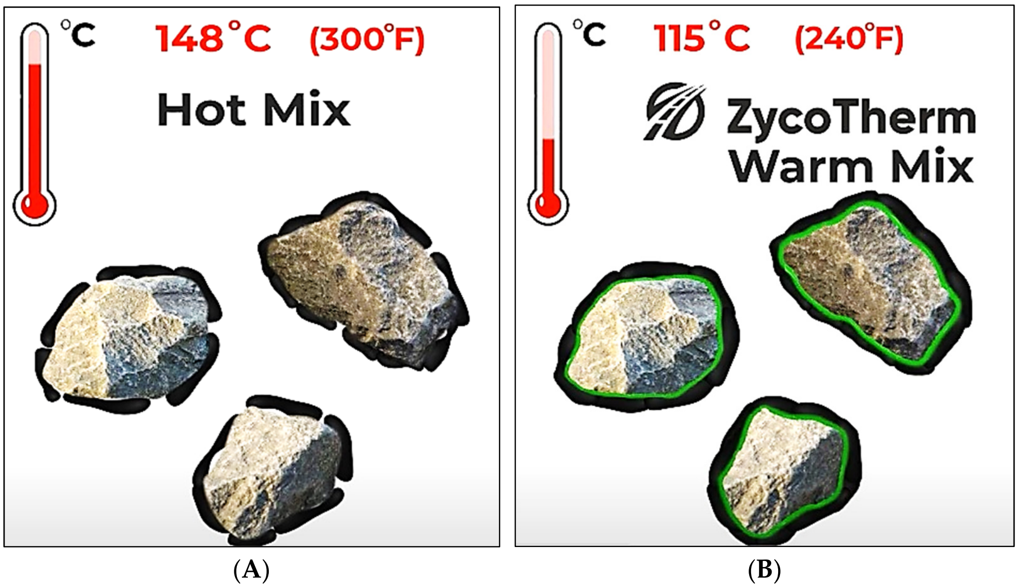


Figure 8. Aggregate-binder bonding in HMA and modified WMA mixtures [20]. (**A**) Aggregate-binder bonding in HMA; (**B**) Aggregate-binder bonding in WMA modified by ZycoTherm.

Table 14. ZycoTherm dosage within the recycled WMA mixtures.

Mixture Type	Recycled WMA Mixtures		
	20% RAP	40% RAP	60% RAP
ZycoTherm dosage by weight of the binder	0.07%	0.1%	0.125%

In general, conducting, mixing and compaction temperatures depend mainly on the percentage of RAP within the mix. Therefore, three levels of mixing and compacting have been selected. Each level has its own temperature, as in Table 15, considering the effective range of temperatures for each type of asphalt mixture as in Figure 9.

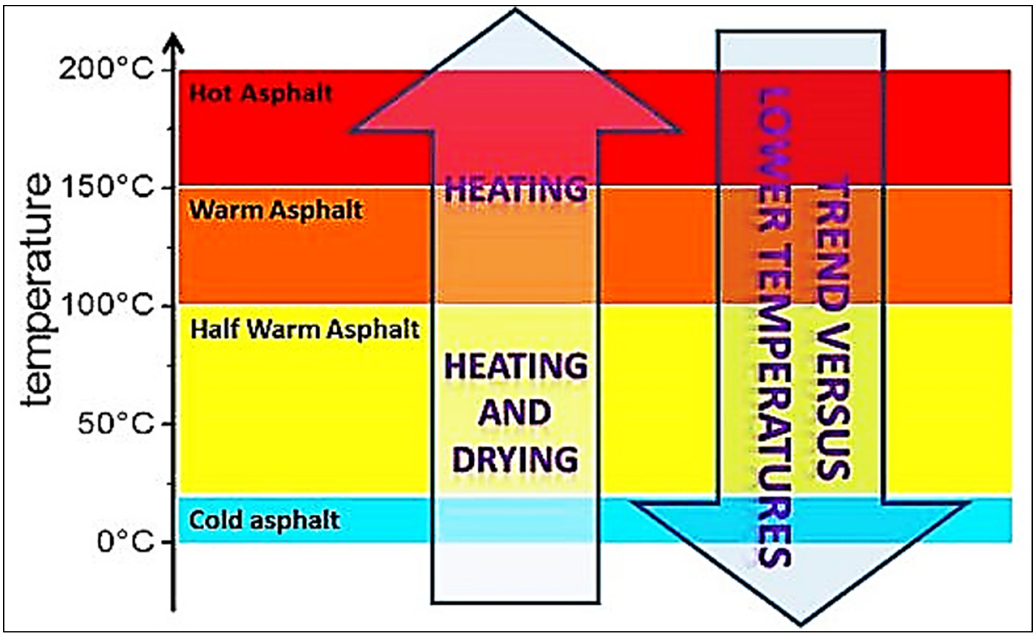


Figure 9. The range of effective temperatures [33].

Table 15. Mixing and compacting temperatures.

Mixture Type	Additive %	Mixing Temperature (°C)	Compaction Temperature (°C)
HMA (Control)	/	160	150
WMA + Sasobit REDUX	1.0% of binder	135	125
		125	115
		115	105
WMA + Sasobit REDUX + 20% RAP		135	125
		125	115
		115	105
WMA + Sasobit REDUX + 40% RAP	1.5% of binder	135	125
		125	115
WMA + Sasobit REDUX + 60% RAP	2.0% of binder	135	125
		125	115
WMA + Aspha-Min	0.3% of the total mix	135	125
		125	115
		115	105
WMA + Aspha-Min + 20% RAP		135	125
		125	115
		115	105
WMA + Aspha-Min + 40% RAP	0.4% of the total mix	135	125
		125	115
WMA + Aspha-Min + 60% RAP	0.5% of the total mix	135	125
		125	115
WMA + ZycoTherm	0.07% of binder	135	125
		125	115
		115	105
WMA + ZycoTherm + 20% RAP	0.07% of binder	135	125
		125	115
		115	105
WMA + ZycoTherm + 40% RAP	0.1% of binder	135	125
		125	115
WMA + ZycoTherm + 60% RAP	0.125% of binder	135	125
		125	115

2.4. Resilient Modulus (M_R) Test

The aim of this test is to evaluate the moisture susceptibility of the generated mixtures by conducting the ratio of resilient modulus (RM_R) for conditioned wet samples to unconditioned dry samples. In order to calculate the RM_R, the test of indirect resilient modulus (M_R) must be performed first. The preconditioning process for the samples is implemented according to (AASHTO T283) [34], whereas the conditioned samples had to be vacuum saturated at 55–80%. Consequently, after vacuum saturation, the samples were put in a freeze-thaw cycle starting at 16 hrs under −18 °C and then soaking in a bath of water for 24 hrs under 60 °C, as shown in Figure 10. the unconditioned samples were stored at normal temperatures in order to complete the test.

Figure 10. Soaking in the water bath.

The M_R test was implemented in accordance with ASTM D7369-09 [35] at a testing temperature of 25 °C using a cylindrical specimen subjected to cyclic load for 0.1 sec and rest for 0.9 sec, as shown below in Figure 11. To obtain the values of M_R and RM_R, the following equations are used:

$$M_R = \frac{P\,(v + 0.27)}{H \times L} \tag{2}$$

$$RM_R = \frac{M_{Rwet}}{M_{Rdry}} \times 100\% \ \geq 70\% \tag{3}$$

where

M_R: resilience modulus (Mpa)
P: the applied load at maximum (N)
v: Poisson ratio (0.35)
H: deformation (mm) in the horizontal direction
L: height of sample (mm)
M_{Rwet}: resilience modulus for wet condition
M_{Rdry}: resilience modulus for dry condition

Figure 11. M_R test apparatus.

2.5. Hamburg Wheel-Track Test

The wheel tracking test (WTT) device was utilized to simulate the rutting susceptibility of laboratory-prepared asphalt mixtures to deform under load in accordance with AASHTO T-324 [36], as shown below in Figure 12.

Figure 12. Wheel-track apparatus.

The WTT was used to simulate the permanent deformations (rut depth) formed by repeated wheel load cycles at a specified temperature. The mechanical wheel tracking device has the ability to move a rubber wheel with (203.2 mm) diameter and (47 mm) width over a test specimen. The device table has an alternative harmonic over a distance of (230 ± 5 mm) at 52 RPM with wheel one to and fro motion (two passes), which is considered as one load cycle. A solid rubber tire of (200 mm) diameter is fitted to the wheel with a maximum speed of approximately 0.305 m/s). The wheel load weighs approximately (700 ± 10 N) under standard conditions. The wheel tracker is located inside controlled temperature cabinets up to (65 ± 1.0 °C) and is designed to record at least two readings at 25 points along a (10 cm) line at the center of the sample directly along the wheel path for monitoring the rut depth. For this study, the WTT temperature was selected at 60 °C to represent the most excessive high-performance temperature in hot areas. The WTT test is accomplished when the wheel has passed 10,000 cycles over the specimens or when the rut depth goes beyond (20 mm).

Sample Preparation

A slab sample was compacted by using a pneumatic roller compactor and a rectangular metal mold of (300 mm in width), (400 mm in length), and (120 mm in thickness) as shown in Figures 13 and 14. As in Figure 15, two slab samples were made for each type of the designed mixture with a batch of 11,200 gm to produce samples with a thickness of (40 mm) (thickness must be at least twice the nominal aggregate maximum size) (EN 12697-22) [37].

Additionally, the air void should be checked for each compacted slab before performing the test. If the air void is more than 4 ± 0.5%, the compacted slab is discarded and remade. Warm mix asphalt samples were conditioned for 2 h at the planned field compaction temperatures determined from equiviscous mixing and compaction procedures.

The conditioning criteria for WMA mixtures were used to represent the absorption and binder stiffening that occur during construction. While the control asphalt mixture was conditioned for 4 h at 135 °C according to AASHTO R 30. WWT tests were conducted on asphalt mixtures containing different WMA additives, prepared using the same aggregate blends having several types of WMA additives with varying contents. Prior to testing, the specimens were conditioned for 4 h at a test temperature of 60 °C in accordance with (EN 12697-22).

Figure 13. Samples pneumatic roller compactor.

Figure 14. Samples rectangular metal mold.

Figure 15. Asphalt slab samples.

3. Results and Discussion

To conduct the optimum asphalt content, all the trial mixtures have to be evaluated in terms of volumetric properties (air voids, VFA, and VMA) and the percentage of G_{mm} at $N_{initial}$, and N_{design} in accordance with (NCHRP-673, 2011), as demonstrated below in Table 16 and Figure 16.

Table 16. Trial mixture to conduct the optimum asphalt content.

Binder Content %	G_{mb}	G_{mm}	Air Voids %	VFA %	VMA %	Gmm %	
						@ N_{design} = 100	@ $N_{initial}$ = 8
4.3	2.311	2.472	6.7	59	16	94	86
4.8	2.383	2.432	3.3	77	14.5	97	88
5.3	2.352	2.411	2.0	85	15	98	92
5.8	2.341	2.382	1.5	92	15.6	99	95

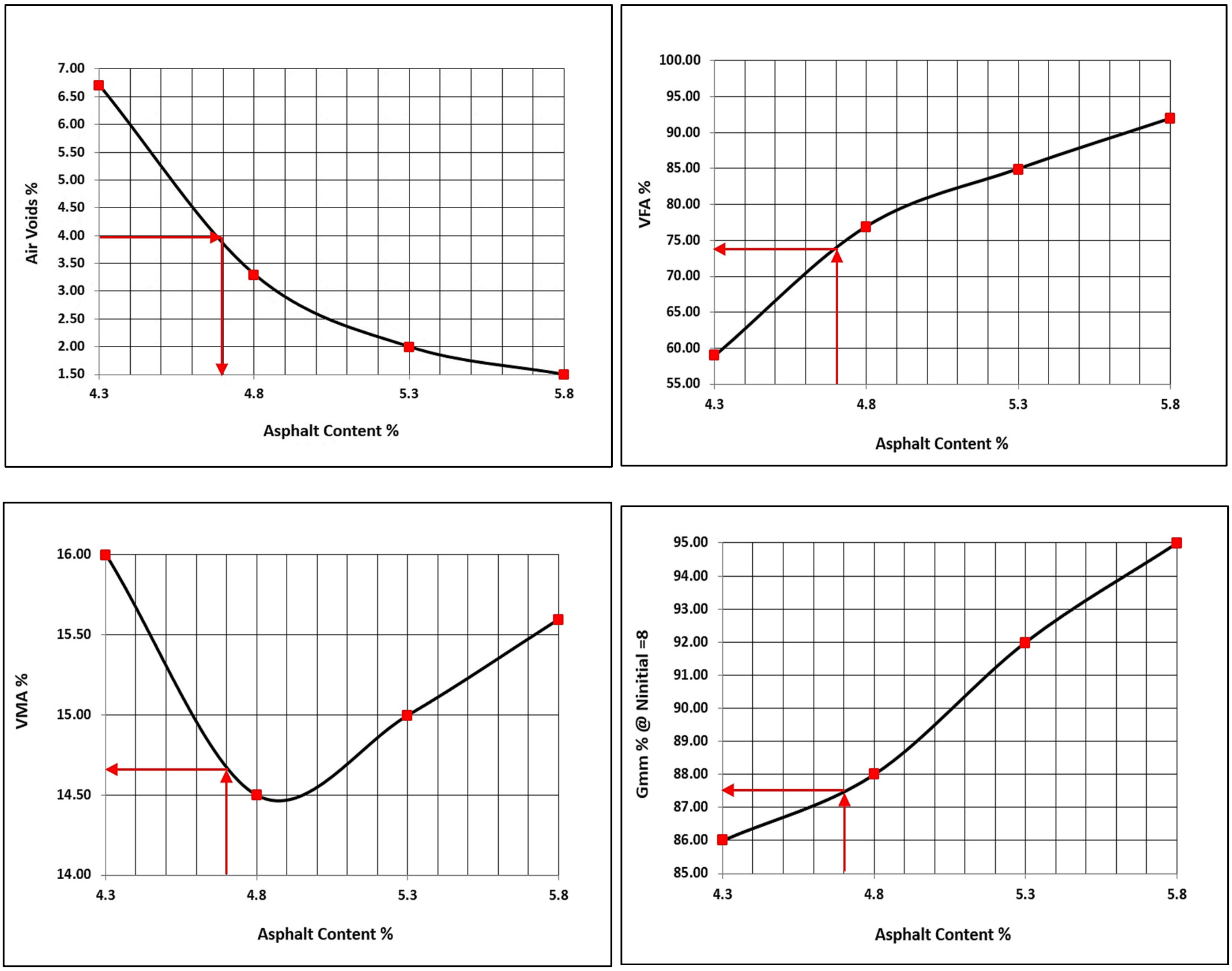


Figure 16. The volumetric properties of the trial WMA mixtures.

The optimum binder content for the WMA mixtures is determined at 4.7%, equal to the control HMA mixture. In addition, the volumetric properties of the developed

Superpave samples (air voids, VFA%, and VMA%, proportion of dust, and G_{mm} @ $N_{initial}$) are summarized below in Table 17.

Table 17. The volumetric properties at the optimum Binder content.

Property	The Result	AASHTO M 323 Standards
Optimum Binder Content %	4.7	@ 4% Air Voids
Air Voids %	4.0	4.0
VFA %	74	(65–75)%
VMA %	14.7	Minimum 15%
Proportion of Dust %	1.3	0.6–1.2
G_{mm} @ $N_{initial}$	87.5	<89%

The percentage of the added virgin binder to the recycled WMA mixture is fixed below in Table 18.

Table 18. Percentages of the virgin binder in the recycled WMA mixtures.

Mixture Type	WMA + 20% RAP	WMA + 40% RAP	WMA + 60% RAP
The Percentage of the Added Virgin Binder	4.0%	3.3%	2.6%

The effects of additive type and the amount of RAP on the volumetric properties of the generated Superpave samples (air voids, VFA%, and VMA%) for the modified virgin and recycled WMA mixtures are demonstrated below:

1- The Air Content Within the Mixtures

As shown below in Figure 17, the variation in the level of air content within the WMA mixtures can be interpreted depending on the type and the amount of the used additives and the percentage of the added RAP as in the points below.

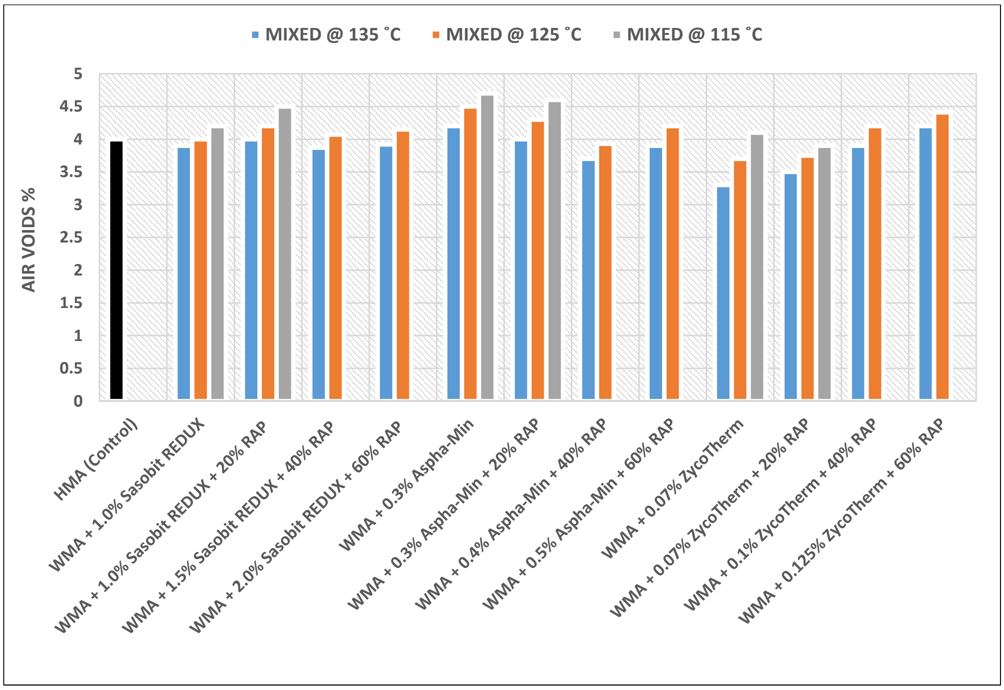


Figure 17. Air content for the modified virgin and recycled WMA mixtures.

- WMA Mixture + 1.0% Sasobit REDUX Additive:

This air content decreased by 1.0% below the control level at a mixing temperature of 135 °C, and then it started to increase, reaching the level of the control HMA mixture at a mixing temperature of 125 °C and above that level, at 115 °C. The used additive works to reduce the viscosity of the binder in order to increase the workability of the mixtures at low temperatures. This result ties well with the previous study of Almeida A. et al. [18], wherein new mixing parameters are presented to continue the prior study. Additionally, Sasobit REDUX has the ability to reduce the compaction resistance and aging of mixtures.

- WMA Mixture + Sasobit REDUX Additive + RAP:

Three percentages of Sasobit REDUX (1.0%, 1.5%, and 2.0%) corresponding to three percentages of RAP (20%, 40%, and 60%) have been used within WMA mixtures. The air content for the mixture with (1.0% Sasobit REDUX + 20% RAP) has the same level as the control mix at 135 °C mixing temperature, and that level begins to increase gradually by decreasing the mixing temperature from (135 °C to 125 °C to 115 °C). Additionally, the air content for the mixtures containing (1.5% Sasobit REDUX + 40% RAP) and (2.0% Sasobit REDUX + 60% RAP) decreased below the control level at a mixing temperature of 135 °C. Then, that low level begins to rise at a mixing temperature of 125 °C above the control level of the HMA mixture. This result is in line with the previous study of Sukhija M. et al. [38], in addition to offering new mixing techniques to enhance the prior study.

- WMA Mixture + 0.3% Aspha-Min Additive:

This air content increased above the control level and keeps increasing by decreasing the mixing temperature from 135 °C to 125 °C to 115 °C, in comparison to the control HMA mixture.

The working mechanism of this type of additive is similar to Sasobit REDUX, where it works to reduce the viscosity of the mixing binder and makes it workable to mix and compact at low temperatures. A similar pattern of results was obtained previously by Fakhri M. et al. [39], except the current study offers a variety of used additives under different circumstances.

- WMA Mixture + Aspha-Min Additive + RAP:

Three percentages of Aspha-Min (0.3%, 0.4%, and 0.5%) corresponding to three percentages of RAP (20%, 40%, and 60%) have been used within WMA mixtures. The air content for the mixture with (0.3% Aspha-Min + 20% RAP) has the same level as the control mix at the 135 °C mixing temperature; that level begins to increase gradually by decreasing the mixing temperature from (135 °C to 125 °C to 115 °C). WMA mixtures with (0.4% Aspha-Min + 40% RAP) and (0.5% Aspha-Min + 60% RAP) showed an efficient reduction in the level of air content at 135 °C mixing temperature, and that level keeps lowering down by decreasing the mixing temperatures from (135 °C to 125 °C) under the control HMA level. The current findings are directly in line with previous findings of Hill B. et al. [6] and offer new types of WMA additives and new mixing parameters.

- WMA + 0.07% ZycoTherm Additive:

This air content decreased below the control level at both mixing temperatures of 135 °C and 125 °C, and then it starts to increase, reaching the level of the control HMA mixture at a mixing temperature of 115 °C. The used additive works to reduce the viscosity of the binder in order to increase the workability of the mixtures at low temperatures. Additionally, it improves the adhesion power between the binder and the aggregate. Overall, the current findings are in accordance with findings reported by Meghana and Kavitha [40], in addition to presenting new mixing boundaries.

- WMA + ZycoTherm Additive + RAP:

Three percentages of ZycoTherm (0.07%, 0.1%, and 0.125%) corresponding to three percentages of RAP (20%, 40%, and 60%) have been used within WMA mixtures. WMA mixture with (0.07% ZycoTherm + 20% RAP) has a relatively low level of air content at all the adopted mixing temperatures (135 °C, 125 °C, and 115 °C) in comparison to the control HMA mixture. The air content for the mixtures with (0.1% ZycoTherm + 40% RAP) has decreased below the control level at 135 °C mixing temperature, then it begins to rise above the control level at the mixing temperature of 125 °C. Additionally, the air content of the mixtures with (0.125% ZycoTherm + 60% RAP) increased below the control level at both mixing temperatures (135 °C and 125 °C). The gained results from the current study are broadly in line with the findings of Jomoor NB. et al. [41], in addition to revealing new techniques regarding the whole mixing process of WMA mixtures.

The variations in the air content mainly appeared as a result of generating a WMA mixture using the three types of additives, in addition to adding the adopted percentages of RAP and mixing the whole components at three levels of temperatures. In other words, the difference in the mixing parameters caused that variation in the air content. However, all the values of air content are within the Iraqi specifications (SCRB, R/9) and within the acceptable range of AASHTO M 323.

2- The Content of VFA Within the Mixtures:

As shown below in Figure 18, the variation in the level of VFA within the WMA mixtures can be interpreted depending on the type and the amount of the used additives and the percentage of the added RAP as in the points below.

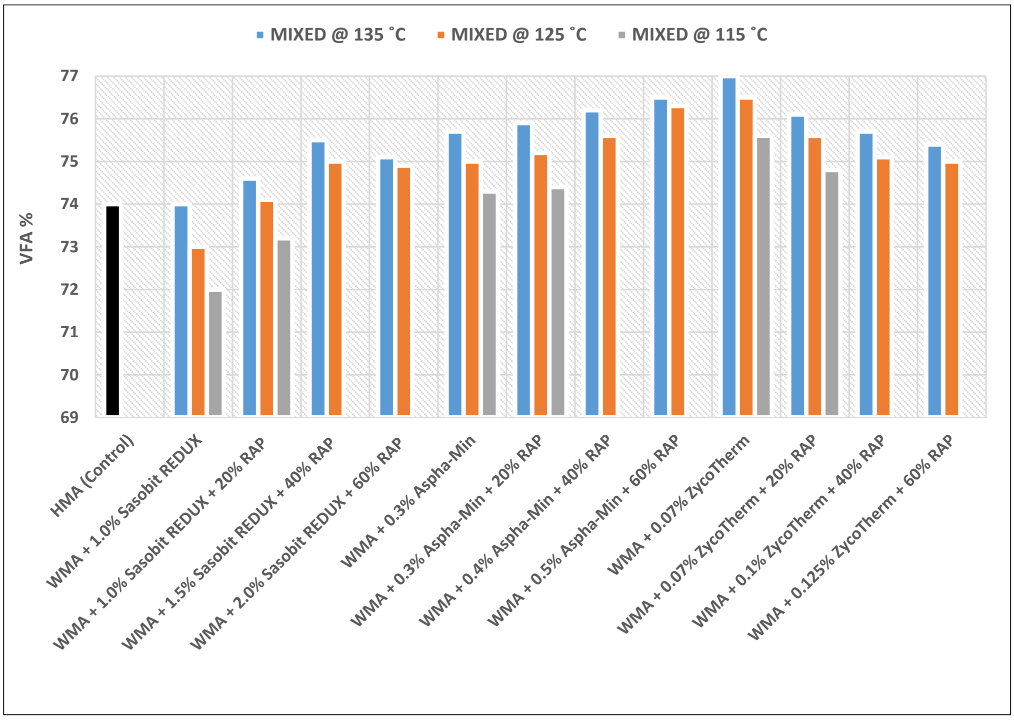


Figure 18. VFA% for the modified virgin and recycled WMA mixtures.

- WMA Mixture + 1.0% Sasobit REDUX Additive:

The content of VFA starts to decrease gradually below the control level of the HMA mixture by decreasing the mixing temperatures from (135 °C to 125 °C to 115 °C) owing to the approximate increase in the air content.

- WMA Mixture + Sasobit REDUX Additive + RAP:

The content of VFA for the mixture with (1.0% Sasobit REDUX + 20% RAP) has increased above the control level at the 135 °C mixing temperature, and then it begins to drop by decreasing the mixing temperature from (125 °C to 115 °C) below the control level of the HMA mixture.

Both WMA mixtures of (1.5% Sasobit REDUX + 40% RAP) and (2.0% Sasobit REDUX + 60% RAP) showed an efficient increase in the level of VFA at the 135 °C mixing temperature, then that level begins to drop by decreasing the mixing temperature from (125 °C to 115 °C) and stabilizes at a level higher than the control level. This fluctuation in the content of VFA has been recorded due to the applied change in the air void content of WMA mixtures.

- WMA Mixture + 0.3% Aspha-Min Additive:

The content of VFA for this type of WMA mixture is relatively high at all mixing temperatures of (135 °C, 125 °C, and 115 °C) in comparison to the control level of the HMA mixture. That high level of VFA is due to the effects of the used additive, which caused a reduction in the viscosity of the used binder. The highest level of VFA is achieved at the 135 °C mixing temperature, then that level decreases gradually by lowering the mixing temperature from (135 °C to 125 °C to 115 °C) and stabilizing at a level higher than the control HMA mixture.

- WMA Mixture + Aspha-Min Additive + RAP:

The Content of VFA for the mixtures containing (0.3% Aspha-Min + 20% RAP), (0.4% Aspha-Min + 40% RAP) and (0.5% Aspha-Min + 60% RAP) are efficiently high in comparison to the control HMA mixture. As the mixing temperature falls below 135 °C, the high level of VFA gradually decreased due to an increase in the air content in the generated mixtures.

- WMA + 0.07% ZycoTherm Additive:

This type of WMA mixture achieved the highest content of VFA, especially at 135 °C. Then, the intended content begins to drop gradually by decreasing the mixing temperature from (135 °C to 125 °C to 115 °C) and stabilizes at a level higher than the control HMA mixture.

- WMA + ZycoTherm Additive + RAP:

The content of VFA for the mixtures containing (0.07% ZycoTherm + 20% RAP), (0.1% ZycoTherm + 40% RAP) and (0.125% ZycoTherm + 60% RAP) is efficiently high in comparison to the control HMA mixture. As the mixing temperature falls below 135 °C, the high level of VFA gradually decreases due to increased air content in the generated mixtures.

The high levels of VFA are mostly caused due to WMA mixtures using the selected types of additives, in addition, to adding the adopted percentages of RAP and mixing the whole components at three levels of temperatures. Furthermore, the used additives have made the mixing binder softer by lowering its viscosity to a point where the new mixtures can be mixed and compacted at low temperatures leading to an increase in the content of VFA, especially at the 135 °C mixing temperature. That high level starts to decrease as the air content increases due to reducing the mixing temperatures below 135 °C. However, all the values of VFA are within the Iraqi specifications (SCRB, R/9) and within the acceptable range of AASHTO M 323.

3- The Content of VMA within the Mixtures:

As shown below in Figure 19, the variation in the level of VMA within the WMA mixtures can be interpreted depending on the type and the amount of the used additives and the percentage of the added RAP as in the points below.

- WMA Mixture + 1.0% Sasobit REDUX Additive:

This content of VMA has decreased below the control level of the HMA mixture at a mixing temperature of 135 °C. Then, that content begins to increase by decreasing the mixing temperature from (125 °C to 115 °C), which is owing to the approximate increase in the air content.

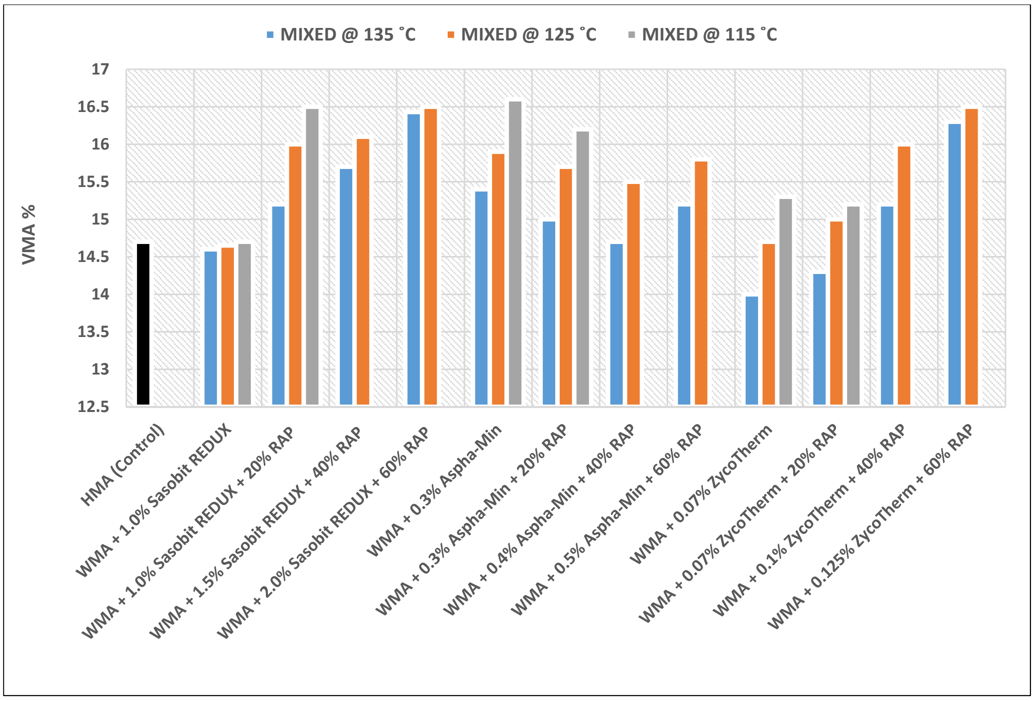


Figure 19. VMA% for the modified virgin and recycled WMA mixtures.

- WMA Mixture + Sasobit REDUX Additive + RAP:

The content of VMA for the mixtures containing (1.0% Sasobit REDUX + 20% RAP), (1.5% Sasobit REDUX + 40% RAP), and (2.0% Sasobit REDUX + 60% RAP) is effectively at a high level at all mixing temperatures in comparison to the control content of the HMA mixture. The reason behind such a high level of VMA is owing to the increase in the level of air content within the mixtures as the mixing temperature decreased from (135 °C to 125 °C to 115 °C).

- WMA Mixture + 0.3% Aspha-Min Additive:

This type of mixture has shown a high level of VMA when mixed at 135 °C, 125 °C, and 115 °C in comparison to the control mix. Basically, the level of VMA begins to increase gradually above the control level as the air content increases within the generated mixtures.

- WMA Mixture + Aspha-Min Additive + RAP:

The content of VMA for the mixtures containing (0.3% Aspha-Min + 20% RAP), (0.4% Aspha-Min + 40% RAP) and (0.5% Aspha-Min + 60% RAP) is approximately at a high level in comparison to the control mixture. That level of VMA has begun to rise by decreasing the mixing temperature from (135 °C to 125 °C to 115 °C) as the air content increases.

- WMA + 0.07% ZycoTherm Additive:

The content of VMA for this type of mixture has a low level in comparison to the control HMA mixture when mixed at 135 °C. Thereafter, that low content begins to increase by decreasing the mixing temperature from (125 °C to 115 °C) surpassing the control level. The reason behind such an increase in the level of VMA is an increase in the air content by lowering the mixing temperatures.

- WMA + ZycoTherm Additive + RAP:

The content of VMA for the mixture containing (0.07% ZycoTherm + 20% RAP) is relatively under the control level of the HMA mixture at a mixing temperature of 135 °C. The low level of VMA begins to grow gradually above the control level by decreasing the mixing temperature from (125 °C to 115 °C) and owing to increasing the level of air content in the mixtures.

WMA mixtures with (0.1% ZycoTherm + 40% RAP) and (0.125% ZycoTherm + 60% RAP) have a high level of VMA and that level keeps growing by decreasing the mixing temperature below 135 °C as the air content of the mixtures increases.

The gradual increase in the levels of VMA within the generated WMA mixtures are due to increasing the air content within the mixtures as a collateral effect of using the adopted additives to produce mixtures with the ability to mix and compact at approximately low temperatures. In addition, adding the RAP increased the air content in the mixtures naturally. However, all the values of VMA are within the Iraqi specifications (SCRB, R/9) and within the acceptable range of AASHTO M 323.

It can be concluded that all the used additives have the same effect in reducing the viscosity of the used binder in the original mix. Additionally, these additives work to soften the high-viscosity blend of the aged RAP binder and the new one and make it workable to mix and compact at approximately low temperatures [42].

To make the WMA mixtures absorb a high amount of RAP (>25%), the dosage of the used additives has been increased within the recommended limits to equalize the hardened effect of the aged binder and to soften the high viscosity of the combined blend.

3.1. The Results of the Resilient Modulus (M_R) Test and Resilient Modulus Ratio (RM_R)

The effects of additive type and the percentage of RAP on the resilient modulus (M_R) and resilient modulus ratio (RM_R) are demonstrated in Figures 20 and 21 and interoperated as below:

1- WMA Mixtures Modified by Sasobit REDUX (virgin and recycled ones)

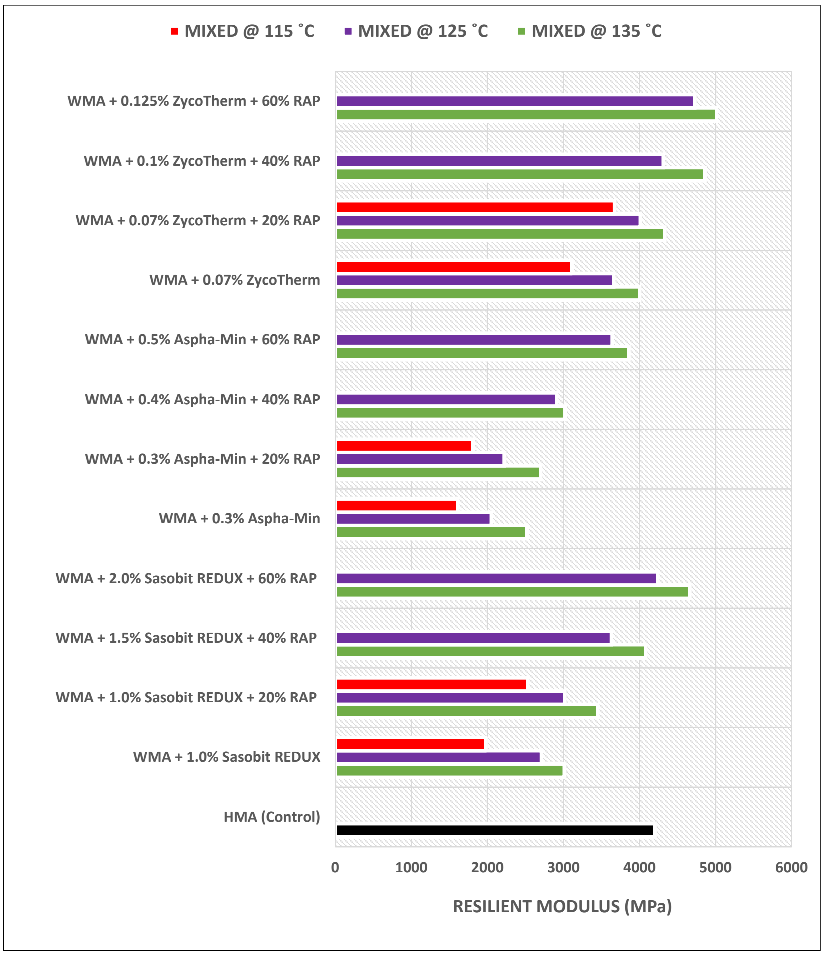


Figure 20. The results of resilient modulus (M_R) test.

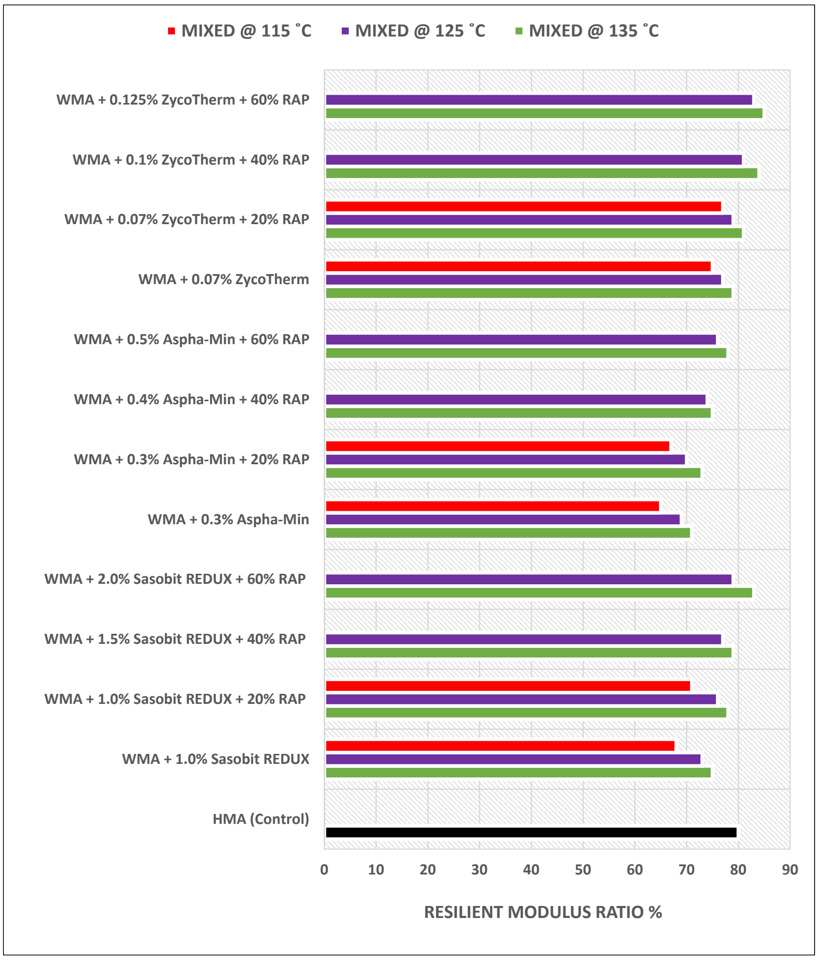


Figure 21. The results of resilient modulus ratio (RM_R) test.

The resilient modulus (M_R) of the virgin mixtures containing 1.0% Sasobit REDUX is relatively low at a mixing temperature of 135 °C in comparison to the control HMA mixture, and that low level is getting lower by decreasing the mixing temperature from (135 °C to 125 °C to 115 °C). Similarly, M_R for mixtures with (1.0% Sasobit REDUX + 20% RAP) and (1.5% Sasobit REDUX + 40% RAP) is approximately lower than the control level when mixed at 135 °C, and that low level becomes lower by decreasing the mixing temperature from (135 °C to 125 °C to 115 °C). The WMA mixture with (2.0% Sasobit REDUX + 60% RAP) has a relatively high M_R, especially when mixed at 135 °C in comparison to the control mixture. That high level of M_R begins to drop slightly by decreasing the mixing temperature below 135 °C. This result ties well with the previous study conducted by Caputo P. et al. [33]; new mixing boundaries are adopted by the current study.

- The resilient modulus ratio (RM_R) for the mixture containing 1.0% Sasobit REDUX is slightly lower than the control HMA mixture at a mixing temperature of 135 °C, and that level keeps dropping by decreasing the mixing temperature from (135 °C to 125 °C to 115 °C). RM_R for mixtures containing (1.0% Sasobit REDUX + 20% RAP) and (1.5% Sasobit REDUX + 40% RAP) is insignificantly below the level of the control mix at a mixing temperature of 135 °C. That sufficient level begins to drop by decreasing the mixing temperature below 135 °C. The WMA mixture with (2.0% Sasobit REDUX + 60% RAP) has a relatively high RM_R, especially when mixed at 135 °C in comparison to the control mixture. That high level of M_R begins to drop slightly by decreasing the mixing temperature below 135 °C.

2- WMA Mixtures Modified by Aspha-Min (virgin and recycled ones)

- The resilient modulus (M_R) of the mixture containing 0.3% Aspha-Min is very low at a mixing temperature of 135 °C in comparison to the control HMA level. That low level keeps dropping down by decreasing the mixing temperature from (135 °C to 125 °C to 115 °C). The M_R value for mixtures containing (0.3% Aspha-Min + 20% RAP), (0.4% Aspha-Min + 40% RAP) and (0.5% Aspha-Min + 60% RAP) is relatively low and keeps dropping by decreasing the mixing temperature below 135 °C. The current result is directly in line with the prior findings of Albayati AH. et al. [43] and offers a variety of used WMA additives.
- The resilient modulus ratio (RM_R) for the mixture containing 0.3% Aspha-Min is under the level of the control HMA mixture at the three temperatures of mixing (135 °C, 125 °C, and 115 °C). Additionally, RM_R for mixtures containing (0.3% Aspha-Min + 20% RAP), (0.4% Aspha-Min + 40% RAP), and (0.5% Aspha-Min + 60% RAP) is at a low level in comparison to the control mix, and that level keeps dropping by decreasing the mixing temperature below 135 °C.

3- WMA Mixtures Modified by ZycoTherm (virgin and recycled ones)

- The resilient modulus (M_R) of the mixture containing 0.7% ZycoTherm is nearly at the same level as the control HMA mixture at the 135 °C mixing temperature. By decreasing the mixing temperature from (135 °C to 125 °C to 115 °C) the level of M_R for the mentioned mixture begins to decrease gradually. The M_R value for mixtures containing (0.07% ZycoTherm + 20% RAP), (0.1% ZycoTherm + 40% RAP) and (0.125% ZycoTherm + 60% RAP) is efficiently high at the 135 °C mixing temperature.

That high level of M_R for the recycled WMA mixtures begins to drop slightly to a level equal to or higher than the control HMA mixture. A similar pattern of results was gained previously by Ameli A. et al. [44], except the current study offers a variety of used additives under different conditions.

- The resilient modulus ratio (RM_R) for the mixture containing 0.7% ZycoTherm is barely at the same level as the HMA mixture, and that level decreased slightly by reducing the mixing temperature from (135 °C to 125 °C to 115 °C). The RM_R value for mixtures containing (0.07% ZycoTherm + 20% RAP), (0.1% ZycoTherm + 40% RAP) and (0.125% ZycoTherm + 60% RAP) is efficiently at a high level at all mixing temperatures (135 °C, 125 °C, and 115 °C).

The values of the resilient modulus (M_R) for the generated WMA mixtures are at a good level in comparison to the HMA mixture, and some of the values surpassed the control level, which indicates the behavior of these mixtures in resisting permanent deformation to be remarkably high.

The high levels of the resilient modulus ratio (RM_R) for the developed WMA mixtures indicate a high resistance to moisture susceptibility by these mixtures [45], whereas almost all of the RM_R values are above 70%.

3.2. The Results of the Hamburg Wheel-Track Test

The effects of additive type and the amount of RAP on the values of rutting depth at three levels of mixing temperatures are presented below in Figures 22–24, and interoperated as below:

1- WMA Mixtures Mixed at 135 °C and 125 °C (virgin and recycled ones)

All types of WMA mixtures modified by Sasobit REDUX showed great resistance to rutting in comparison to the control HMA mixture at all the adopted test cycles.

WMA mixtures modified by Aspha-Min showed considerable resistance to rutting, whereas the mixtures containing (0.3% Aspha-Min), (0.3% Aspha-Min + 20% RAP), and (0.4% Aspha-Min + 40% RAP) have a low rutting resistance in comparison to the control mixture while the mixture with (0.5% Aspha-Min + 60% RAP) has efficiently high resistance to rutting for all the test cycles.

The best results were achieved by all the types of WMA mixtures modified by ZycoTherm, whereas the rutting resistance for these mixtures is at a high level in comparison to the control mixture.

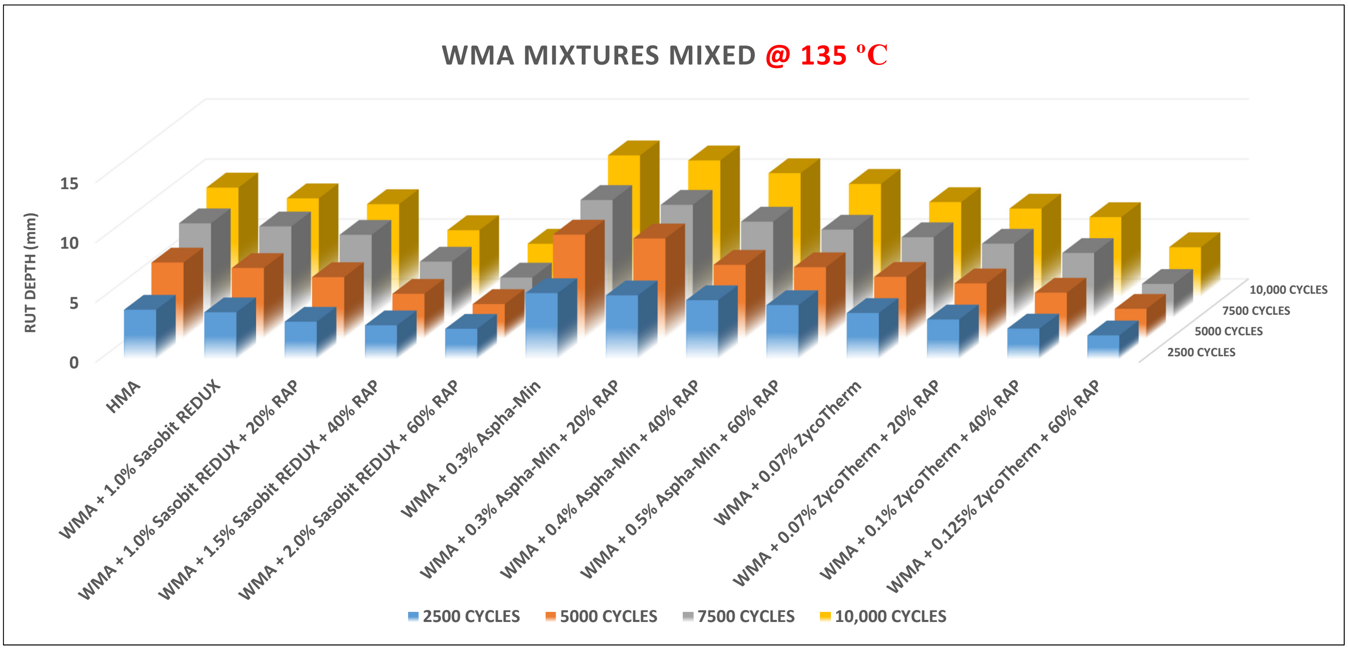


Figure 22. Rutting depth for the modified virgin and recycled WMA mixtures mixed @ 135 °C.

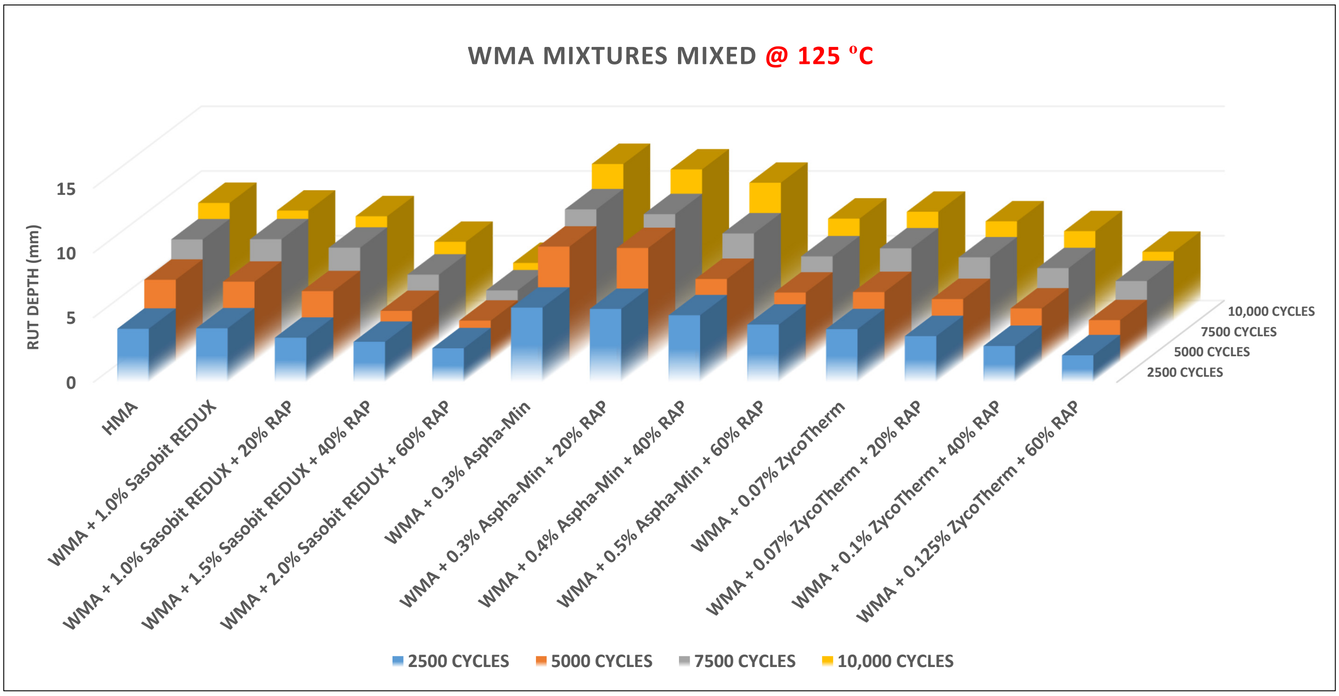


Figure 23. Rutting depth for the modified virgin and recycled WMA mixtures mixed @ 125 °C.

2- WMA Mixtures Mixed at 115 °C (virgin and recycled ones)

WMA mixture with 1.0% Sasobit REDUX showed considerable resistance to rutting, whereas the rutting depth for this mixture is insignificantly higher than the control HMA mixture. The WMA mixture with (1.0% Sasobit REDUX + 20% RAP) showed high resistance to rutting similar to the control HMA mixture. The WMA mixture with 0.3% Aspha-Min showed a relatively low rutting resistance in comparison to the control HMA mixture. Additionally, the WMA mixture containing (0.3% Aspha-Min + 20% RAP) has a low resistance to rutting compared to the control mix.

The best results were recorded by the types of mixtures modified by ZycoTherm, whereas the rutting resistance for these mixtures is at a remarkably high level in comparison to the control mixture.

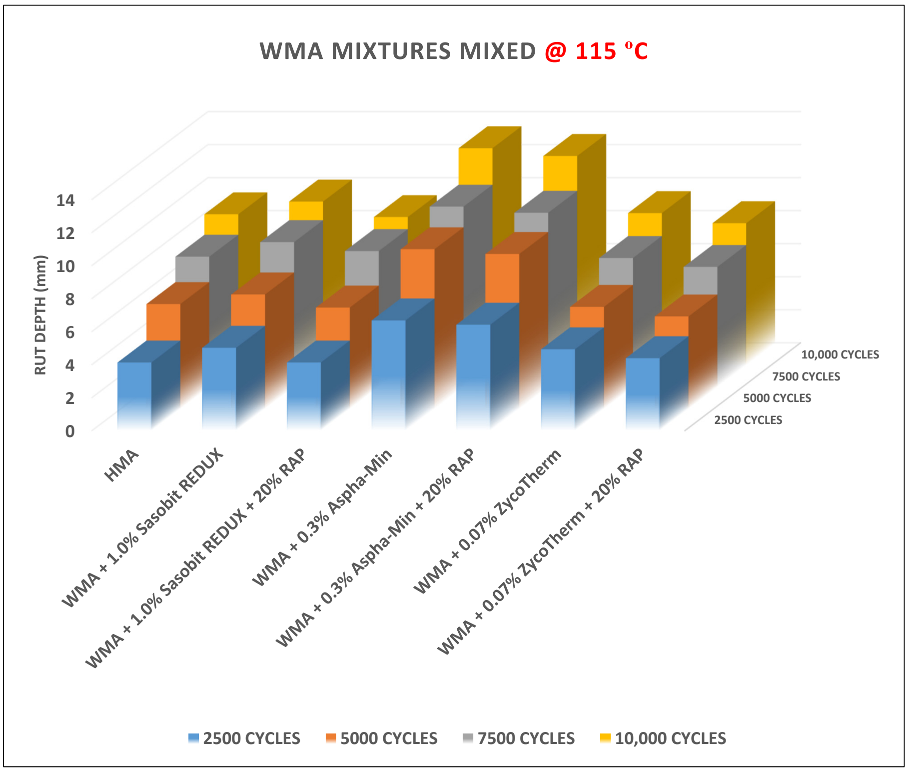


Figure 24. Rutting depth for the modified virgin and recycled WMA mixtures mixed @ 115 °C.

4. Conclusions

After investigating the mechanical and durable properties of the generated WMA mixtures in terms of the volumetric properties (air voids %, VFA %, and VMA %) and the performance tests (Resilient Modulus, Resilient Modulus Ratio, and Hamburg Wheel-Track) to evaluate the permanent deformation, moisture susceptibility, and rutting resistance, the following conclusions are drawn from the results and foregone discussion.

1. The mechanism of setting three individual heating levels of mixing and compacting for the generated mixtures proved to be very effective in selecting the optimal range of temperatures to mix and compact. In addition, the conducted optimal range of temperatures is suitable enough for the WMA mixtures to achieve the best mechanical and durable performance.
2. The best percentages of the used WMA additives in terms of the mechanical properties are set below in Table 19, in addition to the corresponding optimal range of mixing temperatures.
3. To produce WMA mixtures with a high amount of RAP (>25%), the dosage of the used additive has to increase within the recommended limits by increasing the employed percentage of RAP within the WMA mixtures in order to equalize the hardened effect and high viscosity of the combined blend.
4. The best durable properties have been achieved by mixing the mentioned WMA mixtures containing 0%, 20%, 40%, and 60% of RAP with 0.07%, 0.07%, 0.1%, and 0.125% of ZycoTherm® at 153 °C, respectively.

5. WMA-RAP mixtures which contain a high amount of RAP (>25%) have to be mixed at a temperature higher than 120 °C because the RAP requires a preheating and mixing process at restricted heating temperatures between (180 and 120 °C) in order to activate its binder and make it workable for mixing with the virgin materials.

Table 19. The best percentages of the used WMA additives, in addition to the optimal mixing temperatures for each type.

RAP % \ Additives %	Sasobit REDUX®		Aspha-Min®		ZycoTherm®	
	Percent	Optimal Mixing Temp. °C	Percent	Optimal Mixing Temp. °C	Percent	Optimal Mixing Temp. °C
0% RAP	1.0%	125 °C	0.3%	>135 °C	0.07%	115 °C
20% RAP	1.0%	135 °C	0.3%	135 °C	0.07%	<115 °C
40% RAP	1.5%	125 °C	0.4%	<125 °C	0.1%	125–135 °C
60% RAP	2.0%	125–135 °C	0.5%	125–135 °C	0.125%	>135 °C

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References

1. Zumrawi, M.M.E. Investigating causes of pavement deterioration in Khartoum State. *Int. J. Civ. Eng. Technol.* **2016**, *7*, 203–214.
2. Abuawad, I.M.A.; Al-Qadi, I.L.; Trepanier, J.S. Mitigation of moisture damage in asphalt concrete: Testing techniques and additives/modifiers effectiveness. *Constr. Build. Mater.* **2015**, *84*, 437–443. [CrossRef]
3. Mirzababaei, P. Effect of zycotherm on moisture susceptibility of Warm Mix Asphalt mixtures prepared with different aggregate types and gradations. *Constr. Build. Mater.* **2016**, *116*, 403–412. [CrossRef]
4. Mirzababaei, M.; Karimiazar, J.; Teshnizi, E.S.; Arjmandzadeh, R.; Bahmani, S.H. Effect of Nano-Additives on the Strength and Durability Characteristics of Marl. *Minerals* **2021**, *11*, 1119. [CrossRef]
5. Wang, T.; Xiao, F.; Zhu, X.; Huang, B.; Wang, J.; Amirkhanian, S. Energy consumption and environmental impact of rubberized asphalt pavement. *J. Clean. Prod.* **2018**, *180*, 139–158. [CrossRef]
6. Hill, B.T.; Behnia, B.; Buttlar, W.G.; Reis, H. Evaluation of warm mix asphalt mixtures containing reclaimed asphalt pavement through mechanical performance tests and an acoustic emission approach. *J. Mater. Civ. Eng.* **2013**, *25*, 1887–1897. [CrossRef]
7. Li, X.; Zhou, Z.; You, Z. Compaction temperatures of Sasobit produced warm mix asphalt mixtures modified with SBS. *Constr. Build. Mater.* **2016**, *123*, 357–364. [CrossRef]
8. Yousefi, A.; Behnood, A.; Nowruzi, A.; Haghshenas, H. Performance evaluation of asphalt mixtures containing warm mix asphalt (WMA) additives and reclaimed asphalt pavement (RAP). *Constr. Build. Mater.* **2021**, *268*, 121200. [CrossRef]
9. Ghabchi, R.; Singh, D.; Zaman, M. Laboratory evaluation of stiffness, low-temperature cracking, rutting, moisture damage, and fatigue performance of WMA mixes. *Road. Mater. Pavement Des.* **2015**, *16*, 334–357. [CrossRef]
10. Liu, S.; Zhou, S.; Peng, A. Analysis of moisture susceptibility of foamed warm mix asphalt based on cohesion, adhesion, bond strength, and morphology. *J. Clean. Prod.* **2020**, *277*, 123334. [CrossRef]
11. Praticò, F.G.; Giunta, M.; Mistretta, M.; Gulotta, T.M. Energy and environmental life cycle assessment of sustainable pavement materials and technologies for urban roads. *Sustainability* **2020**, *12*, 704. [CrossRef]
12. Padula, F.R.G.; Nicodemos, S.; Mendes, J.C.; Willis, R.; Taylor, A. Evaluation of fatigue performance of high RAP-WMA mixtures. *Int. J. Pavement Res. Technol.* **2019**, *12*, 430–434. [CrossRef]
13. Oner, J.; Sengoz, B. Utilization of recycled asphalt concrete with warm mix asphalt and cost-benefit analysis. *PLoS ONE* **2015**, *10*, e116180. [CrossRef] [PubMed]
14. Shu, X.; Huang, B.; Shrum, E.D.; Jia, X. Laboratory evaluation of moisture susceptibility of foamed warm mix asphalt containing high percentages of RAP. *Constr. Build. Mater.* **2012**, *35*, 125–130. [CrossRef]
15. Fakhri, M.; Maleki, H.; Hosseini, S.A. Investigation of different test methods to quantify rutting resistance and moisture damage of GFM-WMA mixtures. *Constr. Build. Mater.* **2017**, *152*, 1027–1040. [CrossRef]

16. Saleh, M.; Nguyen, N.H.T. Effect of rejuvenator and mixing methods on behaviour of warm mix asphalt containing high RAP content. *Constr. Build. Mater.* **2019**, *197*, 792–802.
17. Rodezno, C.; Brown, R. Improving accuracy of asphalt content determination by ignition test. *Road. Mater. Pavement Des.* **2017**, *18*, 112–127. [CrossRef]
18. Almeida, A.; Sergio, M. Evaluation of the potential of Sasobit REDUX additive to lower warm-mix asphalt production temperature. *Materials* **2019**, *12*, 1285. [CrossRef]
19. Wasiuddin, N.M.; Selvamohan, S.; Zaman, M.M.; Guegan, M.L.T.A. Comparative laboratory study of sasobit and aspha-min additives in warm-mix asphalt. *Transp. Res. Rec.* **2007**, *1998*, 82–88. [CrossRef]
20. Alam, M.N.; Aggarwal, P. Effectiveness of anti stripping agents on moisture susceptibility of bituminous mix. *Constr. Build. Mater.* **2020**, *264*, 120274. [CrossRef]
21. Austerman, A.J.; Mogawer, W.S.; Stuart, K.D. Variability of reclaimed asphalt pavement (RAP) properties within a state and its effects on RAP specifications. *Transp. Res. Rec.* **2020**, *2674*, 73–84. [CrossRef]
22. Tran, N.; Hall, K.; Easley, T. Evaluation of the Rapid Angle Measurement (RAM) device for calibration of the superpave gyratory compactor internal angle. In Proceedings of the 10th International Conference on Asphalt Pavements, Quebec City, QC, Canada, 12–17 August 2006.
23. Kumar, R.; Chandra, S. Warm mix asphalt investigation on public roads—A review. *Civ. Eng. Urban Plan. Int. J.* **2016**, *3*, 75–86. [CrossRef]
24. Cominsky, R.J.; Huber, G.A.; Kennedy, T.W.; Anderson, M. *The Superpave Mix Design. Manual for New Construction and Overlays*; Strategic Highway Research Program: Washington, DC, USA, 1994.
25. Design, S.M. *Asphalt Institute, Superpave Ser.*; The Asphalt Institute: College Park, MD, USA, 1969.
26. National Academies of Sciences, Engineering, and Medicine. *AASHTO T 209: Effect of Agitation Equipment Type on Theoretical Maximum Specific Gravity Values*; National Academies of Sciences, Engineering, and Medicine: Washington, DC, USA, 2012.
27. Prowell, B.D.; Dudley, M.C. Evaluation of measurement techniques for asphalt pavement density and permeability. *Transp. Res. Rec.* **2002**, *1789*, 36–45. [CrossRef]
28. Newcomb, D.E.; Arambula, E.; Yin, F.; Zhang, J.; Bhasin, A.; Li, W.; Arega, Z. *Properties of Foamed Asphalt for Warm Mix Asphalt Applications*; The National Academies Press: Washington, DC, USA, 2015.
29. Yu, X.; Zaumanis, M.; Santos, S.D.; Poulikakos, L.D. Rheological, microscopic, and chemical characterization of the rejuvenating effect on asphalt binders. *Fuel* **2014**, *135*, 162–171. [CrossRef]
30. Zhang, Y.; Cheng, H.; Sun, L.; Liu, L.; Hu, Y. Determination of volumetric criteria for designing hard asphalt mixture. *Constr. Build. Mater.* **2021**, *278*, 122243. [CrossRef]
31. Meng, Y.; Liu, L. Impact of Preheating Temperatures and RAP Characteristics on the Activation of RAP Binder. *Appl. Sci.* **2020**, *10*, 8378. [CrossRef]
32. Wang, D.; Riccardi, C.; Jafari, B.; Falchetto, A.C.; Wistuba, M.P. Investigation on the effect of high amount of Re-recycled RAP with Warm mix asphalt (WMA) technology. *Constr. Build. Mater.* **2021**, *312*, 125395. [CrossRef]
33. Caputo, P.; Abe, A.A.; Loise, V.; Porto, M.; Calandra, P.; Angelico, R.; Oliviero Rossi, C. The role of additives in warm mix asphalt technology: An insight into their mechanisms of improving an emerging technology. *Nanomaterials* **2020**, *10*, 1202. [CrossRef]
34. Bausano, J.; Steger, R. New Approach to Determine Standard Deviation and Precision Estimates for ASTM D4867/D4867M and AASHTO T283. *J. Test Eval.* **2021**, *50*. [CrossRef]
35. Deepa, S.; Krishnan, J.M. An investigation on resilient modulus of bituminous mixtures. In *Transport Research*; Lecture Notes in Civil Engineering; Springer: Singapore, 2020; pp. 895–905.
36. Tsai, B.-W.; Coleri, E.; Harvey, J.T.; Monismith, C.L. Evaluation of AASHTO T 324 hamburg-wheel track device test. *Constr. Build. Mater.* **2016**, *114*, 248–260. [CrossRef]
37. Morea, F.; Zerbino, R. Wheel tracking test (WTT) conducted under different standards. Study and correlation of test parameters and limits. *Mater. Struct.* **2015**, *48*, 4019–4028.
38. Sukhija, M.; Saboo, N.; Pani, A. Economic and environmental aspects of warm mix asphalt mixtures: A comparative analysis. *Transp. Res. Part. D. Transp. Environ.* **2022**, *109*, 103355. [CrossRef]
39. Fakhri, M.; Ghanizadeh, A.R.; Omrani, H. Comparison of fatigue resistance of HMA and WMA mixtures modified by SBS. *Procedia Soc. Behav. Sci.* **2013**, *104*, 168–177. [CrossRef]
40. Meghana, A.N.; Kavitha, G. Laboratory Studies on Warm Mix Asphalt (WMA) using ZycoTherm Additive with Partial Replacement of Reclaimed Asphalt Pavement (RAP). *i-Manag. J. Mater. Sci.* **2017**, *4*, 18–24.
41. Jomoor, N.B.; Fakhri, M.; Keymanesh, M.R. Determining the optimum amount of recycled asphalt pavement (RAP) in warm stone matrix asphalt using dynamic creep test. *Constr. Build. Mater.* **2019**, *228*, 116736. [CrossRef]
42. Doyle, J.D.; Howard, I.L. *Laboratory Investigation of High RAP Content Pavement Surface Layers*; Mississippi State University: Starkville, MS, USA, 2010.
43. Albayati, A.H. Performance evaluation of plant produced warm mix asphalt. *J. Eng.* **2018**, *24*, 145–164. [CrossRef]

44. Ameli, A.; Nasr, D.; Babagoli, R.; Pakshir, A.H.; Norouzi, N.; Davoudinezhad, S. Laboratory evaluation of rheological behavior of binder and performance of stone matrix asphalt(SMA) mixtures containing zycotherm nanotechnology, sasobit, and rheofalt warm mixture additives. *Constr. Build. Mater.* **2020**, *262*, 120757. [CrossRef]
45. Ameri, M.; Abdipour, S.V.; Yengejeh, A.R.; Shahsavari, M.; Yousefi, A.A. Evaluation of rubberised asphalt mixture including natural Zeolite as a warm mix asphalt (WMA) additive. *Int. J. Pavement Eng.* **2022**, 1–12. [CrossRef]