Journal of Building Engineering 75 (2023) 106985

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Mechanical performance and statistical analysis of natural and synthetic zeolite-warm mix asphalt as a function of compaction efforts

A.I. Al-Hadidy [a,*], Radhwan Alzeebaree [b,c], Juma Abdulla Abdal [b], Anıl Niş [d]

[a] *Civil engineering department, University of Mosul, Mosul, Iraq*
[b] *Highway and Bridge Department, Duhok Polytechnic University, Duhok, Iraq*
[c] *Civil Engineering Department, Nawroz University, Duhok, Iraq*
[d] *Civil Engineering Department, Istanbul Gelisim University, Istanbul, Turkiye*

ARTICLE INFO

Keywords:
Synthetic zeolite
Warm-mix asphalt
Natural zeolite
Compaction effort
Resilient modulus
Tensile strength
Creep compliance

ABSTRACT

The compaction effort of mixes should be studied with caution since it significantly influences the mixtures' performance. A laboratory evaluation of warm mix asphalt (WMA) including synthetic zeolite (SZ) and natural zeolite (NZ) was conducted in this study. Marshall properties, tensile strength ratio, indirect tensile strengths at 25 and 60 ˚C, resilient modulus at 25 ˚C, and creep compliances at 40 ˚C were all examined. The NZ and SZ binders were produced by mixing one base binder (40/50 penetration grade) with 5% NZ and SZ binder components by weight. The 90 specimens were produced using the Marshall compactor at three different compaction efforts (35, 50, and 75 blows/face). Statistical analysis was conducted to examine the behavior and outcomes of asphalt binders. The results showed that (1) Both NZWMA and SZWMA combinations require 35 blows/face compaction effort to meet the minimum criteria of 8 kN stability, 2–4 mm flow, 85% tensile strength ratio, 14% VMA, and 448 kPa unconditioned tensile strength; (2) The production of NZWMA mixtures saves more time and fuel in the field than SZWMA mixtures while meeting the Marshall properties, creep performance, and moisture susceptibility at 35 blows/face compaction effort; and (3) A general trend of the Marshall, creep compliance, tensile strength, and resilient modulus performance as a function of compaction effort was observed for the NZWMA and SZWMA mixes used in this study.

1. Introduction

Standard hot mix asphalt (HMA) constructions with a higher temperature production (>140 ˚C) outcomes in higher fuel costs, toxic pollutants, and significant gaseous emissions [1–3]. Over the years, the HMA industry has made consistent efforts to protect nonrenewable resources to prevent environmental contamination [4,5]. That has resulted in a search for methods that minimize fuel consumption and energy while still producing asphalt mixes with the required properties and workability. The utilization of warm-mix asphalt technology is a positive move. The four varieties of asphalt mixes are hot-mix asphalt (>150 ˚C); warm-mix asphalt (100 ˚C–140 ˚C); half-warm mix asphalt (60 ˚C–100 ˚C); and cold-mix asphalt (0 ˚C–30 ˚C) [6]. The organization of asphalt mixes in

* Corresponding author.
E-mail addresses: alhadidy@uomosul.edu.iq, abdet76@gmail.com (A.I. Al-Hadidy), radhwan.alzeebaree@dpu.edu.krd (R. Alzeebaree), gumaabdal@gmail.com (J.A. Abdal), anis@gelisim.edu.tr (A. Niş).

https://doi.org/10.1016/j.jobe.2023.106985
Received 22 March 2023; Received in revised form 21 May 2023; Accepted 31 May 2023
Available online 9 June 2023

Fig. 1 is based on energy consumption, the required temperature, and gas emissions. It was investigated that every 10-degree Celsius reduction in asphalt manufacturing temperatures reduces fuel exhaustion by roughly 1 L and CO_2 emissions by 1 kg/t [7].

Among the methods mentioned above, WMA is commonly utilized to produce asphalt pavement under higher temperatures [8,9]. However, the temperature requires for WMA (100°C–150 °C) is much less than the temperature required for HMA (>150 °C), so WMA may be manufactured at low temperatures without sacrificing mix performance [10]. WMA minimizes hazardous emissions and gaseous pollutants from asphalt manufacturers, while also enhancing the working environment [11,12]. Aside from the profits of lower temperatures, using WMA leads to extended hauling distances and enhanced workability. Furthermore, a low manufacturing temperature reduces energy usage and lowers production costs [13,14].

In 1928; Jacob realized and innovated "Foamed Asphalt" in Germany. After the inception, numerous additional devices obtained patent rights and licenses to sell in the United States for laboratory and field testing. In the mid-1990s, researchers led the first experimental work on warm-mix foaming techniques in Europe. In 2006, the National Centre for Asphalt Technology (NCAT) published studies on Evotherm, Asphamin, and Sasobit. Furthermore, the National Cooperative Highway Research Program (NCHRP) established several initiatives to study the behavior of WMA in pavement construction. Several papers and ongoing research have currently been presented to defend the utilization of WMA on technical, environmental, and economic considerations [15–23]. It should be noted that low emission construction materials, in particular asphalt mixtures, are achieved by lowering mixing temperature [24] and using recycled/waste materials instead of using virgin aggregates [25]. Besides WMA, many additives and foaming mixtures have been conducted throughout time. Before using any of these technologies in infrastructure projects, it is necessary to evaluate the many factors carefully. WMA is classified into three types: organic additives, chemical agents, and foaming technology [26–30]. Warm mix asphalt (WMA) technology has gained significant attention recently as an environmentally friendly alternative to traditional hot mix asphalt (HMA) production and compaction methods. WMA allows for lower mixing and compaction temperatures, resulting in reduced energy consumption, lower emissions, and enhanced worker safety. One approach to further improve the performance of WMA is the incorporation of additives such as zeolites, which are porous minerals with unique properties that can modify the asphalt binder and improve the overall performance of the mixture [31].

The compaction process plays a critical role in achieving the desired density and durability of asphalt pavements. Compaction efforts, including compaction temperature, compaction energy, and number of compaction passes, can significantly influence the performance of asphalt mixtures. Therefore, it is essential to investigate the effects of incorporating zeolite additives into WMA mixtures and evaluate their performance under different compaction efforts [32]. One of the key components of WMA is the addition of various additives to lower the mixing and compaction temperatures, thereby reducing energy requirements and emissions. Zeolites, both natural and synthetic, have gained significant attention as potential additives in WMA due to their unique properties, including high surface area, ion exchange capacity, and water absorption capability [33]. These properties make zeolites excellent candidates for enhancing the mechanical performance of asphalt mixtures. The mechanical performance of zeolite-WMA mixtures plays a crucial role in determining the long-term durability and service life of pavements. Therefore, understanding the effects of zeolite additives on the mechanical properties of WMA mixtures under different compaction efforts is essential for optimizing asphalt mixture design and construction practice [34].

Some experiments have been realized recently to analyze the impact of different types and shapes of zeolites and petroleum wax on the characteristics of the asphalt mix without considering the impact of compaction efforts [35–44]. Understanding the impact of compaction efforts on the performance of WMA containing natural zeolite (NZ) and synthetic zeolite (SZ) is a necessity from an economical point of view. A zeolite is a crystalline hydrated aluminum silicate with three-dimensional structures, and it contains about 20% H_2O [45]. The interaction of these components having hot-asphalt binders gradually discharges H_2O; converting it into steams at ambient pressures and causing foaming [46]. Meanwhile, the amount of steam produced by zeolite is lower compared to water-based systems. Nonetheless, the determination of the H_2O content is a significant difficulty. The H_2O content should be enough to increase the binder phases without rendering the mix vulnerable to moisture-induced degradation. Investigators suggested introducing coating or adhesion enhancers to lower the moisture sensitivity of asphalt mixes [47]. Zeolites have been extensively studied as additives

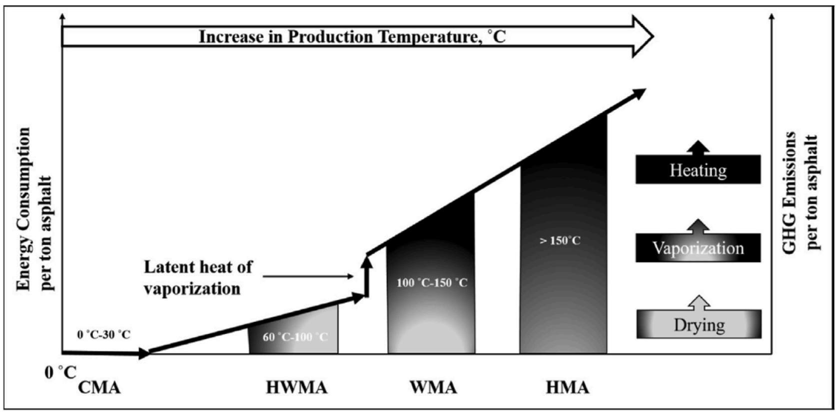


Fig. 1. Asphalt mixture classification [6].

in asphalt mixtures due to their ability to improve workability, moisture susceptibility, rutting resistance, and aging characteristics. Natural zeolites, such as clinoptilolite and mordenite, as well as synthetic zeolites, have shown promising results in enhancing the performance of asphalt mixtures. However, the effectiveness of these additives and their interaction with compaction efforts are still not fully understood [48].

Zeolites are porous, hydrated alum inosilicates with a general formula of M x/m [(AlO_2) x (SiO_2y)]. H_2O, where M x/m designates ion-exchangeable cations, and the [(AlO_2) x (SiO_2y)] unit constitutes the zeolite framework characteristic property of zeolite group minerals is the presence of water particles in their composition that are bound in a specific way, which is the so-called zeolite water. When heating the mineral to a temperature of approximately 400 °C, water is constantly released without a change in the zeolite crystal structure. In the WMA technologies, the zeolite water is not released in a whole amount because of the lower processing temperature. However, the amount of released zeolite water at a particular temperature (e.g., WMA production temperature) can be determined using thermal analysis [49]. Synthetic zeolite is utilized to manufacture the foaming mechanism in water-containing technologies. The product's alkali metal aluminosilicates have been hydrothermally crystallized. When the temperature increases, the crystallization procedure started by zeolite structures occurs with around 20% H_2O, resulting in a micro-foaming influence in asphalt mixtures. The micro-foaming action continues for around 6–7 h. Zeolites have highly distinct structures that are made up of huge air fractions that can be occupied by molecules, and cations (sodium and calcium). Zeolite is created in a silicate framework and contains enormous empty places in its structures, allowing for the existence of massive cations. The fundamental properties of the unique silicate frameworks lead it to absorb and lose water simultaneously without causing damage to the crystalline structure [50,51]. Most of the studies on natural Zeolite (NZ) and synthetic zeolite (SZ) additives for utilization in WMA mixtures are focused on the performance characteristics of NZWMA and SZWMA mixtures without considering compaction temperatures and efforts. Thus, it seems worthwhile to study the effect of compaction temperatures and efforts on the properties of NZWMA and SZWMA mixtures and compare it to that of HMA mixtures. From an economic point of view, the low cost of NZ and SZ in Iraq (about 7.0–9.0 and 5.0–7.0 USD/kg, respectively) compared to other WMA additives is an attractive option that satisfies the various benefits of using WMA mixtures at 3–5% of the weight of asphalt [7].

In recent years, several studies were conducted to assess the effect of zeolites (natural and synthetic) and petroleum wax on asphalt mix properties without considering the impact of compaction efforts [52,53]. Understanding the influence of compaction efforts on the behavior of warm-asphalt mixtures containing natural zeolite (NZ) and synthetic zeolite (SZ) is a necessity from an economical point of view. This study aims to investigate the mechanical performance of natural and synthetic zeolite-WMA mixtures as a function of compaction efforts. The research will involve a comprehensive experimental program, including laboratory testing and statistical analysis, to evaluate the following key performance indicators:

- ➢ Marshall stability and flow: The Marshall method will be employed to assess the resistance to deformation and flow characteristics of zeolite-WMA mixtures at various compaction efforts.
- ➢ Indirect tensile strength: The tensile strength of zeolite-WMA specimens will be determined using the indirect tensile test, which provides insights into the resistance to cracking and fracture behavior.
- ➢ Dynamic modulus: The dynamic modulus test will be conducted to evaluate the stiffness and viscoelastic properties of zeolite-WMA mixtures, which are critical for predicting pavement response under traffic loads.
- ➢ Moisture susceptibility: The susceptibility of zeolite-WMA mixtures to moisture-induced damage will be investigated through laboratory moisture conditioning tests, such as the AASHTO T283 test.

Statistical analysis is performed to analyze the data obtained from the laboratory tests and establish relationships between the mechanical properties and compaction efforts. The results provide valuable insights into the performance of zeolite-WMA mixtures, enabling a better understanding and optimization of their application in asphalt pavement construction.

2. Mix ingredients and experiments

2.1. Mix ingredients

The binder in the study is a widely utilized material having penetration grades of 40/50 in various places for the production of pavements. The basic characteristics of the binder are illustrated in Table 1. Two WMA additives; synthetic zeolites (SZ) and natural zeolites (NZ) were utilized in these experiments. The physical characteristics of the given additives are presented in Table 2. The additive ratios (by binder weight) were chosen in accordance with the recommendations of the producers. WMA binders were produced by incorporating 5% NZ and 5% SZ into the plain (reference) binders. A stirrer (500 rpm) was used to produce the mixtures at 130 ± 5 °C for 15 ± 2 min [54]. The mixing procedure and conditions match the Saybolt-Furol viscosity of 85 s utilized in other investigations [54], to manufacture SZWMA and NZWMA mixtures.

River sand and crushed gravel were utilized as fine aggregates during sample manufacturing (Table 3). The gradation of the aggregates was shown in Fig. 3. A sedimentary rock includes high silica concentration was used as gravel in the study. The filler material is a $CaCO_3$ with a specific gravity of 2.75 passed through a 200 sieve. Fig. 2 illustrates the experimental flow chart for this study and the materials used in the mixtures.

2.2. Mixture design

In this study, Type D5 asphalt mixture according to the ASTM D3515 requirements [55] was utilized. Aggregates were sieved into various sizes with $CaCO_3$ filler to satisfy approximately the mid-range of the gradation limits specified by ASTM D3515 of surface courses [55]. Fig. 2 shows the grading curve of the aggregates with fillers. The Marshall Method is utilized to design asphalt mixtures

Table 1
Rheological properties of asphalt cement.

Property	Results	NCCL limits [16]
Penetration (25 deg. C,100 gm,5 s,0.1 mm)	44	40–50
Softening point (°C)	51.3	51–62
Ductility (25 °C, 50 mm/min, cm)	>150	–
Specific gravity (25 °C/25 °C)	1.03	–
Flash point (°C)	305	–
Fire point (°C)	317	230 min.
Loss on heat (5 hrs, 163 deg. C, %)	0.12	0.75 max.
Retained Penetration % of original (25 deg. C,100 gm,5 s,0.1 mm)	61	55 min.
Residue Ductility (25 °C, 50 mm/min, cm)	55	25 min.
Rotational viscosity at 135 °C, cP	575.6	3000 max.
Asphaltenes (%)	28	–

Table 2
Properties of the WMA additives.

Additive	Dosage (%)	*Physical properties*
NZ	5	Physical state: Solid Color: Light brown Bulk density (gr/cm^3 at 20 °C): 0.73 Water absorption (%): 18.5
SZ	5	Physical state: Solid Color: White Bulk density (gr/cm^3 at 20 °C): 0.66 Static water adsorbs (%): 21.5

Table 3
Source and consensus properties of aggregate.

Property	ASTM No.	Coarse Agg	Fine Agg	ASTM limits [47]
Toughness (%)	D-131	19.8	–	40 max.
Angularity (%)	D5821& C-1252	95.7	43.0	55 min. (Coarse agg.) 40 min. (Fine agg.)
Soundness, Na_2SO_4 (%)	C-88	0.91	0.68	10 max.
Water absorption (%)	D127 & D-128	0.987	1.40	4.0 max.
Bulk sp. gr.	D127 & D-128	2.666	2.646	–
Apparent sp. gr.	D127 & D-128	2.739	2.748	–

[56]. The flow (mm) of the mixes, air void analyses (%), the void ratio in a mineral aggregate (%), and stability (kN) was evaluated to realize the NCCL [49] and ASTM specifications [55]. The optimum binder amount (OBC) is 5.08 ± 0.3% by weight of aggregates for the NZWMA reference mixture containing 5% $CaCO_3$ filler. Maintaining uniformity throughout the study with OBC obtained at 75 Marshall blows and used in the NZ and SZ asphalt mix productions. NZWMA and SZWMA mixes have suitable mixing and compaction temperatures of 130 + 5 and 128 °C, respectively, and 118 + 5 and 116 °C. The viscosity vs temperature relations were plotted to evaluate the obtained relations.

After the mix design procedure, the variables of the amounts of NZWMA and SZWMA mixes and compaction efforts were evaluated, and 3 SZWMA and NZWMA mix at 3 various compactions (i.e., 75, 50, and 35) were chosen. The total specimens prepared in this study were 90 specimens (2 binders × 3 compaction efforts × 5 tests × 3 repetitions).

2.3. Analysis method

The Minitab application was used to perform variance analysis (ANOVA) with $\alpha = 0.05$ significance level. The main variables include the binder type and the compaction efforts. An analysis of the variance model with a significant level of 0.05 is conducted to evaluate the effect of compaction effort on the performance of asphalt with different levels of zeolite additive under different compaction values. For this, Marshall stability, static indirect tensile strength at 25 °C and 60 °C, semicircular bending (SCB) at 25 °C, static creep at (40) °C, and permanent deformation (Kim test) at 60 °C, for warm asphalt mixtures, containing natural zeolite (NZ) and synthetic zeolite (SZ) were designated as the dependent variables, while the different compaction efforts (i.e., 35, 50 and 75 of Marshall blows) were the independent factors. In order to determine significant factors with a p-level of smaller than 0.05, a statistical analysis was carried out. The P-level that is smaller than 0.05 shows that the related parameter is a significant parameter in the resulting performance. In addition, the percent contribution was also determined to find out the degree of effectiveness of the parameter on the resulting performance. If this value is higher, then it can be accepted as the influence of the parameter is significant on the resulting performance. Meanwhile, the performance of asphalt was significantly influenced by the addition of zeolite; and the effect of natural zeolite was much more than synthetic zeolite.

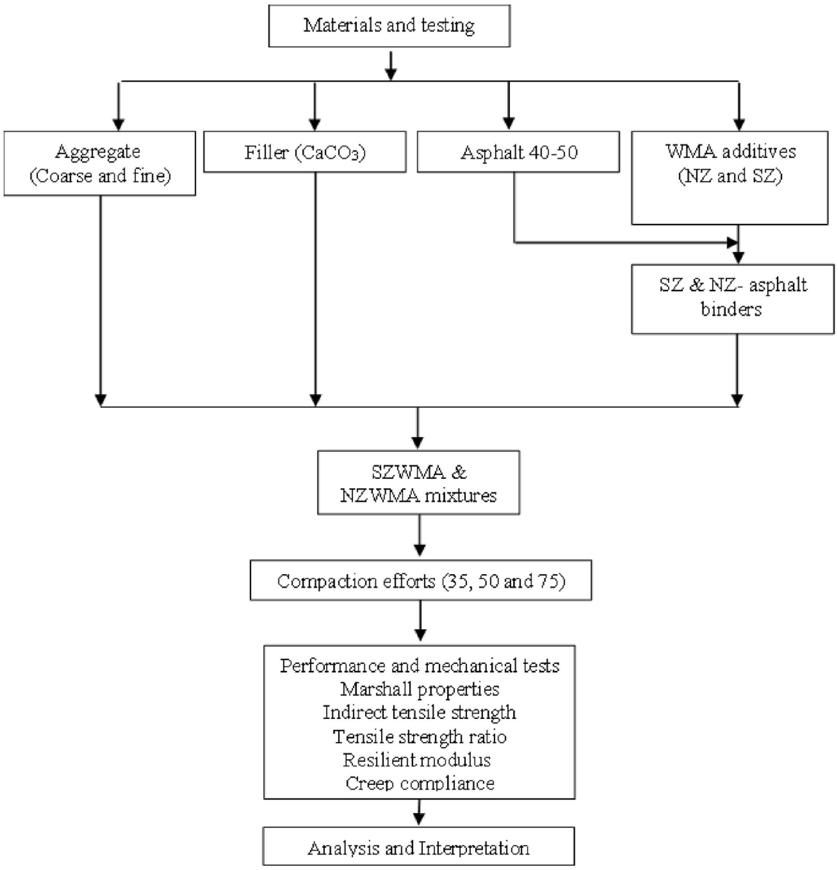


Fig. 2. Flow chart of the study's experimental works.

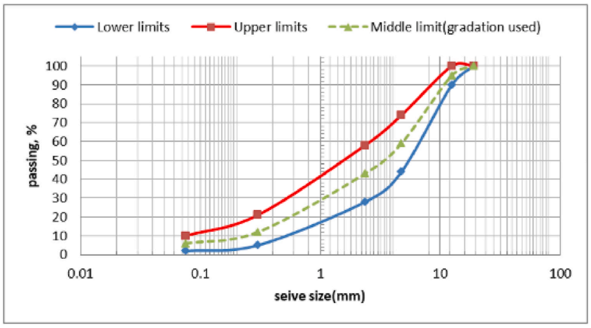


Fig. 3. Aggregate gradation.

2.4. Marshall stability and flow tests

Flow tests and Marshall stability were conducted on asphalt compacted samples for NZWMA and SZWMA mixtures by ASTM D6927 [56]. In the Marshall tests, cylindrical compressed samples having a 100 mm diameter and a 63.5 mm height are put in water at 60 °C for 30–40 min before being broken with curved steel loading plates at a constant velocity of 51 mm/min throughout the diameter. The Marshall stability value in (kN) is the highest load measured at compression, whereas flow (mm) is the highest measured deformation.

The Marshall quotient (MQ) (kN/mm) is the ratio of stability (kN)/flow (mm), which indicates the stiffness of the mix. The Marshall test method in accordance with the Draft BSEN 12697-34 reintroduces the Marshall quotient (MQ). The aforementioned BSEN 12697-34 is expected to replace BS 598 - Part 107 [57].

2.5. Tensile properties

Bitumen detachment from aggregates, called also stripping, is connected with mixtures that are sensitive to long-term moisture degradation. Stripping is unlikely with low void content in thick asphalts. Stripping is a problem on a water-permeable material, even if it is relatively dense, leading to a loss of internal cohesiveness and possible collapse of the surface. The stripping phenomena are determined by the affinity between aggregates and bitumen, and the capacity of an aggregate to withstand the displacing action of water.

Immersion tests determine how a compacted bituminous mix's mechanical feature changes following immersion into water. Thus, stripping can be calculated as the ratio of the property after immersion divided by the initial one, and indirect tensile strength (ITS) tests are the most considered in calculations. Meanwhile, the tensile strength ratio-TSR is the ratio of the indirect tensile strength of bituminous specimens after the wet condition to the original condition of similar specimens and is generally mentioned as percentages.

The tensile strength property and moisture susceptibility of the SZWMA mix and NZWMA mix combinations were evaluated using indirect tensile strength (ITS) by ASTM D7369-12 [58]. These mixtures are compressed to the 7% air void contents. The specimens were divided into two subgroups for ITS tests; conditioned (C) and unconditioned (U). The former ones were placed in water at 25 °C for 2 h, while the latter ones were kept in water at 60 °C for 24 h before being placed in a water bath at 25 °C for 2 h. These specimens were tested at a displacement-controlled rate of 51 mm/min using Marshall equipment up to the failure of the samples. Eq. (1) was used to calculate the indirect tensile strengths of the specimens.

$$\mathrm{ITS} = 2\mathrm{P}/\ \pi \mathrm{dt} \tag{1}$$

Where d is the specimen diameter (mm), P is the ultimate load (N), ITS is the indirect tensile strength (N/mm^2), and t is the specimen thickness (mm).

The conditional (C) tensile strength ratio and unconditional (U) tensile strength ratio (TSR) can be calculated using the ITS test at 25 °C using Eq. (2).

$$\mathrm{TSR}\ (\%) = \mathrm{ITSC}\ /\ \mathrm{ITSU} \times 100 \tag{2}$$

Where ITSC and ITSU are the conditional-unconditional indirect tensile strengths (MPa).

Fig. 4 shows the specimens and the instrument used to indicate the tensile test.

2.6. Resilient modulus test

The elasticity of the asphalt mixture is represented in its ability to flexible bending without making cracks, and its ability to deformation which occurs to it as a result of the gradual decline of the layers of the foundation and sub-base. We can get a flexible asphalt mixture by increasing the ratio of asphalt, using various grades of aggregate, and there are other factors that affect the flexibility of the asphalt mixture like the thickness of the asphalt layer and temperature.

The elastic modulus is one of the most important mechanical properties of the asphalt mixture. It is considered the major criterion for designing two layers of elastic paving in the elastic theory of layers. In addition, being very critical, the elastic modulus is used for

Fig. 4. (A) Condition samples (B) Indirect Tensile Strength (ITS) device.

the asphalt mixture in predicting the performance of elastic paving. Thus, it is preferable to calculate the elastic modulus of the asphalt mixture during the design stage.

An indirect tensile test (ITT) was conducted at 25 °C according to ASTM D7369-11 [59] to determine the resilient modulus (MR). The MR was calculated using ITT from tests on cylindrical specimens for each mixture at the prescribed asphalt percentages. For the mixed specimens, the vertical diameter is stressed. The cylindrical specimens were subjected to a repetitive haversine compressive load that is delivered at 1 Hz frequency for 0.1 s to simulate field circumstances and 0.9 s resting duration. For each blend, triplicate samples were examined, and the mean value was reported. Fig. 5 indicates the process of ITT for the semi-circular specimen.

2.7. Creep compliance

To examine the rutting of asphalt mixtures, researchers utilized a variety of experiments, including creep compliance, wheel tracking, and dynamic creep. The rutting capabilities of asphalt mixes were investigated in this work by performing creep compliance tests by AASHTO T-322 standard [60]. To analyze the performance of NZWMA and SZWMA mixes against permanent deformations, creep compliance tests were executed on the samples. These tests were conducted for 1 h at a high-temperature level of 40 °C with a stress level of 0.1 MPa. By the way, recovered deformation (r) assesses the capacity of the mix to recover deformations upon unloading, whereas permanent deformations (p) assess the discomfort of permanent deformation upon unloading. Fig. 6 presents the process of the creep compliance test.

3. Results and discussions

3.1. Flow, MS, and MQ test results

Fig. 7 illustrates the properties of Marshall for NZWMA and SZWMA mixes, and these presented results are the average values of three identical tested samples. Fig. 7a illustrates the stability of the Marshall compactor-fabricated specimens as a proportion of compaction effort. In general, NZWMA or SZWMA mixtures had almost the same stability value over a range of compaction efforts (35–75 blows/face). For instance, the stability changes of NZWMA mixtures produced at 75 compaction effort was 0.95 kN (14.416 kN at 35 blows/face - 15.363 at 75 blows/face) and 0.78 kN (14.586 kN at 50 blows/face - 15.363 at 75 blows/face) for 35 compaction efforts and 50 compaction efforts. This means that it is possible to satisfy the minimum stability values of 8 kN using 35 blows/face for both NZWMA and SZWMA mixtures [56].

However, at similar compaction efforts, NZWMA mixtures showed a relatively higher Marshall stability than the SZWMA mixtures. A higher stability value was found for NZWMA mixtures produced at 75 compaction levels. NZWMA mixtures showed 2,5%, 2,6%, and 6,4% improvements in stability values than the SZWMA mixes for 35, 50, and 75 compaction efforts, respectively. Also, Fig. 7a shows that NZWMA mixtures produced at 35 or 50 compaction efforts give a similar Marshall stability value to SZWMA mixtures produced at 75 compaction efforts. ~~This indicates that NZWMA mixtures need less compaction effort than SZWMA mixtures.~~

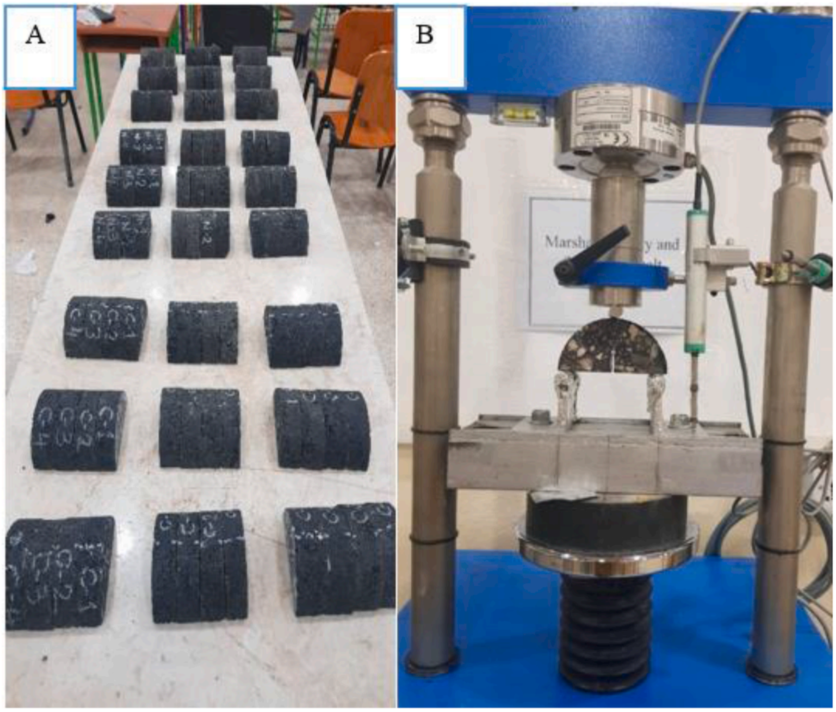


Fig. 5. (A) SCB samples (B) Semi-Circular Bending (SCB) device.

Fig. 6. (A) Creep samples (B, C, D) Creep Compliance Test.

The NZWMA mixes have higher stability than the SZWMA mixtures, implying higher rutting resistance, which can be due to the increased density of the mixtures with "NZ" than the mixtures with "SZ".

The statistical significance of the variation in Marshall stability with increasing compaction effort was tested using one-way variance analysis (ANOVA), and the findings were reported in Table 4. The obtained results showed there is no significant difference in the stability values of three compaction attempts within both NZWMA and SZWMA mixes at the 0.05 level. Furthermore, in most situations, the difference in stability values among NZWMA and SZWMA combinations was found insignificant statistically, except for NZWMA produced at 75 compaction efforts which are different from SZWMA mixes produced at 35 and 50 compaction efforts. For instance, the stability change was 1.153 kN (15.363 kN for NZWMA at 75 blows/face and 14.2 kN for SZWMA at 50 blows/face), and 1.30 kN (15.363 kN for NZWMA at 75 blows/face and 14.063 kN for SZWMA at 35 blows/face). This finding implies that the effect of compaction efforts on stability is substantial, which favorably affects the stability of NZWMA mixes.

Similar to the Marshall stability, the flows (Fig. 7b) of NZWMA or SZWMA samples were found almost similar values over the three compaction efforts. The flow values of the samples containing NZ and SZ/asphalt binders were found similar to the trends seen for stability at the same compaction efforts as in the case of optimal binder concentration. However, the NZWMA mixtures' flow values were greater than those of the SZWMA mixtures. The increased stability and flow parameters of NZWMA result in increased material toughness. Asphalt mixes are prone to thermal fatigue and low-temperature cracks, but increased toughness helps to prevent crack formations and propagation. The finding confirmed that NZWMA combinations showed better performance than the SZWMA mixtures.

The Marshall quotient (MQ) of samples formed using the Marshall compactor is presented in Fig. 7c as a percentage of compaction effort. In general, more compaction efforts result in higher MQ for both NZWMA and SZWMA combinations. However, the change in MQ of the NZWMA or SZWMA mixes as a function of compaction effort was much smaller. In compared to SZWMA mixes, NZWMA

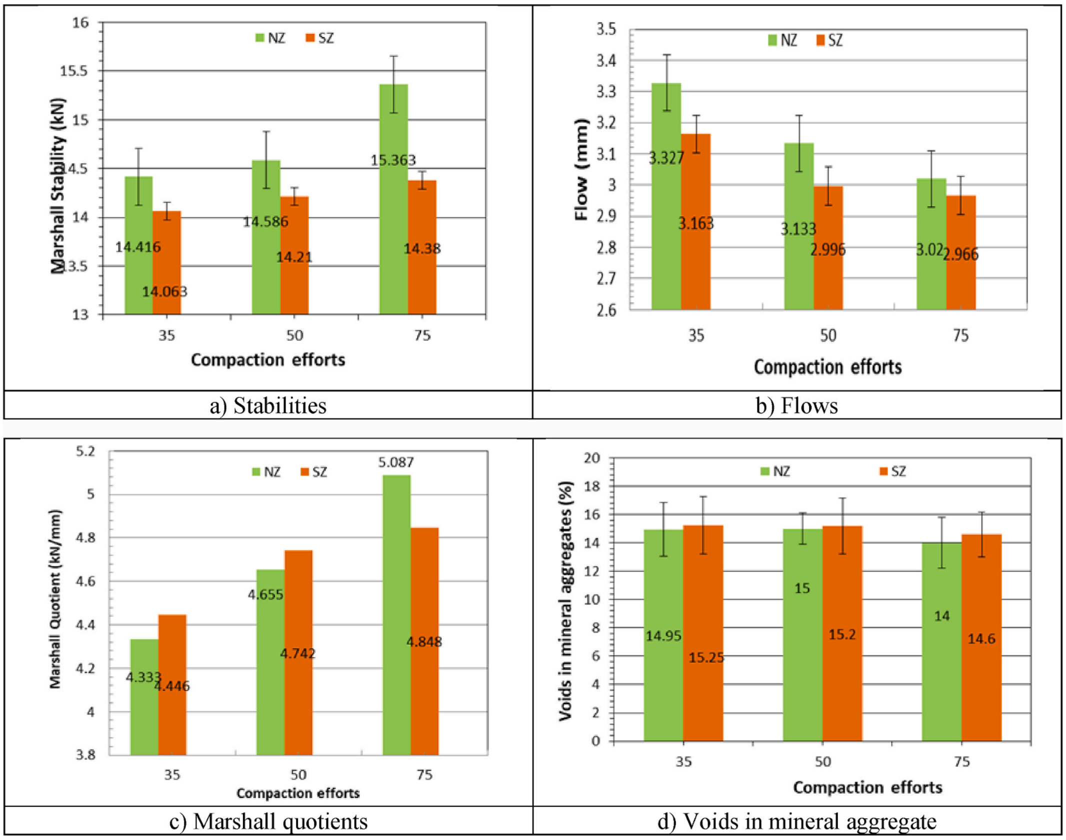


Fig. 7. The properties of Marshall for NZWMA and SZWMA mixes.

Table 4
Statistical analysis results of Marshall stability of NZWMA and SZWMA mixtures at different compaction efforts.

		NZWMA			SZWMA		
		1	2	3	1	2	3
NZWMA	1	–	N	N	N	N	N
	2		–	N	N	N	N
	3			–	S	S	N
SZWMA	1	N	N	S	–	N	N
	2	N	N	S		–	N
	3	N	N	N			–

Compaction effort: (1) 35 blows/face, (2) 50 blows/face, and (3) 75 blows/face.
N, non-significant; S, significant.

mixes have lower MQ (i.e., MQ reduces 2.6% and 1.8% for 35 and 50 compaction effort, respectively) but exhibit substantially greater MQ (4.93%) at 75 compaction effort. Higher rises in MQ values in NZWMA mixes may be due to their higher stability and lower flow values.

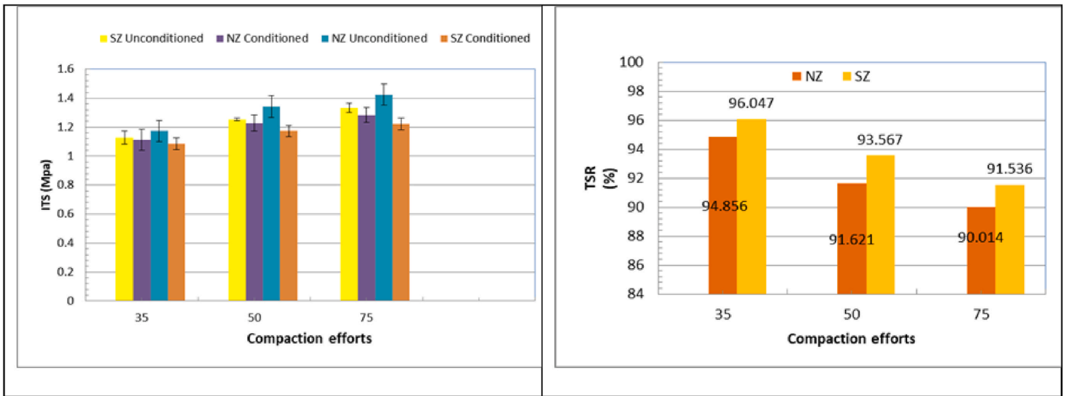
Fig. 7d illustrates the variation in VMA values of the samples formed with the Marshall compactor as the compaction effort is increased from 35 to 75 blows/face. The VMA values obtained by the NZWMA and SZWMA specimens were identical to the flow patterns at the same compaction effort. However, the VMA values of the NZWMA combinations were found to be lower than those of the SZWMA mixtures with the same asphalt component. This is probably attributed to the complete evaporation of H_2O from zeolite; therefore, decreasing the effective asphalt content of the mixtures. Compared to SZWMA mixtures, NZWMA mixtures show a lower VMA of 2.0% for 35 compaction effort, 1.3% for 50 compaction effort, and 4.1% for 75 compaction effort. That finding reveals that NZWMA mixes have relatively poor durability than the NZWMA mixtures. In general, at mentioned compaction efforts, SZWMA and NZWMA mix meet the lowest ASTM [56] and NCCL [57] requirements of 8 kN stability, 2–4 mm flow, and 14% VMA.

3.2. Indirect tensile strength (ITS) results

The indirect tensile strength (ITS) tests were used to investigate the temperature and moisture effects on the ITS of the NZWMA and SZWMA mixes formed at 35, 50, and 75 compaction efforts. Fig. 8a depicts the findings for the conditioned and unconditioned tensile strength of various mixes. A general trend is that the higher compaction effort leads to higher unconditioned and conditioned tensile strength for NZWMA and SZWMA mixes. In addition, the statistical significance of conditioned and unconditioned ITS with the increase in compaction effort was assessed by a one-way ANOVA, and these findings are presented in Table 5. The change in the unconditioned ITS for the NZWMA mixes was a significant difference for 35 compaction efforts only. In contrast, there is no significant difference in the case of conditioned ITS for all compaction efforts as shown in Fig. 8a. For instance, the unconditioned ITS change of the NZWMA mixtures produced at 35 compaction effort was 168 kPa (1173 kPa at 35 blows/face – 1341 kPa at 50 blows/face) for 50 compaction efforts, and 252 kPa (1173 kPa at 35 blows/face – 1425 kPa at 75 blows/face) for 75 compaction efforts. Likewise, the variation in unconditioned ITS for the SZWMA mixtures was a significant difference between 35 and 75 compaction efforts only. In contrast, there was a significant difference in the case of conditioned ITS for 35 compaction efforts only (Fig. 8a). Moreover, the change in unconditioned (U) and conditioned (C) ITS among the SZWMA and NZWMA mixes were found as insignificant statistically in most cases.

Fig. 5a also shows that increases in compaction efforts for the NZWMA and SZWMA mixes give relatively more unconditioned and conditioned ITS. Overall, the NZWMA mixtures show a higher unconditioned and conditioned ITS at the same compaction efforts than the SZWMA mixtures. The NZWMA mixtures showed an increase of 3.7% for 35 compaction efforts, 13.7% for 50 compaction efforts, and 6.3% for 75 compaction efforts of the ITS values of unconditioned specimens. Similarly, the increase in the conditioned ITS values of the NZWMA mixes was 2.5% for 35 compaction efforts, 4.5% for 50 compaction efforts, and 6.1% for 75 compaction efforts. A relatively higher unconditioned and conditioned ITS value of the NZWMA mixes could be attributed to the more stiffness of NZ-asphalt binders.

The moisture weakness of SZWMA and NZWMA mixes was estimated using the tensile strength ratio-TSR of the unconditioned to the conditioned group shown in Fig. 8b. Compared to the NZWMA mixtures, SZWMA mixtures show slightly higher TSR, indicating enhanced durability to moisture damages. The increases in TSR values for the SZWMA mixes were 1.3% for 35 compaction efforts, 2.2% for 50 compaction efforts, and 1.7% for 75 compaction efforts.



a. Indirect tensile strength b. Tensile strength ratio

Fig. 8. The properties of tensile strength for NZWMA and SZWMA mixtures.

Table 5
Statistical analysis results of unconditioned and conditioned ITS of NZWMA and SZWMA mixtures at different compaction efforts.

		NZWMA						SZWMA					
		U			C			U			C		
		1	2	3	1	2	3	1	2	3	1	2	3
NZWMA	1	–	S	S	–	N	N	N	N	S	N	N	N
	2		–	N		–	N	S	N	N	N	N	N
	3			–			–	S	S	N	S	N	N
SZWMA	1	N	S	S	N	N	S	–	N	S	–	S	S
	2	N	N	S	N	N	N		–	N		–	N
	3	S	N	N	N	N	N			–			–

Compaction effort: (1) 35 blows/face, (2) 50 blows/face, and (3) 75 blows/face.
(U) Unconditioned ITS, and (C) Conditioned ITS. N, non-significant; S, significant.

When the values of 448 kPa and 85% as the lowest allowable conditioned ITS and TSR were considered [59], the values of the SZWMA and NZWMA mixes are higher than the limit values of 448 kPa and 0.85, respectively. Therefore, it is possible to satisfy these values using 35 blows/face for NZWMA and SZWMA mixes.

3.3. Resilient modulus (MR)

Results of the MR test at 25 °C are illustrated in Fig. 9. Overall, at the same compaction efforts, NZWMA mixtures show slightly higher MR values than SZWMA mixtures. NZWMA mixtures show a 2.3%, 2.8%, and 6.9% increase in MR value than the SZWMA mixes for 35, 50, and 75 compaction efforts, respectively.

Furthermore, the statistical significance of the change in unconditioned and conditioned ITS with the increase in compaction effort was assessed by a one-way ANOVA, and obtained findings are presented in Table 6. The change in MR for the NZWMA mixes was a significant difference for 75 compaction efforts only, whilst, there was no significant difference in MR for SZWMA mixtures at all compaction efforts as shown in Fig. 9. For instance, the MR change of NZWMA mixtures produced at 75 compaction effort was 340 MPa (4870 MPa at 35 blows/face – 5210 MPa at 75 blows/face) and 278 kPa (4932 MPa at 50 blows/face – 5210 MPa at 75 blows/face), for 35 and 50 compaction efforts, respectively. In addition, the change in MR among SZWMA and NZWMA mixes was found insignificant statistically in most cases, except for NZWMA produced at 75 compaction efforts which differ from SZWMA produced at the three compaction efforts. Statistical analysis results of MR indicated that NZWMA mixtures produced at 35 compaction efforts give similar MR values to SZWMA mixtures produced at 75 blows/face. This means that the production and construction of NZWMA mixtures save more time and less fuel consumption in the field than SZWMA mixtures.

3.4. Creep compliance

The creep compliance tests were used to evaluate the combinations' rutting resistances. Fig. 10 presents the creep compliance findings of the SZWMA and NZWMA mixes. The variation in permanent deformation (εp) for the NZWMA mixtures was significant at all compaction efforts, whilst, there is no significant difference between SZWMA mixtures produced at 35 and 50 compaction efforts as shown in Fig. 9. Furthermore, the change in εp among SZWMA and NZWMA mixes was found significant statistically in most cases (Table 7).

Fig. 10, also shows that increases in compaction efforts for NZWMA and SZWMA mixtures give decreasing in εp. Overall, at the same compaction effort, NZWMA mixtures show lower εp than SZWMA mixtures. NZWMA mixtures show a decrease in the εp re-

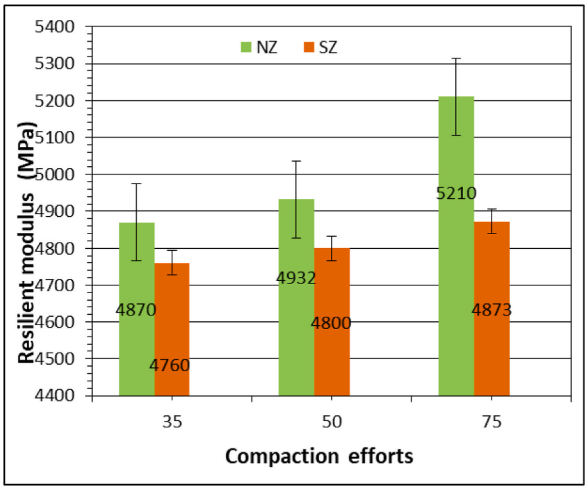


Fig. 9. Resilient modulus of NZWMA and SZWMA mixes.

Table 6
Statistical analysis results of resilient modulus of NZWMA and SZWMA mixtures at different compaction efforts.

		NZWMA			SZWMA		
		1	2	3	1	2	3
NZWMA	1	–	N	S	N	N	N
	2		–	S	S	N	N
	3			–	S	S	S
SZWMA	1	N	S	S	–	N	N
	2	N	N	S		–	N
	3	N	N	S			–

Compaction effort: (1) 35 blows/face, (2) 50 blows/face, and (3) 75 blows/face.
N, non-significant; S, significant.

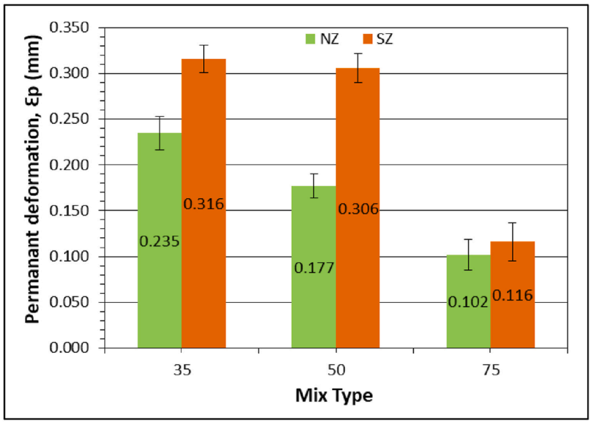


Fig. 10. Permanent deformation of NZWMA and SZWMA mixes.

Table 7
Statistical analysis results of creep compliance of NZWMA and SZWMA mixtures at different compaction efforts.

		NZWMA			SZWMA		
		1	2	3	1	2	3
NZWMA	**1**	–	S	S	S	S	S
	2		–	S	S	S	S
	3			–	S	S	N
SZWMA	**1**	S	S	S	–	N	S
	2	S	S	S		–	S
	3	S	S	N			–

Compaction effort: (1) 35 blows/face, (2) 50 blows/face, and (3) 75 blows/face. N, non-significant; S, significant.

sults of specimens by 25.7% for 35 compaction efforts, 42.2% for 50 compaction efforts, and 12% for 75 compaction efforts. In accordance with these results, it can be seen that SZWMA mixes show a reduction in permanent deformation resistance (higher εp) for all compaction efforts than the NZWMA mixes. The better rutting resistance of NZWMA mixes is attributed to the full evaporation of H_2O from the zeolite, leading to higher stiffness of the NZ/asphalt binder at high temperatures (40 °C). A previous investigation has also revealed higher p values of WMA because of the utilization of synthetic zeolite in asphalt mixes [36].

4. Conclusions and recommendations

The purpose of the research was to assess the influence of various compaction efforts on the performance and mechanical qualities of natural zeolite warm-mix asphalt (NZWMA) and synthetic zeolite warm-mix asphalt (SZWMA) mixes, indirect tensile strength, Marshall stability, resilient modulus, creep compliance tests, and durability (tensile strength ratio) were also performed. The following findings may be presented at the same optimal binder concentration (5.2% by weight of total mix) and 5% by weight of asphalt of both NZ and SZ:

1. The compaction effort to satisfy 8 kN stability, 2 mm–4 mm flow, 14% VMA, 448 kPa unconditioned ITS, and 85% TSR was found to be 35 blows/face for both NZWAM and SZWMA mixtures used in this study.
2. Statistical analysis results indicated that the NZWMA mixtures offered better mechanical performance than the SZWMA mixtures at lower (35 blows/face) compaction efforts.
3. A general trend of the mechanical properties as a function of compaction effort was found for the NZWMA and SZWMA mixtures used in this study. For the NZWMA and SZWMA mixtures at the $\alpha = 0.05$ level, the difference in the Marshall stability, unconditioned tensile strength, conditioned tensile strength, and resilient modulus as a function of the compaction efforts was found to be statistically insignificant in most cases. On the other hand, the difference in the creep compliance was found significant statistically.
4. The NZWMA and SZWMA specimens had almost the same voids in mineral aggregates at a range of compaction efforts from 35 to 75 blows/face. The variation of voids in mineral aggregates of the NZWMA and SZWMA mixes with compaction effort was relative.
5. Further studies with many other aggregates and zeolite sources are required to generalize these findings.

These findings showed that the production and construction of NZWMA mixtures save more time and less fuel consumption in the field than the SZWMA mixtures while satisfying the Marshall properties, moisture susceptibility, and creep performance at 35 blows/face compaction effort.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to thank the National Center for Construction Laboratories (NCCL) and Kashe hot mix plant for their material contribution and technical assistance.

References

[1] S. Caro, D.P. Beltrán, A.E. Alvarez, C. Estakhri, Analysis of moisture damage susceptibility of warm mix asphalt (WMA) mixtures based on Dynamic Mechanical Analyzer (DMA) testing and a fracture mechanics model, Construct. Build. Mater. 35 (2012) 460–467, https://doi.org/10.1016/j.conbuildmat.2012.04.035.
[2] A. Diab, C. Sangiorgi, R. Ghabchi, M. Zaman, A.M. Wahaballa, Warm Mix Asphalt (WMA) technologies: benefits and drawbacks-a literature review, in: Funct. Pavement Des. - Proc. 4th Chinese-European Work. Funct. Pavement Des. CEW 2016, 2016, pp. 1145–1156, https://doi.org/10.1201/9781315643274-126.
[3] S. Xu, F. Xiao, S. Amirkhanian, D. Singh, Moisture characteristics of mixtures with warm mix asphalt technologies – A review, Construct. Build. Mater. 142, https://doi.org/10.1016/j.conbuildmat.2017.03.069.
[4] L.P. Ingrassia, X. Lu, G. Ferrotti, F. Canestrari, Renewable materials in bituminous binders and mixtures: speculative pretext or reliable opportunity? Resour. Conserv. Recycl. 144 (2019) 209–222, https://doi.org/10.1016/j.resconrec.2019.01.034.
[5] C. Robinette, J. Epps, Energy, emissions, material conservation, and prices associated with construction, rehabilitation, and material alternatives for flexible pavement, Transport. Res. Rec. (2010) 10–22, https://doi.org/10.3141/2179-02.
[6] M. Zaumanis, V. Haritonovs, Research on properties of warm mix asphalt, Sci. J. Riga Tech. Univ. Constr. Sci. 11 (2010) 77–84.
[7] J. Wang, X. Hu, B. Huang, L. Ling, Review of warm mix asphalt containing zeolite, Construct. Build. Mater. 197 (2019) 18–30.
[8] S.R. Moafimadani, K. Rahimov, S. Hesami, The effect of warm additive on the properties and behavior of an asphalt binder, Petrol. Sci. Technol. 34 (2016) 1654–1662, https://doi.org/10.1080/10916466.2016.1217238.
[9] L.A. Qtaish, M.D. Nazzal, A. Abbas, S. Kaya, S. Akinbowale, M.S. Arefin, S.S. Kim, Micromechanical and chemical characterization of foamed warm-mix asphalt aging, J. Mater. Civ. Eng. 30 (2018) 1–9, https://doi.org/10.1061/(ASCE) MT.1943-5533.0002430.
[10] H. Wang, X. Liu, P. Apostolidis, T. Scarpas, Review of warm mix rubberized asphalt concrete: towards a sustainable paving technology, J. Clean. Prod. 177 (2018) 302–314, https://doi.org/10.1016/j.jclepro.2017.12.245.
[11] R. Kumar, N. Saboo, P. Kumar, S. Chandra, Effect of warm mix additives on creep and recovery response of conventional and polymer modified asphalt binders, Construct. Build. Mater. 138 (2017) 352–362, https://doi.org/10.1016/j.conbuildmat.2017.02.019.
[12] H. Martin, Z. Kerstin, M. Joachim, Reduced emissions of warm mix asphalt during construction, Road Mater. Pavement Des. 20 (2019) S568–S577, https://doi.org/10.1080/14680629.2019.1628426.
[13] M.R. Mohd Hasan, Z. You, X. Yang, A comprehensive review of theory, development, and implementation of warm mix asphalt using foaming techniques, Construct. Build. Mater. 152 (2017) 115–133, https://doi.org/10.1016/j.conbuildmat.2017.06.135.
[14] V. Ranieri, K.J. Kowalski, N. Berloco, P. Colonna, P. Perrone, Influence of wax additives on the properties of porous asphalts, Construct. Build. Mater. 145 (2017) 261–271, https://doi.org/10.1016/j.conbuildmat.2017.03.181.
[15] A. Chowdhury, J.W. Button, Report 473700–00080-1: A Review of Warm Mix Asphalt, TEXAS TRANSPORTATION INSTITUTE, Texas, 2008.
[16] H. Eric D'Angelo, B. John, B. Gaylon, C. Matthew, FHWA-PL-08-007: warm-mix asphalt : European practice, www.international.fhwa.dot.gov, 2008. (Accessed 4 June 2020).
[17] G.C. Hurley, B.D. Prowell, Evaluation of Sasobit for use in warm-mix asphalt, NCAT report 5 (6) (2005) 1–27.
[18] V. Gaudefroy, F. Olard, B. Cazacliu, C. De La Roche, E. Beduneau, J.P. Antoine, Laboratory investigations of mechanical performance of foamed bitumen mixes that use half-warm aggregates, Transport. Res. Rec. (2007) 89–95, https://doi.org/10.3141/1998-11.
[19] P.S. Kandhal, Warm mix asphalt technologies: an overview, Indian Road Congr 71–2 (2010).
[20] J.W. Button, C. Estakhri, A. Wimsatt, Report 0–5597-1: A Synthesis of Warm-Mix Asphalt, TEXAS TRANSPORTATION INSTITUTE, Texas, 2007.
[21] K.J. Jenkins, Mix Design Considerations for Cold and Half-Warm Bituminous Mixes with Emphasis on Foamed Bitumen, Ph.D Thesis, 2000, p. 385.
[22] A.E. Martin, E. Arambula, F. Yin, L.G. Cucalon, A. Chowdhury, R. Lytton, J. Epps, C. Estakhri, E.S. Park, Evaluation of the Moisture Susceptibility of WMA Technologies, Trans. Res. Board, 2014.
[23] B.D.P. Graham, C. Hurley, Evaluation of aspha-min zeolite for use in warm mix asphalt, NCAT Rep 5–4 (2005) 27.
[24] J. Gong, Y. Liu, Q. Wang, Z. Xi, J. Cai, G. Ding, H. Xie, Performance evaluation of warm mix asphalt additive modified epoxy asphalt rubbers, Construct. Build. Mater. 204 (2019) 288–295.
[25] K. Sapkota, E. Yaghoubi, P.L.P. Wasantha, R. Van Staden, S. Fragomeni, Mechanical characteristics and durability of HMA made of recycled aggregates, Sustainability 15 (6) (2023) 5594.
[26] A. Banerjee, A. De Fortier Smit, J.A. Prozzi, The effect of long-term aging on the rheology of warm mix asphalt binders, Fuel 97 (2012) 603–611, https://doi.org/10.1016/j.fuel.2012.01.072.
[27] S. Hesami, H. Roshani, G.H. Hamedi, A. Azarhoosh, Evaluate the mechanism of the effect of hydrated lime on moisture damage of warm mix asphalt, Construct. Build. Mater. 47 (2013) 935–941, https://doi.org/10.1016/j.conbuildmat.2013.05.079.
[28] H.A. Kassem, G.R. Chehab, Characterisation of the mechanical performance of asphalt concrete mixtures with selected WMA additives, Int. J. Pavement Eng. 1–18 (2019), https://doi.org/10.1080/10298436.2019.1632452.
[29] A. Modarres, A. Aloogar, Comparison between the fatigue response of hot and warm mix asphalts based on the dissipated energy approach, Int. J. Pavement Eng. 18 (2017) 60–72, https://doi.org/10.1080/10298436.2015.1053481.
[30] H. Zelelew, C. Paugh, M. Corrigan, S. Belagutti, Laboratory evaluation of the mechanical properties of plant- produced warm-mix asphalt mixtures, Road Mater. Pavement Des. 14 (2013) 37–41.
[31] X. Liu, J. Chen, B. Huang, X. Shu, F. Wang, Laboratory evaluation of the moisture resistance of warm mix asphalt containing zeolite, J. Clean. Prod. 255 (2020) 120282.
[32] W. Fan, S. Wu, S. Zhang, C. Yang, J. Zhu, Investigation of the performance of zeolite-warm mix asphalt mixture based on the AASHTO design guidelines, Construct. Build. Mater. 293 (2021) 123619.
[33] S. Chen, C. Hu, Y. Xiao, B. Huang, Y. Li, Laboratory evaluation of zeolite warm mix asphalt using natural zeolite and synthetic zeolite, Construct. Build. Mater. 209 (2019) 307–316.
[34] Y. Xiao, C. Hu, B. Huang, Y. Li, Investigation of the effects of zeolite content and compaction temperature on performance of warm mix asphalt using response surface methodology, Construct. Build. Mater. 185 (2018) 194–204.
[35] A. Topal, B. Sengoz, B.V. Kok, M. Yilmaz, P.A. Dokandari, J. Oner, D. Kaya, Evaluation of mixture characteristics of warm mix asphalt involving natural and synthetic zeolite additives, Construct. Build. Mater. 57 (2014) 38–44.

[36] Afshar Yousefi, Behnood Ali, Ata Nowruzi, Hamzeh Haghshenas, Performance evaluation of asphalt mixtures containing warm mix asphalt (WMA) additives and reclaimed asphalt pavement (RAP), Construct. Build. Mater. 268 (2021) 121200.
[37] G. Valdes-Vidal, A. Calabi-Floody, E. Sanchez-Alonso, Performance evaluation of warm mix asphalt involving natural zeolite and reclaimed asphalt pavement (RAP) for sustainable pavement construction, Construct. Build. Mater. 174 (2018) 576–585.
[38] J. De Visscher, F. Vervaecke, A. Vanelstraete, H. Soenen, T. Tanghe, P. Redelius, Asphalt production at reduced temperatures using zeolites and the impact on asphalt performance, Road Mater. Pavement Des. 11 (1) (2010) 65–81, https://doi.org/10.1080/14680629.2010.9690260.
[39] A. Sengöz, A. Topal, C. Gorkem, Evaluation of moisture characteristics of warm mix asphalt involving natural zeolite, Road Mater. Pavement Des. 14 (4) (2013) 933–945, https://doi.org/10.1080/14680629.2013.817352.
[40] H.H.M. Al-Araji, Studying the Mechanical Properties of Warm Mix Asphalt Designed by Superpave Method, MSc thesis, University of Technology, 2018, p. 85.
[41] C. Droge, Verfahren der Temperaturabsenkung--Mineralische Zusatze zum Asphalt. Methods for Reduction of Temperature - mineral Additives used in Asphalt, Strasse und Autobahn, Bielefeld: Kirschbaum 56 (10) (2005) 564–567 1950.
[42] G.C. Hurley, B.D. Prowell, Evaluation of Aspha-Min Zeolite forUse in Warm Mix Asphalt, National Center for Asphalt Technology NCATReport, 2005, p. 30 (5–4).
[43] A. Vaitkus, D. Cygas, A. Laurinavicius, V. Vorobjovas, Z. Perveneckas, Influence of warm mix asphalt technology on asphalt physicaland mechanical properties, Construct. Build. Mater. 112 (2016) 800–806, https://doi.org/10.1016/j.conbuildmat.2016.02.212.
[44] M. Marinkovic, T. Milovic, B. Matic, Zeolite as additive in warm mix asphalt, Zbornik radova Gradevinskog fakulteta 33 (2017) 483–490 (30), 5th International Conference Contemporary Achievements in Civil Engineering 21. April 2017, Subotica, SERBIA.
[45] A. Topal, B. Sengoz, B.V. Kok, M. Yilmaz, P. Aghazadeh Dokandari, J. Oner, D. Kaya, Evaluation of mixture characteristics of warm mix asphalt involving natural and synthetic zeolite additives, Construct. Build. Mater. 57 (2014) 38–44, https://doi.org/10.1016/j.conbuildmat.2014.01.093.
[46] S.W. Goh, Development and Improvement of Warm-Mix Asphalt Technology, Ph.D Thesis, Michigan Technological University, 2012. https://digitalcommons.mtu.edu/etds.
[47] M.F.C. Van De Ven, K.J. Jenkins, J.L.M. Voskuilen, R. Van Den Beemt, Development of (half-) warm foamed bitumen mixes: state of the art, Int. J. Pavement Eng. 8 (2007) 163–175, https://doi.org/10.1080/10298430601149635.
[48] G. Airey, A. Collop, J. Grenfell, The influence of zeolite on warm mix asphalt, Construct. Build. Mater. 147 (2017) 391–401.
[49] A. Woszuk, A. Zofka, L. Bandura, W. Franus, Effect of zeolite properties on asphalt foaming, Construct. Build. Mater. 139 (2017) 247–255 2017, 2017.
[50] J. D'Angelo, E. Harm, J. Bartoszek, G. Baumgardner, M. Corrigan, J. Cowsert, T. Harman, M. Jamshidi, W. Jones, D. Newcomb, B. Prowell, R. Sines, B. Yeaton, Warm-Mix Asphalt: European Practice, Federal Highway Administration (FHWA), Alexandria, 2008 FHWA Report 08-007.
[51] G.C. Hurley, B.D. Prowell, Evaluation of Aspha-Min® Zeolite for Use in Warm-Mix Asphalt, National Center for Asphalt Technology (NCAT), Auburn, 2005 NCAT Report 05–04.
[52] A. Topal, B. Sengoz, B.V. Kok, M. Yilmaz, P.A. Dokandari, J. Oner, D. Kaya, Evaluation of mixture characteristics of warm mix asphalt involving natural and synthetic zeolite additives, Construct. Build. Mater. 57 (2014) 38–44 57, p. 2014, 2014.
[53] H.H.M. Al-Araji, MSc thesis, Studying the Mechanical Properties of Warm Mix Asphalt Designed by Superpave Method, vol. 85, University of Technology, 2018, p. 2018 2018.
[54] Noor Jabbar Mahdi Al-Tamimi, Application of Warm Asphalt Mixture in Iraq", MSc. Thesis, Civil Engineering Department College of Engineering/University of Anbar, Anbar-Iraq, 2020.
[55] ASTM Standard Specifications, Part IB, Volume 04.03 Road and Paving Materials Vehicle Pavement Systems, 2015.
[56] ASTM D6927-15, Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures, American Society for Testing and Materials, 2015.
[57] National Center for Construction Laboratories (NCCL), Materials and Construction Works Specification", Ministry of Housing and Construction and Public Works. Directorate of Research and Technical Affairs, Baghdad-Iraq, 2018 January.
[58] British Standards Institution, Sampling and Examination of Bituminous Mixture for Road and Other Paved Areas. Part 3: Method for Design and Physical Testing, vol. 598, 1990 BS.
[59] ASTM D7369–11, Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension Test, American Society for Testing and Materials, 2011.
[60] AASHTO T 322. Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device.