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MECHANICAL AND DURABILITY PROPERTIES OF WARM ASPHALT MIXTURE INVOLVING SYNTHETIC ZEOLITE

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ABSTRACT

Warm mix asphalt (WMA) blends at temperatures lower than those in conventional mixtures by 20-50 °C. this study examines and contrasts the mechanical properties of hot mix asphalt (HMA) mixtures with those of WMA mixtures using synthetic zeolite (SZ) addition. 3.0%, 5.0%, and 7.0% of the total asphalt mass were added as additive to create the WMA mixes. The following tests were conducted: Marshall stability, indirect tensile strength at 25°C and 60°C, tensile stiffness modulus (TSM), deformation strength (DS), and semi-circular bending (SCB) tests. Tensile strength ratio (TSR) calculations were used to assess the combinations' durability performance and determine their susceptibility to moisture. The findings showed that WMA mixtures with 5% SZ achieved the minimal ASTM standards for stability, flow, voids in mineral aggregates, and TSR at the same optimum binder concentration. Besides, this mixture showed higher resistance to deformation and cracking than the control HMA. A SZ content of 5% by weight of asphalt is recommended for the production of the WMA mixtures similar to that investigated in this study.

KEYWORDS: WMA; Synthetic Zeolite; Tensile strength; Tensile stiffness modulus; Semi-circular bending; Deformation Strength.

1. INTRODUCTION

In recent years, a new technology has appeared that allows asphalt to reduce mixing and compaction temperature lower than conventional hot mix asphalt (HMA), it is called warm mix asphalt (WMA). This technology can provide a better working environment, reductions in energy consumption, asphalt oxidation and carbon dioxide emission, increases the hauling distance and paving season. In addition to offering several advantages over hot mix asphalt (HMA), warm mix asphalt (WMA) technology was developed in Europe to save fuel and cut emissions. These advantages include a lower production temperature, placement in cold weather, longer hauling distances, better compaction with harder mixes, reduced thermal cracking, as well as cost and risk reduction [1-5]. Despite the advantages of reduced temperature, the main issue with WMA-paved roads is the potential of water damage and decreased rutting resistance as a result of less binder oxidation [6–9].

Recent advancements in WMA technology have enabled lower mixture construction temperatures, lower air pollution levels, and better fuel efficiency. The performance parameters of the combination remain unchanged as a result of the drop in production temperature [10, 11]. Additionally, this technology reduces the emissions of gases, greenhouse gases, or odors from asphalt plants, improving the working environment for those who work in factories or on construction sites [12].

Even though WMA blends have a number of advantages in terms of performance, it is important to look into the drawbacks of this technology. WMA asphalt samples are less resistant to water degradation than hot mixed asphalt mixtures, according to a number of studies [13]. Since the WMA mixtures are prepared at lower mixing and compaction temperatures than hot mix asphalt mixtures (usually 30 to 50 ºC lower), the aggregates may not be totally dry, which allows moisture to seep between the bitumen and the aggregate and weaken their adhesive bond. Additionally, for the preparation of the WMA mixture, many researchers recommended using dry aggregate because some types of WMA additives release water to lessen the viscosity of the bitumen,

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which results in a weaker binding between bitumen and aggregate [14, 15].

WMA mixes can be created using one of three techniques [16, 17]. Wax additives, chemical additives, and foam technologies are the order in which these methods are used. The viscosity of the binder drops in the first approach, resulting in a reduction in the mixing and compaction temperatures. While in the second and third procedures, moisture susceptibility may happen as a result of the WMA mixes being produced with water. Additionally, production at lower temperatures may result in aggregates that have not fully dried. The compromising effects of the aforementioned WMA additives have been shown in several investigations [18]. In contrast to HMA mixes, other investigations [19] discovered that the additives had no impact.

In this paper, the performance WMA is assessed using indirect tensile strength (ITS) at 25 and 60 °C, tensile strength ratio (TSR), semi-circular bending (SCB) at 25 °C, and deformation strength (DS) at 60 °C. Its objective is to establish an experimental base for the application of "SZ" in projects involving the building and rehabilitation of highway paving.

2. MATERIALS AND EXPERIMENTAL METHOD

2.1. Materials

In the experimental work, conventional bitumen of 40–50 penetration grade from Dora refinery were utilized in preparing the bituminous mixes. The tested characteristics of these bitumens are reported in Table 1.

As aggregate, sand and crushed gravel from the Al-Kazer quarry (located in Mosul city) were used. The selected gradation in this study was in the middle of the ASTM (D3515) [20] limitations, as shown in (Fig. 1). The aggregates' characteristics, including their angularity, toughness, soundness, water absorption, and specific gravities, were identified; the test results are shown in Table 2.

Mineral filler calcium carbonate (CaCo3) was utilized. It had a specific gravity of 2.731 and the ASTM designation D854 after being passed through a 200 sieve (ASTM, 2004).

Table (1): Properties of asphalt cement's physiochemistry

Property	Result	SCRB limits	ASTM limits
Penetration(25°C, 100g, dmm)	47	40-50	40-50
Ductility (25°C, cm)	150	100 min	100 min
Flash point, °C	267	240 min	240 min
Softening point, °C	52	51-62	50-58
Specific gravity	1.037	----	1.01-1.06
Loss of heat and air, %	0.18	0.75 max	0.2 max
Rotational Viscosity @ 135 °C. (CP)	465	----	----
Rotational Viscosity @ 165 °C. (CP)	133	----	----
Residue penetration, % of original	67	55 min	----
Solubility, %	99.7	99 min	99 min
Residue ductility (25°C, 5cm/min)	62	50 min	----
Increase of softening point after TFOT, °C	6	10 max	----

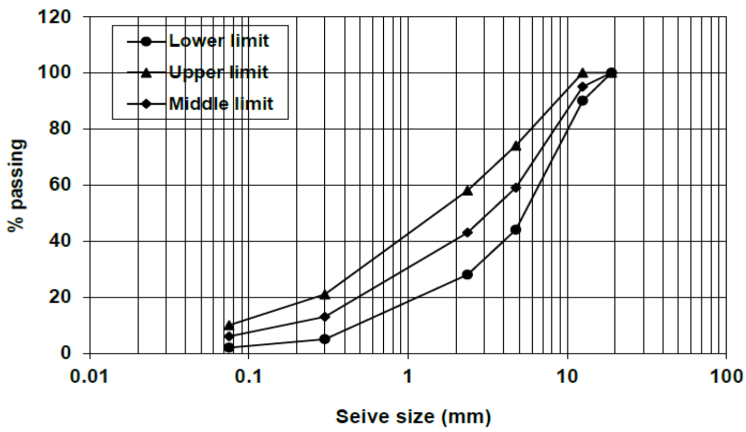

Fig. (1)|: Limits on aggregate gradation

Table (2): Results of Physical Properties of Selected Aggregate

Property	Aggregate		ASTM Designation No.
	Course	Fine	
Bulk sp.gr.	2.653	2.542	C – 127 C – 128
Apparent sp.gr.	2.692	2.591	C – 127 C – 128
Absorption %	0.763	1.42	C – 127 C – 128
Toughness,%	20 (≤ 30)*	----	C – 131
Angularity,%	98 (≥ 95)*		D – 5821

(*) Represent the minimum limits as per SCRB [33].

A white, fine powder of sodium-aluminum-silicate crystal that has been hydrothermally crystallized is the synthetic zeolite employed in this study as a WMA addition. In the warm mix, which includes 21% water by weight, all the crystalline water is released, resulting in the formation of an extremely fine water spray and a volumetric expansion of bitumen. The combination will be more workable and compatible at lower temperatures as a result of this volume expansion [21]. The additive percentages, i.e. increase by 2, was used in this study within the range 3 to 7% by weight of the binder. The producer developed the Synthetic Zeolite in accordance with the physical characteristics and chemical composition shown in Table 3.

Table 3. Physiochemical properties of synthetic zeolite

Property	SZ
Shape	Powder
Color	White
Ingredients	$Na_2O.Al_2O_3.2SiO_2$
Al_2O_3, %	29.1
Na_2o, %	16.1
SiO_2, %	32.8
L.O.I., %	21.2
Bulk density, g/cc	0.56

2.2 Sample preparation

It was determined in earlier investigations that either a manual or mechanical mixing method may be employed for this kind of additive [22]. Initially, a stirring bubble is used to progressively heat the bitumen to 140 ± 5 ºC while swirling it at a speed of 200 rpm. The stirrer speed is then raised to 240 rpm while the additives are gradually introduced to the binder. For 20 minutes, the asphalt binder and additives were combined.

The WMA mixtures were fabricated using a dry technique; the WMA component was heated, added to the asphalt, and mechanically mixed for 30 minutes at 150 °C to provide the mixtures the qualities they needed to mix at compaction temperatures. The asphalt was combined with the heated aggregate in a mixing bowl for several minutes, until the aggregates' surfaces were suitably covered with asphalt. The asphalt binder is compatible with the mixing temperatures. In Iraq, there are no available standards for the manufacture and compaction temperatures of WMA. Warm and hot asphalt mixtures that were being tested were all made in accordance with the (ASTM Designation: D 6925-03).

3. EXPERIMENTAL METHODS

Many mixtures were prepared for control and warm mixture with three different percentages of Synthetic Zeolite. All mixtures were evaluated with the following tests:

3.1. Marshall Stability and Flow Tests

Marshall stability and flow experiments were conducted on compacted specimens with varied synthetic zeolite contents according to ASTM D6927 [23]. After being submerged in 60°C water for 30 to 40 minutes, cylindrical compacted specimens with diameters of 100 and heights of 63.5 millimeters are continuously compressed at a rate of 51 millimeters per minute along their diameters. The Marshall stability value in (kN) is the maximum force measured during compression, whereas the flow in (mm) is the maximum deformation recorded at maximum force (kN). The Marshall quotient (kN/mm), which is the stability (kN) divided by the flow, is used to quantify stiffness (mm). After testing three samples, an average was calculated and used in the analysis.

3.2. Tensile characteristics and moisture susceptibility tests

Mixtures that are vulnerable to long-term moisture degradation are connected with bitumen detaching from the aggregate (also known as stripping). In dense Asphalts or Macadams with little void content, stripping is not a major concern. Even relatively solid materials that are porous to water run the danger of stripping, which could lead to a loss of internal cohesiveness and even the disintegration of the surfacing. The affinity between the aggregate and bitumen and, as a result, its capacity to withstand water's displacing impact, determine the likelihood of stripping.

Mechanics of a compacted bituminous mix that has been immersed in water is the focus of immersion mechanical testing. The ratio of the property after immersion divided by the prior property serves as an indirect indicator of stripping. The tensile strength ratio (TSR) is expressed as a percentage and compares identical bituminous specimens that have undergone wet conditioning to identical specimens that have not.

Tensile characteristics and moisture susceptibility of AC and SZ mixtures' were evaluated using indirect tensile strength (ITS) in accordance with ASTM D6931[24]. The air void content of the mixes averaged 7.0 percent. After being split into two groups for the ITS test, the AC and SZ samples were recombined (C). Marshall samples in triplicate were created for both the unconditional and conditional groups. The unconditional specimens were maintained at 25°C for 2 h, whereas the conditional samples were kept at 60°C for 24 h followed by 2 h at 25°C. On Marshall equipment, the samples were then tested until they failed at a rate of 51 mm/min. ITS has been computed using Eq (1). based on the specimen's failure load maximum.

$$ITS = 2P/\pi dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

P stands for ultimate load (N), t stands for specimen thickness (mm), and d stands for specimen diameter (mm) where ITS stands for indirect tensile strength (MPa).

The ITS test at 25ºC was used to calculate the conditional (C) to unconditional (U) tensile strength ratio (TSR), as given in Eq (2).

$$TSR\,(\%) = ITS_C / ITS_U \times 100 \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

For conditional and unconditional specimens, respectively, ITSC and ITSU is the indirect tensile strength (MPa).

The road base and base course layers' stiffness modulus is regarded as a crucial performance characteristic. The degree of traffic-generated tensile strains at the base of the road foundation, which lead to fatigue cracking, as well as the compressive strains induced in the subgrade, which may lead to permanent deformation, are controlled by this measurement of the bituminous layers' capacity to distribute load. The ratio of the highest stress to the maximum strain under uniaxial loading is known as the stiffness modulus. This is frequently referred to as the complicated modulus in visco-elastic materials such as bituminous composites. The phase angle is the amount of time that the strain always lags behind the tension due to the viscous nature of bituminous materials. Using the mean value of the horizontal deformation and the peak value of the applied vertical load from Eq (3), the tensile stiffness modulus (TSM) in (N/mm2) was calculated at 25°C and 60°C [25].

$$TSM = [P\,(\mu + 0.27)]/Dt] \ldots\ldots\ldots\ldots (3)$$

and where t is the test specimen's mean thickness (mm) and P is its peak value of applied vertical load (N), D is its average value of horizontal deformation (mm),and the Poisson's ratio is (a value of 0.35 is normally used).

3.3. Deformation strength test (S_D)

The ability to assess this failure using quick and easy testing can be highly helpful to evaluating the performance of asphalt mixtures given the significance of rutting damage in asphalt mixtures, especially in WMA combinations. A static test is used to assess the rutting potential of asphalt, and the mixture with the higher deformation strength is recognized as demonstrating higher resistance to rutting [26, 27]. Deformation strength is one of the easiest tests for evaluating the rutting of asphalt mixtures. The use of static deformation strength is advised due to the test's simplicity, according to Fakhri et al. [28], given the Wheel Track test's significant association between rutting resistance and static deformation strength. The Marshall technique is used to start this test by heating the sample to 60 °C for 30 minutes. The sample is put in the loading frame after drying the surface (Figure 3). After that, a loading head applies a vertical static load to the top of the specimen in the direction of sample compaction at a speed of 50.8 mm/min. The diameter and curvature radius of a loading head, which has a flat bottom and a round edge, are 40 mm and 10 mm, respectively. The specimen's force versus displacement is then recorded. The amount of deformation strength in this test is determined as follows:

$$SD = 0.32P / [10P + \sqrt{20y - y^2}]^2 \quad \text{………..(4)}$$

where P is the maximum load (N), y is the vertical deformation (mm), and SD is deformation strength (MPa).

3.4. Semi-Circular Bending (SCB) test

Cracks can occur through a number of propagation processes including fatigue, reflective (bottom-up), and thermal, is one of the key problems with asphalt mixtures that can considerably influence their durability, especially at low and intermediate temperatures (top-down). Indirect tensile tests, disk-shaped compact tension, single-edge notched beams, and SCB are a few of the methods that have been used to assess the fracture resistance of asphalt mixtures. Due to its simplicity, consistency of test results, and strong connection with field results, SCB is one of the tests that has been used the most in prior research [29]. In this investigation, the resistance to intermediate-temperature cracking was examined using SCB specimens with diameter and thickness measurements of 102 mm and 30 mm, respectively. The cylindrical specimens were made in accordance with ASTM D 8044-16 [30] and had a diameter and height of, respectively, 102 mm and 64 mm. To create the SCB specimens, the specimens were divided into 4 discs with a 30 mm thickness, then cut in half. The middle of the discs were then cut with notches that were 2 mm thick and a variety of lengths, including 25 mm, 32 mm, and 38 mm.

The SCB fracture test was carried out using a Universal Testing Machine UTM that had a three-point bend fixture. The specimens were put in the environmental chamber for temperature equilibrium prior to testing, with a goal of 1.5 ± 0.5 hours at 25 ± 1ºC. The loading rate for this study was set at 0.5 mm/min. According to the principles of linear elastic fracture mechanics, the flexibility index and fracture energy as well as the critical J-integral (Jc) based on the principles of nonlinear elastic fracture mechanics were used to assess the cracking resistance of asphalt mixes. Calculations for the fracture energy (Gf) and flexibility index (FI) are as follows:

$$FI = [G_f / \text{absolute}(m)] \times 0.01 \quad \text{…………….. (4)}$$

$$G_f = W_f / A$$

Where m stands for the load-displacement curve's inflection point's slope, Wf for the area under the curve, and A for the ligament's unit area.

Kasser et al. [31] established the cracking resistance index (CRI) as follows to study the intermediate-temperature cracking resistance:

$$CRI = G_f / p_{max} \quad \text{………………………….. (5)}$$

Pmax is the highest load determined by the load-displacement curve. The critical J-integral, or the rate at which critical strain energy is released, is expressed in units of kJ/m^2:

$$J_C = -(1/b)(dU/da) \quad \text{…………………….. (6)}$$

Where a and b are the notch length and specimen's thickness, respectively, U is the strain energy, and dU/da is the change of strain energy with notch depth (i.e., the area under the load-displacement curve up to the maximum load).

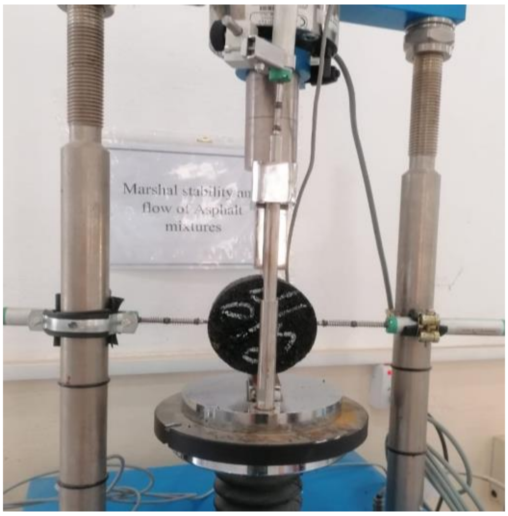

Fig. (2): ITS test

(a) (b)

Fig. (3): Kim test (a- Mold, b- Kim test)

(a) (b)

Fig. (4): Semi-Circular Bending (SCB) test (a- SCB specimens, b- Test set-up used for SCB.)

4. RESULTS AND DISCUSSIONS

4.1. Statistical considerations

In this study, the null hypothesis (H0=0) and 0.05 level of significance (ANOVA) were utilized to compare AC and SZ-mixes [28]. To determine whether there is a significant difference between two averages, the least significant difference value (LSDV) was provided. The difference between two averages is regarded significantly different if it is more than or equal to the LSDV, and vice versa. Table 4 shows the average differences as alphabet letters. Averages with the same letters indicate that the averages were not significant.

Table (4): Statistical analysis of Marshall properties, ITS, SD and SCB of AC and SZ mixtures

Property	AC	SZ3	SZ5	SZ7
Marshall stability at 60°C, Kn	12.36±0.35A	10.11±1.22A	11.14±0.68A	10.34±0.71A
Marshall flow, mm	3.4±0.1A	3.2±0.34A	3.5±0.26A	3.3±0.45A
MQ kN/mm	3.63±0.21A	3.16±0.37A	3.18±0.3A	3.3±0.56A
ITS at 25°C, MPa	0.95±0.071A	0.91±0.033A	0.94±0.027A	0.84±0.066A
ITS at 60°C, MPa	0.82±0.051A	0.69±0.042C	0.79±0.038B	0.68±0.013C
SD, MPa	4.23±0.27A	4.14±0.30A	5.03±0.15A	4.66±0.22A
Maximum load, P_{max}, Kn 25 mm notch size	1.295±0.077A	1.626±0.116A	1.579±0.095A	1.629±0.130A
32 mm notch size	1.073±0.179A	1.220±0.121A	1.136±0.129A	1.089±0.148A
38 mm notch size	0.777±0.124A	1.019±0.150A	0.647±0.142A	1.047±0.129A
Fracture energy, kJ/m^2 25 mm notch size	1.654±0.275A	1.661±0.277A	1.429±0.34A	1.680±0.263A
32 mm notch size	1.562±0.205A	1.481±0.252A	1.171±0.220A	1.384±0.194A
38 mm notch size	1.098±0.165A	1.369±0.178A	0.971±0.197A	1.375±0.143A

N.B.: Means with different letters vertically have a significant difference at $p \leq 0.05$ using the Fisher LSD Method.

4.2. Marshall stability, flow, and Marshall quotient

Synthetic zeolite mixes made with penetration 40 – 50 binder have marginally lower Marshall stability ratings as compared to the AC reference mix (Fig. 5a). Among SZ mixtures, SZ5 has a stability value that is nearly comparable to that of the AC control mix.

To better disperse applied loads and resist creep deformation, a dense-graded mixture with an elevated Marshall quotient (MQ) (Fig. 5d) has a higher stiffness. Very high stiffness mixtures must be handled with attention since they are more prone to break if placed on foundations that are not adequately supported by the materials.

The synthetic zeolite mixes had relatively a higher flow value at SZ5 (Fig. 5b) than the AC reference mixtures, indicating that the synthetic zeolite specimens are less brittle than the control mix. All synthetic zeolite combinations meet the minimal ASTM [32] and SCRB [33] standards of 8kN stability, 2-4mm flow, 3-5 percent air voids, and 14 percent VMA at the same optimum binder concentration.

It is possible that while having lower Marshall stability than control samples, synthetic zeolite mixtures have a greater capacity for causing failure. The MQ value of synthetic zeolite is relatively lower than that of the control mixtures. What's known as the MQ (a pseudo stiffness) is a well-known gauge for the resistance of a substance to rutting due to long-term deformations and shear stresses [25].

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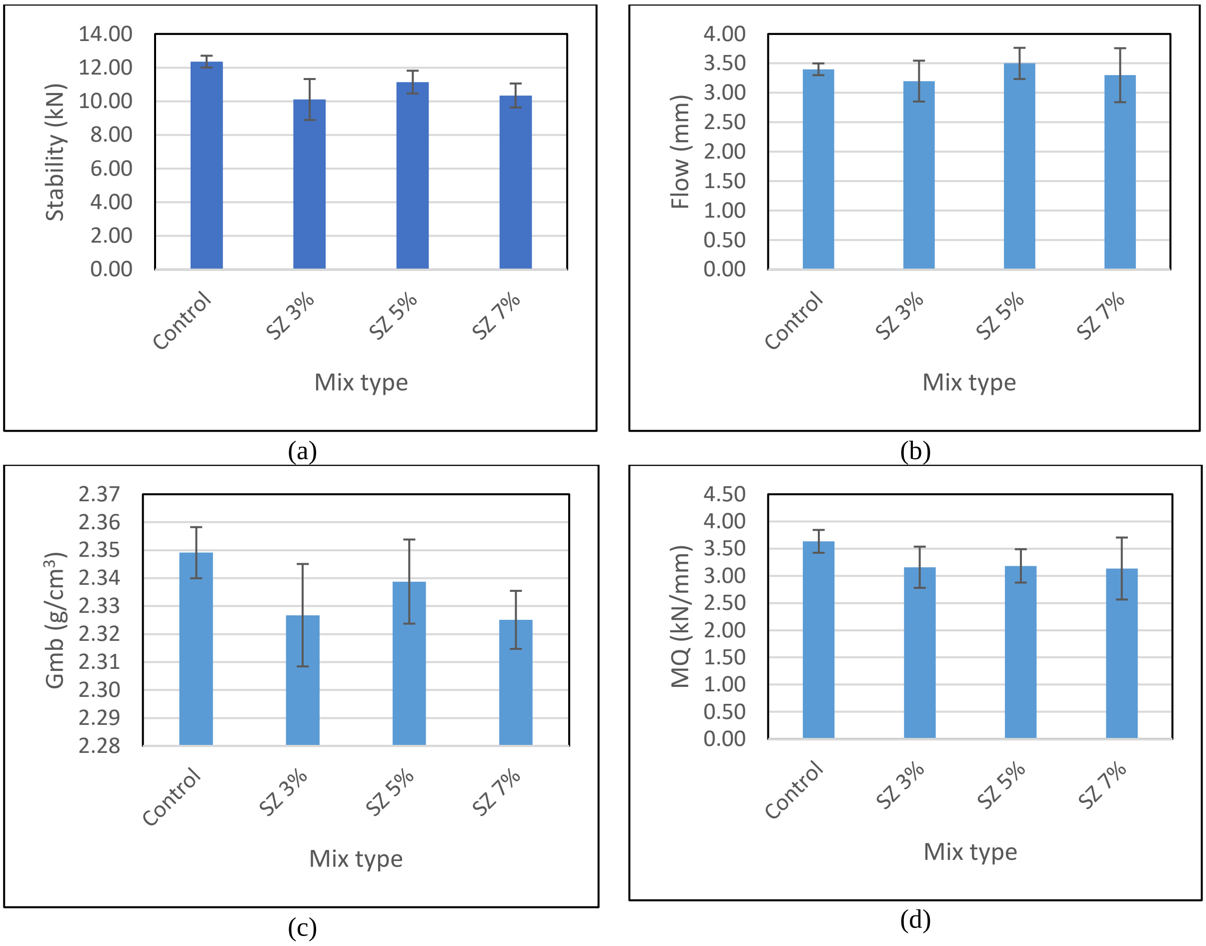

Fig. (5): Marshall parameters of control and SZ mixtures
(a- stability, b- flow, c- Gmb, & d- Marshall quotient)

4.3. Indirect tensile strength (ITS)

Synthetic zeolite mixes were subjected to the ITS test to examine the effect of moisture and temperature on tensile strength. Figure 6a depicts the tensile strength of various blends in terms of unconditioned and conditioned tensile strength. For both conditioned and unconditioned synthetic zeolite specimens, as indicated in the figure, ITS magnitudes are smaller than those from control AC mixtures. The ITS values of conditioned specimens drop when synthetic zeolite is used in asphalt mixtures.

The ITS values of unconditioned specimens drop when synthetic zeolite is used in asphalt mixtures. The elongation and ductility of the binder may have been harmed at intermediate temperatures by the synthetic zeolite used in its production.

SZ 3, SZ 5, and SZ 7 combinations reduce the ITS value of unconditioned specimens by 4.21 percent,1.0 percent, and 11.6 percent, respectively, as compared to the AC mixture. Similarly, the average ITS values of conditioned specimens of SZ 3, SZ5, and SZ 7 combinations decrease by 15.8%, 3.7%, and 17.1%, respectively. Decreased ITS values of unconditioned specimens, maybe, due to the addition of Zeolite material in asphalt mixtures as reported in a previous studie [5].

To further test AC and SZ combination moisture susceptibility, the tensile strength ratio (TSR) of the treated vs untreated group is depicted in Fig. 6b. All SZ mixtures have a lower TSR than the AC mixture, which indicates that they are less resistant to moisture damage. Adding synthetic zeolite to a combination has been found to lower the tensile strength ratio by other researchers [22, 34]. When compared to an AC mixture, the TSR values of SZ 3, SZ 5, and SZ 7 mixtures are lowered by 11.6%, 2.3%, and 5.55%, respectively. This observation points out that the impact of SZ on moisture damage is negatively impacts the tensile characteristics of AC mixtures.

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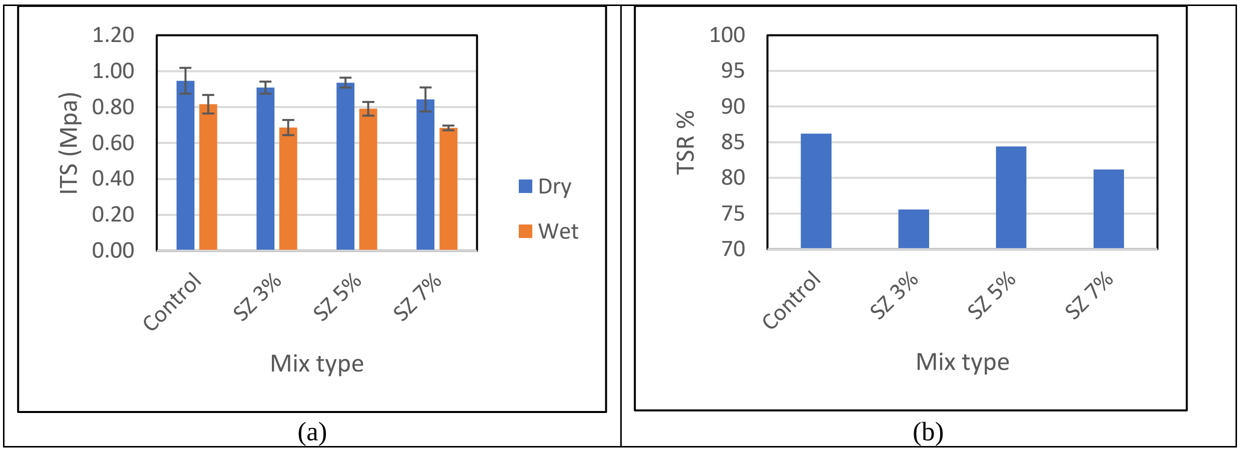

Fig. (6): Indirect tensile strength properties of control and SZ mixtures
(a- In direct tensile strength & b- tensile strength ratio)

4.4. Tensile stiffness modulus (TSM)

Fig. 7 shows the tensile stiffness modulus (TSM) values obtained at 25°C for dry condition and 60°C for wet condition. The average of three measurements was utilized for each type of mixture. According to the results, the TSM values of the synthetic zeolite mixes are lower than those of the control mixes at both testing temperatures (25°C and 60°C). The TSM values of SZ 3, SZ 5, and SZ 7 mixtures evaluated at 25°C are 6.8%, 1.9 percent, and 11.2 percent lower than the AC control mixture, as seen in the graph. The average TSM values of SZ 3, SZ 5, and SZ 7 combinations decrease by 7%, 4.8%, and 26.4%, respectively, when tested at 60°C. This exam's findings are comparable to those of the ITS test.

The synthesized zeolite specimens' TSM values were considerably lower than those of the reference mix, however this shows that the synthetic zeolite combinations have lower values of tensile strength at failure ITS while not being as stiff as the control mix, which would imply significantly bigger values of stresses. This would also imply that the artificial zeolite mixtures seem to be able to endure somewhat higher tensile strains before breaking. The flow value supports the conclusions.

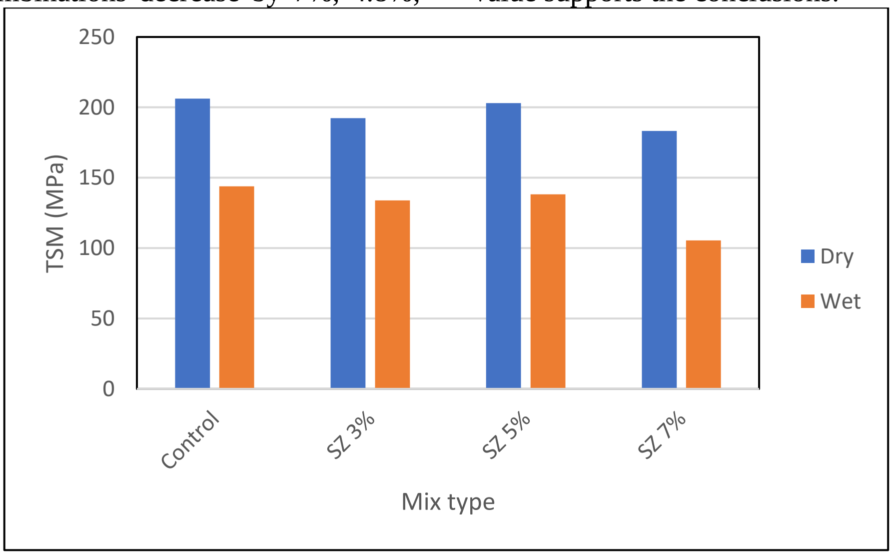

Fig. (7): Indirect tensile stiffness modulus of control and SZ mixtures

4.5. Deformation strength (SD)

The findings of the deformation tests used to gauge the WMA mixes' resistance to rutting are shown in Figure 8. As shown in the figure, adding 5% and 7% SZ increased the deformation strength of WMA mixtures while adding 3% SZ caused it to significantly decrease. The 5% SZ specimens also outperformed the other specimens. This indicates that the combination containing 5% SZ give the most stable WMA to endure rutting because to the mastic layer surrounding the aggregate. The average DS values of SZ 5, and SZ 7 combinations increase by 18.9%, and 10.1%, respectively, whereas the average DS values of SZ 3 is approximately similar to those of AC. SZ5 and SZ7 improving the SD of AC mix is because SZ-asphalt binder is higher elastic recovery than virgin asphalt binder.

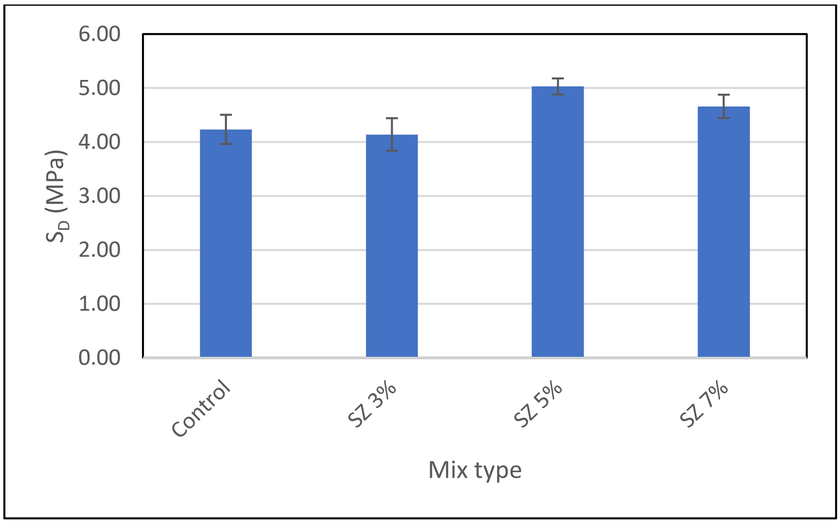

Fig. (8): deformation strength test values for control and SZ mixtures

4.6. Semi-Circular bending (SCB)

SCB experiments were used to analyze the performance at intermediate temperatures and determine Pmax, Gf, FI, CRI, and Jc. The maximum load (i.e., Pmax) of the various combinations at various notch sizes is shown in Fig. 9. The maximum load noted during the SCB test corresponds to Pmax, which measures the asphalt mixture's strength. As anticipated, the Pmax value drops as the notch length increases. It occurs when the length of the notch increases because the ligament area of asphalt mixtures decreases. The findings indicate that the SZ mixes had greater Pmax values than the AC reference mix at all three notch sizes.

Figure (9) also shows the Max. load (Pmax) for mixtures that contain different percentages of synthetic zeolite with different notch depth in the middle of the specimens (25, 32, 38 mm). The results show that (Pmax) increased by 25.5%, 21.9%, and 25.79%, at SZ 3, SZ 5, and SZ 7, respectively at notch depth 25 mm. SZ improving the Pmax of AC mix is because SZ-asphalt binder is higher elastic recovery than virgin asphalt binder.

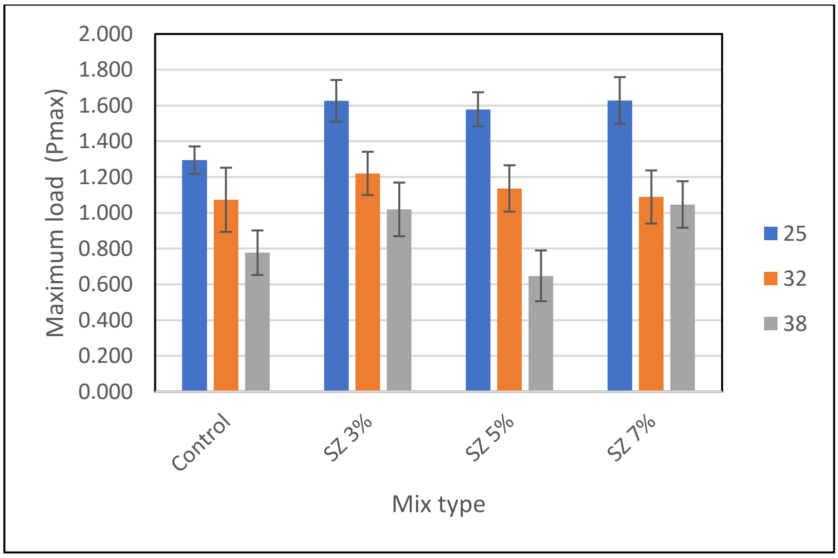

Fig. (9): Maximum load of control and SZ mixtures

Fracture energy, a linear-elastic parameter, is the most popular for analyzing the behavior of asphalt mixtures during fracture. It has been used to evaluate the fracture tolerance of the binder, mixture, and interstitial component at intermediates [35, 36].

The values of fracture energy (Gf), a linear quantity used to evaluate the behavior of fractures, are shown in Fig. 10. As can be shown, the value of fracture energy for AC and SZ combinations falls as the notch size increases. This is because larger notches limit the effective ligament area of the specimens [37].

There was no significant effect for the G_f at the SZ 3 and SZ 7, while there was a decrease of 13.6% at SZ 5 for the notch depth 25 mm, and so on for notch depth 32 and 38 mm.

It should be noted that the quantity of displacement and load-bearing capacity are related to the asphalt mixture's fracture energy at an intermediate temperature. The load-bearing capacity and displacement for the SZ mixes improved and declined, respectively. However, the decrease in displacement was insufficient to offset the rise in peak load, which led to an increase in fracture energy when synthetic zeolite was added to the binder.

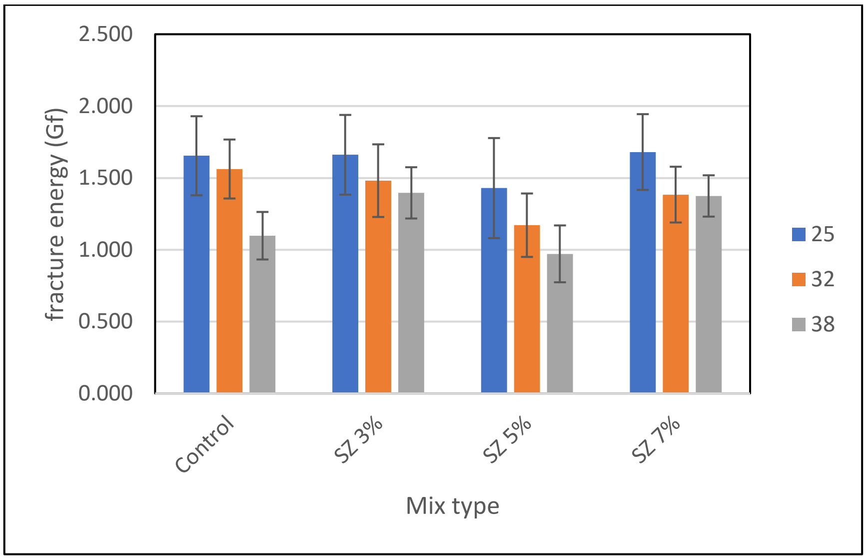

Fig. (10): Fracture energy of control and SZ mixtures

The FI values for various combinations at various notch sizes are shown in Fig. 11. It should be noted that a mixture with a greater FI is likely to be more resistant to crack propagation. From this figure, it is clear that the FI values of all SZ mixes approximately similar to the FI value of AC mix at 38mm notch depth, whilst the addition of SZ reduced the FI values of AC mixes at 25mm and 32mm notch depth.

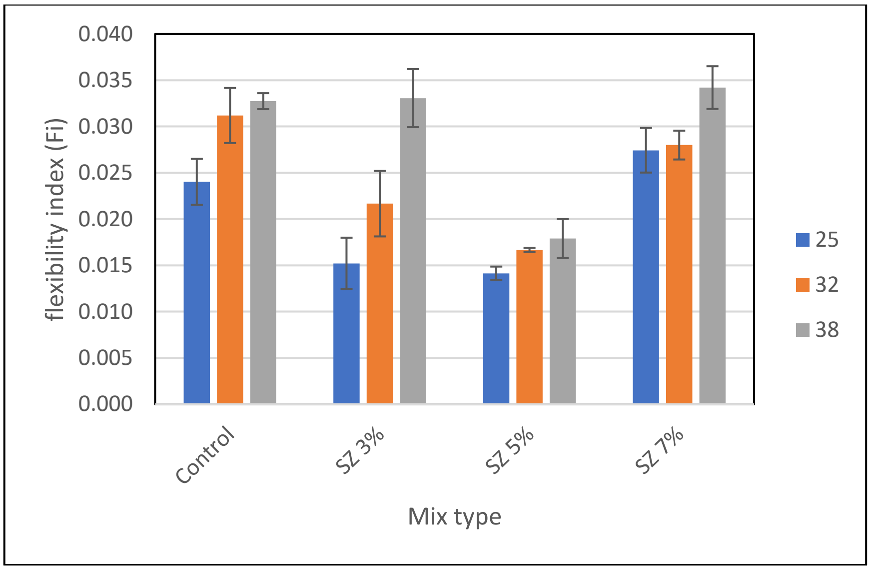

Fig. (11): Flexibility index of control and SZ mixtures

The CRI value for various combinations at various notch sizes is shown in Fig. 12. The findings demonstrate that as the notch size is increased, the CRI values of AC and SZ mixtures rise.

The CRI value of SZ3 mix is approximately similar to that of AC mix at 38mm notch depth. Whereas, SZ5 and SZ7 show decreased in CRI values. The percentages of decreases are 14%, 24.8%, and 28% for SZ 7%, SZ 5%, and SZ 3%, respectively at notch depth 25mm. This indicates that at low-intermediate temperatures, the SZ binder has a lower viscosity than the base asphalt binder. As a result, the SZ mixture has lower crack resistance than the AC mixture.

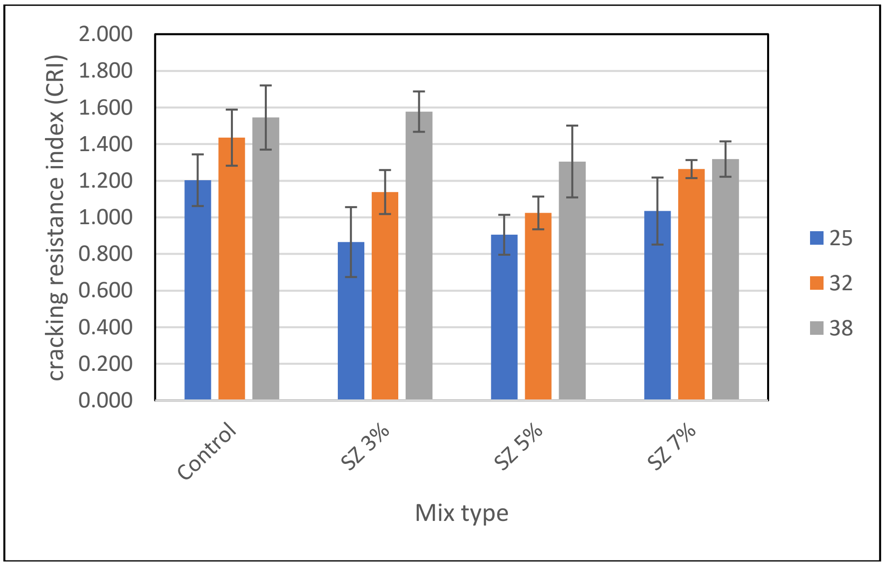

Fig. (12): Cracking resistance index of control AC and SZ mixtures

The critical J-integral values of various AC and SZ mixes are shown in Fig. 13. There is no accepted minimum Jc value that may be used to identify asphalt mixtures that are more prone to fatigue cracking. However, a minimum acceptable value for Jc has been established in the literature in the range of 0.5 to 0.65 [38]. It makes sense to assume that SZ mixes would reduce fatigue resistance. The findings, however, demonstrate that all SZ combinations exhibit higher Jc values than AC mixtures, which is a sign of greater resistance to fatigue cracking. This might be as a result of the use of pre-peak absorbed strain energy in the Jc calculation. Before the mixture's tenacity is lost in the post-peak stage, synthetic zeolite could at this point make the mixture more elastic and stiff.

Fig. 13 also shows that all AC and SZ mixtures the Jc values of SZ 3%, SZ 5%, and SZ 7% mixtures are 0.103, 0.15 and 0.113, respectively. The highest increase in Jc value is associated with SZ 5% followed by SZ 7% and the lowest increase is associated with SZ 3%. This indicates that these mixtures are more resistance to fatigue cracking than AC and other SZ mixtures.

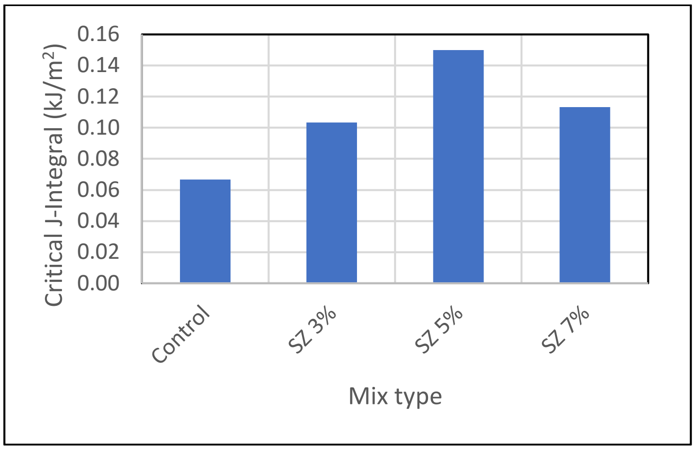

Fig. (13): Critical J-integral of control and SZ mixtures

5. CONCLUSIONS

In this work, the effectiveness of HMA with synthetic zeolite chemical admixtures is assessed. The degree of moisture damage was evaluated using TSR, the degree of cracking resistance was evaluated using SCB, and the degree of rutting resistance was evaluated using DS. Following inferences are made from the test results used in this study:

1. SZ mixes show lower Marshall stability and Marshall quotient values with slightly higher flow values than the control HMA. Moreover, the SZ5 mixture shows approximately similar stability and Marshall quotient values to those of HMA.
2. SZ mixes show lower tensile strength and tensile strength ratio than the control HMA. Moreover, the SZ5 mixture satisfies the minimum tensile strength ratio of 85%. This shows that the SZ5 mixture is more resistant to moisture deterioration (i.e., have a longer lifespan) among other SZ mixtures.
3. SZ mixtures show higher J-integral than HMA. SZ5 resulted in the highest increase in J-integral among other SZ mixes.
4. SZ mixes show higher deformation strength values than the control HMA. Moreover, the SZ5 mixture shows highest increase in deformation strength among other SZ mixes.
5.

6. REFERENCES

Hurley, G.C., B.D. Prowell, and G. Reinke, *Evaluation of potential processes for use in warm mix asphalt.* Journal of the Association of Asphalt Paving Technologists, 2006. **75**(4).

Goh, S.W., Z. You, and T.J. Van Dam. *Laboratory evaluation and pavement design for warm mix asphalt*. in *Proceedings of the 2007 Mid-Continent transportation research symposium*. 2007. Iowa state university Ames, Iowa.

Kristjánsdóttir, Ó., et al., *Assessing potential for warm-mix asphalt technology adoption.* Transportation Research Record, 2007. 2040(1): p. 91-99.

d'Angelo, J., et al., *Warm-mix asphalt: European practice*. 2008, United States. Federal Highway Administration. Office of International Programs.

West, R., et al., *Engineering properties and field performance of warm mix asphalt technologies.* National Cooperative Highway Research Program, Washington, DC, USA, NCHRP Final Report Project, 2014(09-47A).

Hurley, G.C. and B.D. Prowell, *Evaluation of Evotherm for use in warm mix asphalt.* NCAT report, 2006. **2**: p. 15-35.

Gandhi, T., W. Rogers, and S. Amirkhanian, *Laboratory evaluation of warm mix asphalt ageing characteristics.* International Journal of Pavement Engineering, 2010. **11**(2): p. 133-142.

Rushing, J.F., M. Mejías-Santiago, and J.D. Doyle, *Assessment of warm-mix asphalt for heavy* *traffic airfields.* Transportation research record, 2013. **2371**(1): p. 41-48.

Sebaaly, P.E., E.Y. Hajj, and M. Piratheepan, *Evaluation of selected warm mix asphalt technologies.* Road Materials and Pavement Design, 2015. **16**(sup1): p. 475-486.

Hassan, Z., et al., *Influence of bentonite additive on bitumen and asphalt mixture properties.* World Academy of Science, Engineering and Technology, 2012. **6**: p. 08-24.

Babagoli, R., R. Mohammadi, and M. Ameri, *The rheological behavior of bitumen and moisture susceptibility modified with SBS and nanoclay.* Petroleum Science and Technology, 2017. **35**(11): p. 1085-1090.

Ameli, A., et al., *Laboratory evaluation of rheological behavior of binder and performance of stone matrix asphalt (SMA) mixtures containing zycotherm nanotechnology, sasobit, and rheofalt warm mixture additives.* Construction and Building Materials, 2020. **262**: p. 120757.

Zhao, S., et al., *Comparative evaluation of warm mix asphalt containing high percentages of reclaimed asphalt pavement.* Construction and Building Materials, 2013. **44**: p. 92-100.

Chiu, C.-T., *Use of ground tire rubber in asphalt pavements: Field trial and evaluation in Taiwan.* Resources, Conservation and Recycling, 2008. **52**(3): p. 522-532.

Silva, H.M., et al., *Optimization of warm mix asphalts using different blends of binders and synthetic paraffin wax contents.* Construction and Building Materials, 2010. **24**(9): p. 1621-1631.

Gong, J., et al., *Performance evaluation of warm mix asphalt additive modified epoxy asphalt rubbers.* Construction and Building Materials, 2019. 204: p. 288-295.

Norouzi, N., A. Ameli, and R. Babagoli, *Investigation of fatigue behaviour of warm modified binders and warm-stone matrix asphalt (WSMA) mixtures through binder and mixture tests.* International Journal of Pavement Engineering, 2021. 22(8): p. 1042-1051.

Kim, Y.-R., J. Zhang, and H. Ban, *Moisture damage characterization of warm-mix asphalt mixtures based on laboratory-field evaluation.* Construction and Building Materials, 2012. **31**: p. 204-211.

Fathifazl, G., et al., *New mixture proportioning method for concrete made with coarse recycled concrete aggregate.* Journal of materials in civil engineering, 2009. **21**(10): p. 601-611.

American society for Testing and Materials (ASTM), standard Specification for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures, D 3515 – 76a, . 2015.

Hurley, G.C. and B.D. Prowell, *Evaluation of Aspha-Min zeolite for use in warm mix asphalt.* NCAT report, 2005(05-04).

Yousefi, A., et al., *Performance evaluation of asphalt mixtures containing warm mix asphalt (WMA) additives and reclaimed asphalt pavement (RAP).* Construction and Building Materials, 2021. 268: p. 121200.

ASTM, *American Society for Testing and Materials,* in *Road and Paving Materials Vehicle Pavement Systems*. 2015.

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

Zoorob, S. and L. Suparma, *Laboratory design and investigation of the properties of continuously graded Asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt).* Cement and concrete composites, 2000. **22**(4): p. 233-242.

Kim, K.W., Y.S. Doh, and S.N. Amrikhanian, *Feasibility of deformation strength for estimation of rut resistance of asphalt concrete.* Road materials and pavement design, 2004. **5**(3): p. 303-322.

Doh, Y.S., et al., *Framework for developing a static strength test for measuring deformation resistance of asphalt concrete mixtures.* Construction and Building Materials, 2007. **21**(12): p. 2047-2058.

Fakhri, M., H. Maleki, and S.A. Hosseini, *Investigation of different test methods to quantify rutting resistance and moisture* *damage of GFM-WMA mixtures.* Construction and Building Materials, 2017. 152: p. 1027-1040.

Nsengiyumva, G., *Development of semi-circular bending (SCB) fracture test for bituminous mixtures.* 2015.

ASTM (American Society for Testing and Materials) (2016). Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures, D8044.

Kaseer, F., et al., *Development of an index to evaluate the cracking potential of asphalt mixtures using the semi-circular bending test.* Construction and Building Materials, 2018. 167: p. 286-298.

ASTM (American Society for Testing and Materials) (2015). Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures, D6927.

SCRB (State cooperation of road and bridges), Hot mix asphaltic concrete pavement, Iraqi standard specification, Ministry of Housing and Construction, R. Department of Design and Study, Editor. 2003.

Joni, H.H. and H.H. Mohammed, *Effect of warm asphalt additive on pavement performance.* Journal of Engineering and Sustainable Development, 2019. **23**(05).

Yan, Y., D. Hernando, and R. Roque, *Fracture tolerance of asphalt binder at intermediate temperatures.* Journal of Materials in Civil Engineering, 2017. **29**(9): p. 04017108.

Yan, Y., et al., *Fracture energy density of interstitial component of asphalt mixtures.* Materials and Structures, 2018. 51(5): p. 1-13.

Singh, D., P.K. Ashish, and S.F. Chitragar, *Laboratory performance of recycled asphalt mixes containing wax and chemical based warm mix additives using semi circular bending and tensile strength ratio tests.* Construction and Building Materials, 2018. **158**: p. 1003-1014.

Mohammad, L.N., et al., *Laboratory evaluation of asphalt mixtures that contain biobinder technologies.* Transportation research record, 2013. **2371**(1): p. 58-65.