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# Assessment and Statistical Analyses of Rutting, Cracking and Fatigue Resistance of Warm-Mix Asphalt

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***ABSTRACT***

*Warm-mix asphalt (WMA) is produced at lower temperatures than hot-mix asphalt (HMA), suggesting reduced compaction efforts. This study aims to evaluate rutting, cracking, and fatigue resistance of WMA under three compaction efforts (CE: 35, 50, and 75 blows/face) using Kim and Semi-Circular Bending tests to measure deformation strength, fracture energy, flexibility index, and J-integral (fatigue parameter). A 40/50 penetration grade base binder was modified with 5% natural zeolite (NZ) and 5% synthetic zeolite (SZ) by mass to produce natural zeolite-warm mix asphalt (NZWMA) and synthetic zeolite-warm mix asphalt (SZWMA). Seventy-two Marshall-compacted samples underwent statistical analysis to determine optimal CE. Key finding can be listed as follows: NZWMA required 50 blows/face and SZWMA 75 blows/face to meet the minimum 3.2 MPa deformation strength (Kim test) and J-integral ≥ 0.5 (critical strain energy rate); NZWMA at 50 blows saved more time and fuel than SZWMA while satisfying performance criteria; Rutting, cracking, and fatigue resistance exhibited consistent trends with increasing CE for both mixes. The results demonstrate NZWMA's efficiency under moderate compaction, offering practical advantages in asphalt production by balancing performance and energy savings. This study provides insights into optimizing CE for WMA technologies, emphasizing NZWMA's potential for sustainable pavement applications.*

***Keywords:***

*Warm-mix asphalt; Flexibility index; Cracking resistance index; Fracture energy; Kim test, and Semi-circular bending.*


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## 1. INTRODUCTION

Warm-mix asphalt (WMA) mixtures have been produced using natural zeolite (NZ) and synthetic zeolite (SZ) additives due to their technical, financial, and environmental advantages over hot mix asphalt (HMA) [1]. When added to asphalt concrete mixes at a weight percentage of 3–5%, they have been confirmed to enhance the performance of these mixes [2], [3]. Zeolite (Z), an element of WMA, includes water. Zeolite is a white powder formed by hydrothermal crystallization of an aluminosilicate. At lower temperatures, the mixture becomes more workable and compatible due to the interaction between the 18–22% water by weight and the binder. "Z" lowers mixing and compaction temperatures by about 10 to 30 °C, according supplier and literature data [4], [5].

The second genetic category's applications in industry, such as selective molecular sieves, dictate the precise structure characteristics of synthetic zeolites, which are artificially produced with these parameters. Zeolites, which most commonly obtained in industrial synthesis processes are minerals of the Na-X, Na-Y, Na-A, and ZSM-5 kinds. Synthetic zeolites involve the use of chemical reagents, mineral resources like silica-group and clay minerals, and coal mining waste by-products such as fly-ash [6]. In WMA technologies, synthetic zeolites are now produced using chemical reagents [7], fly ash-based synthetic zeolites [8], and natural zeolites as clinoptilolite [9].

Valdes et al. [4] evaluated warm-mix asphalt containing 0.3–0.6% natural zeolite and 10–30% reclaimed asphalt pavement (RAP). They found that NZ-based WMA could be produced at approximately 20 °C lower temperatures while achieving stiffness, cracking resistance, moisture sensitivity, rutting, and fatigue performance comparable to the HMA reference mixture.

Likewise, natural zeolite-based recycled asphalt mixtures produced at a lower temperature showed beneficial characteristics, helping in producing sustainable pavement. Yousefi et al. [10] assessed how RAP components and WMA additives, such as Kaowax®, PAWMA®, Zeolite®, and Sasobit®, affected the mechanical and durability performance of HMA. As control mixtures, the characteristics of WMA and HMA with 50% RAP were assessed. The impact of WMA additions on the characteristics of the two kinds of mixes (with and without RAP) was then investigated. Indirect tensile stress at 25 °C, resilient modulus at three different temperatures, 5 °C, 25 °C, and 40 °C, dynamic creep at 54.4 °C, and semi-circular bending fracture at 25 °C were among the experiments conducted. These experiments assessed the asphalt mixtures' mechanical properties, whereas the durability performance was assessed using the tensile strength ratio (TSR). The results showed that WMA additions enhance the asphalt mixes' fracture energy value and enable the addition of a significant amount of RAP (i.e., 50%) without sacrificing mechanical performance. The strain energy of mixtures with WMA addition was higher than that of mixtures without WMA additive in semi-circular bending tests for both types of mixtures, with and without RAP. Strain energy refers to the energy absorbed by asphalt mixtures; a higher strain energy indicates a greater ability of the mixture to withstand deformation before breaking [10]. The mixtures including zeolite had the highest strain energy values in both kinds of mixtures. Furthermore, the TSR values were most reduced in mixtures containing zeolite. The binder-level study investigated by Haghshenas et al. [11] was set to investigate how different types of recycling agents (rejuvenators) influenced the low-temperature cracking resistance and moisture susceptibility of aged asphalt binders. The findings indicated that appropriate recycling agents can restore ductility and reduce stiffness of aged binders, improving resistance to thermal cracking and moisture-induced damage. However, the study focused primarily on binder rheology and low-temperature tests, with limited linkage to mixture-level performance under field-like conditions. Additionaly, a study conducted by Yousefi et al. [12] employed BMD to evaluate WMA mixtures with RAP, multiple recycling agents (aromatic extracts, triglycerides/fatty acids, tall oil), a WMA additive, and an anti-stripping agent, finding that agent type significantly affects moisture, rutting, and cracking performance, and that proper combination with anti-stripping additives can yield mixtures with satisfactory balanced properties. Further fracture-mode-focused research has examined how RAP and recycling agents influence cracking under various loading modes in WMA. For example, a study by Yousefi et al. [13] investigated WMA+RAP mixtures with different recycling agents under Mode I, Mode II, and mixed-mode loading at subzero and intermediate temperatures using SCB tests, finding that RAP tends to reduce fracture toughness at low temperatures but that recycling agents can mitigate this effect to some extent, with overall WMA mixtures still outperforming HMA under certain conditions.

Based on stability, flow, and moisture damage, Vaitkus et al. [14] studied the best doses of foaming, chemical, and organic technologies. As foaming agents, Asph-min and natural zeolite were employed at concentrations between 0.1% and 0.4%. As chemical additions, cecabase and iterlene were used in dosages that likewise ranged from 0.1% to 0.4% by binder weight. Furthermore, as organic additives, Rediset WMX and Sasobit were added in dosages varying from 1% to 2.5% by binder weight. The control HMA was produced at 150 °C, whilst all WMAs were created at 120°C. The study found that 0.3%, 0.3%, and 2% were the ideal dosages for foamy, chemical, and organic additives, respectively. When compared to conventional HMA procedures, these strategies produced positive outcomes in terms of cutting energy consumption during the manufacturing of asphalt mixtures, reducing gas emissions, and improving worker safety.

Moreover, a study was conducted by Visscher et al. [15] to assess both natural and synthetic zeolite kinds. Different dosages of natural and synthetic zeolite (0.3%, 0.4%, 0.5%, 0.6%, and 0.7%) were employed. The optimal dosage was determined using the Rolling Thin-Film Oven, softening point, and penetration tests. Zeolite generally had the ability to lower compaction and production temperatures. Additionally, it was discovered that the ideal production and compaction temperatures were provided by 0.5% of either natural or synthetic zeolite. Also, it emphasized that synthetic zeolite performs better than natural zeolite.

In light of the aforementioned and the authors' expertise, it would appear beneficial to investigate and contrast the effects of various compaction attempts using the Marshall method on the characteristics of NZWMA and SZWMA mixtures, since the WMA mix produces at 25 °C lower mixing temperature (i.e., more workable mix) than that of HMA mix. This advantage demonstrates that WMA mixes may require less compaction efforts than those for HMA mixes. Warm-mix asphalt (WMA) technologies fall into three main categories: water-foaming, organic, and chemical additives. Zeolite-based WMA relies on the release of water from the zeolite framework during mixing to generate temporary foam, reducing binder viscosity and improving aggregate coating at 20–30°C lower than HMA, thereby cutting energy use and emissions, although its mechanical performance can be sensitive to zeolite type and dosage [15], [8]. Organic waxes (e.g., Sasobit) melt at intermediate temperatures to modify the binder's viscosity–temperature profile and ease compaction but may affect long-term aging resistance [3]. Chemical additives (e.g., Evotherm, Rediset) function as surfactants or adhesion promoters to lower surface tension and boost workability in cooler conditions, yet their efficacy depends on precise formulation and blending procedures [10]. Recent research has also emphasized the importance of integrating mechanical performance with techno-economic and environmental assessments through balanced mix design approaches. For example, a study by Yousefi et al. [16] evaluated WMA mixtures with RAP, recycling agents, and anti-stripping agents using 2-D/3-D performance interaction diagrams along with life-cycle environmental and cost analyses, demonstrating that optimized WMA formulations can simultaneously meet performance targets and reduce $CO_2$-equivalent emissions under balanced mix design criteria. Moreover, NZ and SZ are inexpensive (around 3.25 USD/kg), which makes them a desirable alternative to other WMA additions like Advera (about 5.0 USD/kg).

This research involves comprehensive experiments and statistical analyses to assess deformation strength (rutting resistance) based on the Kim test, and fracture resistance using the semi-circular bending test. The findings provide valuable insights into zeolite-incorporated WMA mixes, enabling in-depth understanding and optimization of their applications in asphalt pavement constructions.

## 2. RESEARCH OBJECTIVES

The main objectives of this study were to determine the influence of different compaction efforts (CE) using the Marshall method on the rutting resistance, cracking resistance, fracture energy, flexibility index, and J-integral of NZWMA and SZWMA mixtures through Kim and Semi-Circular Bending Tests. Besides that, the study aimed to compare the rutting and cracking resistance of NZWMA and SZWMA mixtures and select the optimal CE for both mixtures to achieve the best-performing mix using a statistical analysis approach. It also seeks to provide an experimental basis for NZWMA and SZWMA mixtures for sustainable and economic road infrastructure development.

## 3. MIX COMPONENTS AND TESTS

### 3.1. Materials Used

The locally available asphalt material used in this research is a commonly used material, which have a penetration grade of 40/50 in different places for the pavement production. 40/50 penetration asphalt is often used in regions with moderate temperatures because it strikes a balance between hardness and flexibility [8]. Table 1 presents the fundamental properties of the binders. Locally available Synthetic-zeolite (SZ) and natural-zeolite (NZ) were used as WMA incorporations. The physical properties (As provided from supplier) of these incorporations are illustrated in Table 2. These incorporation ratios (by weights of binders) were selected based on the manufacturer recommendation.

The grading curve of the aggregates used is shown in Fig. 1. Gravel extracted from sedimentary rocks in Mosul, Iraq, was utilized as the coarse aggregates, while calcium carbonate from Mosul, Iraq, with a specific gravity of 2.75, was used as filler material in the research. Fig. 2 illustrates the flow chart of the experimental procedures conducted in this research.

Table 1: Rheological characteristics of the asphalts.

| Property | Test method | Results | NCCL limits [17] |
|---|---|---|---|
| Penetration at 25°C (0.1mm) | ASTM D 5 [18] | 44 | 40-50 |
| Softening point (°C) | ASTM D 36 [19] | 51.4 | 51-62 |
| Ductility at 25°C (cm) | ASTM D 113 [20] | > 150 | ≥ 100 |
| Specific gravity at 25°C | ASTM D 70 [21] | 1.03 | --- |
| Flash point (°C) | ASTM D92 [22] | 305 | ≥ 230 |
| Fire point (°C) | ASTM D 92 [22] | 317 | - |

| | | | |
|---|---|---|---|
| Loss on heat for 5 hrs. at 163°C (%) | ASTM D 1754 [23] | 0.12 | ≤ 0.75 |
| Rotational viscosity at 135°C (cP) | ASTM D 4402 [24] | 375.6 | ≤ 3000 |
| Rotational viscosity at 165°C (cP) | ASTM D 4402 [24] | 132 | --- |
| Mixing temperatures (°C) | ASTM D 4402 [24] | 158-163 | ---- |
| Compaction temperatures (°C) | ASTM D 4402 [24] | 143-151 | ---- |
| Retained penetration of original at 25 °C (%) | ASTM D 5 [18] | 61 | ≥55 |
| Residue ductility at 25 °C (cm) | ASTM D 113 [20] | 55 | ≥25 |
| Asphaltenes (%) | ASTM D 4124 [25] | 28 | --- |

Table 2: Characteristics of warm-mix asphalt additives.

| Additive | Physical Properties* | Chemical Properties* |
|---|---|---|
| NZ | Solid in physical condition; light brown in color; at 20 °C, bulk density (g/cm$^3$) is 0.73; and water absorption (%) is 18.5. | $SiO_2$: 39.46%; $Al_2O_3$: 28.35%; $Na_2O$: 13.16%; CaO: 0.26%; MgO: 0.26%; $Fe_2O_3$: 0.84%; $K_2O$: 0.29%; and (LOI): 15.13%. |
| SZ | Physical state: Solid; Color: White; Bulk density (g/cm$^3$ at 20 °C): 0.66; Static water adsorb (%): 21.5 | $Al_2O_3$: 29.1%; $SiO_2$: 32.8%; LOI: 21.2%; CaO: 0.03%; $TiO_2$: 12.99%; and pH: 11–12 |

(*) As provided from supplier

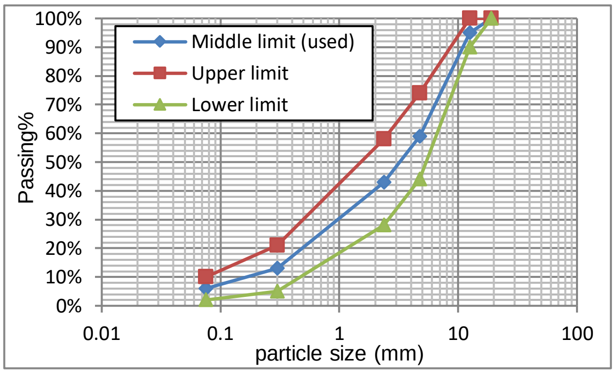


Fig. 1 Aggregates grading curve.

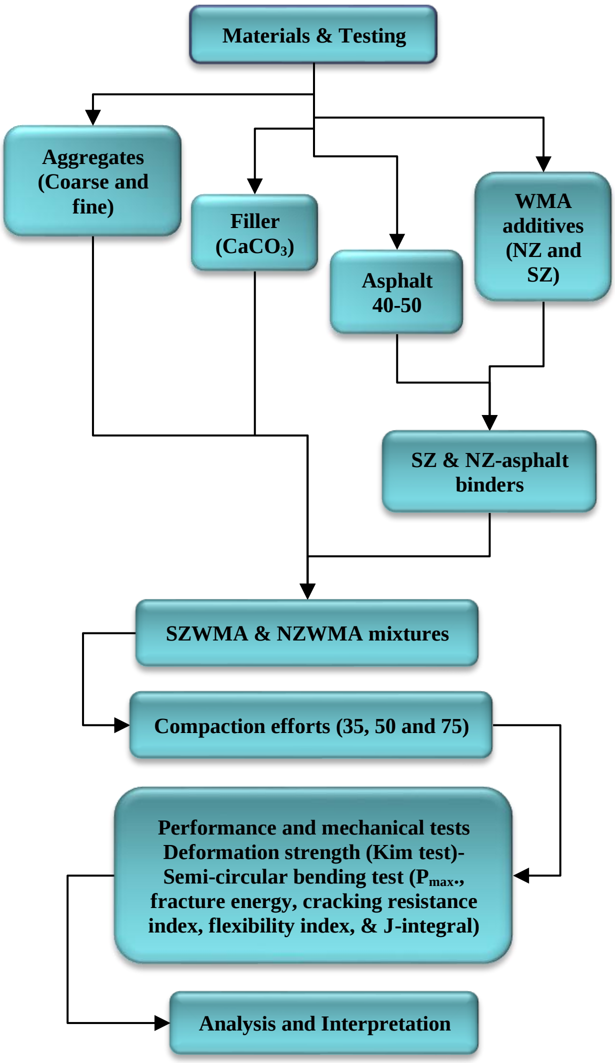


Fig. 2 The flow chart of the experiments.

### 3.2. WMA additives-asphalt preparation

The reference-plain binder was mixed with 5% synthetic zeolite (SZ) and 5% natural zeolite (NZ) (wt. of asphalt) to create the warm-mix asphalt binders. The providers' suggestions and earlier research were taken into consideration while choosing the SZ and NZ contents [2], [3], and [26]. WMA additives (NZ and SZ) were mixed using a 500-rpm stirrer for 15±2 minutes at temperatures that resulted in rotational viscosities of 170±20 cP [10]. Without developing separation, NZ and SZ are evenly dispersed in the asphalt binder at 135±5 °C [27]. Following ASTM D4402 [24], the NZ and SZ asphalt binders were removed from the container, divided into small cans, allowed to cool to at lab temperature, wrapped in aluminum foil, and stored for viscosity testing. After determining the viscosity of the blended binders, the mixing and compaction temperatures were calculated in compliance with ASTM D4402 (Table 3). As can be seen in Table

3, the NZ and SZ asphalt binders reduced the mixing and compaction temperatures of the hot-mix asphalt by 22 and 21°C, respectively, while the compaction temperatures dropped by 36 and 33°C. The results of Woszuk & Franus [8], who demonstrated that mixing and compaction temperatures can be minimized between 20 and 40 °C, are likewise consistent with these observations. The observed reduction in mixing and compaction temperatures for NZWMA and SZWMA (by 22 °C and 21 °C, respectively) is attributed to the water-foaming effect of the zeolites, which supports our findings on energy savings and performance under varying compaction efforts.

Table 3: Properties and production temperature ranges of NZ and SZ/asphalt binders.

| Property | Binder type | | |
|---|---|---|---|
| | Neat | NZ | SZ |
| Penetration (25°C,100g,5s, dmm) | 44 | 37 | 40.5 |
| Softening point (°C) | 51.5 | 49 | 47 |
| Ductility (25°C, 5 cm/min, cm) | > 150 | 148 | 150 |
| Elastic recovery (25°C, %) | --- | 78 | 80 |
| Rotational viscosity at 135°C (cP) | 375.6 | 182 | 187 |
| Rotational viscosity at 165°C (cP) | 132 | 62 | 65 |
| Mixing temperatures (°C) | 158-163 | 133-143 | 135-145 |
| Compaction temperatures (°C) | 143-151 | 103-118 | 106-121 |

### 3.3. Mix Design

In this research, D5 type asphalt mix based on the ASTM D3515 requirements [35] was used. Grading of the coarse and fine aggregates with $CaCO_3$ filler was performed to meet the mid-portion of the gradation limits in accordance with ASTM D3515 [28]. Fig. 1 presents the grading curve of the used materials, and the Marshall method which was used to obtain asphalt mixes [29]. The flowability of the mixtures, percentage air voids, percentage void ratios in mineral aggregates, and stability (kN) were assessed based on National Center for Construction Laboratories (NCCL) limits [17] and ASTM guidelines [28]. The most appropriate binder content (OBC) was found to be 5.08±0.3% (wt. of mix) for NZWMA mixtures having 5% $CaCO_3$ fillers. To ensure consistency throughout this research, SZWMA mixtures were prepared using this optimum asphalt content [30]. Table 4 shows the volumetric parameters of the mixtures.

The variables in NZWMA and SZWMA mixtures and compaction efforts were assessed, and SZWMA and NZWMA mixtures at 3 different compaction efforts (i.e., 35-50-75) were selected. Tests were conducted to evaluate the rutting and cracking characteristics of the NZWMA and SZWMA mixtures including the deformation strength in Kim test, and Semi-Circular Bending. 72 specimens were produced in the scope of the research to evaluate the different mixtures and compaction efforts. A brief summary of experimental matrix used for the study is shown in Table 5.

Table 4: Volumetric parameters of the mixtures.

| Property | Mix type | | | | | | NCCL limits [17] |
|---|---|---|---|---|---|---|---|
| | NZWMA | | | SZWMA | | | |
| | Compaction efforts | | | Compaction efforts | | | |
| | 35 | 50 | 75 | 35 | 50 | 75 | |
| O.B.C% | 5.08 | 5.08 | 5.08 | 5.08 | 5.08 | 5.08 | 6-4 |
| Va% | 6.71 | 5.71 | 4.92 | 6.94 | 5.87 | 5.24 | 3-5 |
| VMA% | 16.04 | 15.15 | 14.44 | 16.22 | 15.26 | 14.69 | 13 min. |
| VFA% | 58.20 | 62.28 | 65.91 | 57.21 | 61.52 | 64.35 | - |
| Gmb ($kg/m^3$) | 2351 | 2376 | 2396 | 2346 | 2373 | 2389 | - |

Table 5: Experimental matrix used in the study with three replicates.

| Testing temperature, °C | Mix type | | | | | |
|---|---|---|---|---|---|---|
| | NZWMA | | | SZWMA | | |
| | Compaction efforts | | | Compaction efforts | | |
| | 35 | 50 | 75 | 35 | 50 | 75 |
| 25 | xxx | xxx | xxx | xxx | xxx | xxx |
| 60 | xxx | xxx | xxx | xxx | xxx | xxx |

Note:
1. Deformation strength was tested at all compaction efforts and temperature of 60 °C.
2. Semi-Circular Bending was tested at all compaction efforts and notch depth (25mm, 32mm, 38mm) but at temperature of 25 °C.

### 3.4. Deformation Strength Via Kim Test

Asphalt mixtures' deformation strength ($S_D$) was assessed using the Kim test. It has been shown that the results of rut-related tests, like wheel tracking for dense-graded mixtures, have a very good correlation ($R^2 > 0.9$) with the $S_D$ determined by the Kim test [31]. It is also comparatively easy and quick to complete. Consequently, the $S_D$ was set up as a standard criterion, which is ≥3.2 MPa in asphalt mixture design by the Korean Ministry of Land, Transport, and Maritime Affairs [32].

The Kim test is carried out by applying a static load at a rate of 50.8 mm/min through a loading head with a circular edge radius of 7.5 mm and a diameter of 30 mm, placed at the top center of the specimen, after a specimen preparation process akin to the Marshall method [33]. The specimen was immersed in water at 60 °C for 30 minutes prior to being set on the loading frame. Specimen was consolidated and then gradually reduced by the loading head, which simulated a stationary wheel and created shear action. Because of the wedge effect of the loading head, cracking developed at the highest load and spread radially as a failure indication [33]. Kim arrived at the Eq. (1), which illustrates the link between deformation strengths, displacements, and maximum force at failure:

$$S_D = \frac{4P}{\pi\left[D-2\left(r-\sqrt{2ry-y^2}\right)\right]^2} \qquad (1)$$

The symbols '$S_D$', 'P', 'D', 'r', and 'y' stand for deformation strength (MPa), maximum load (N), loading head diameter (mm), and radius of curvature at the loading head's bottom (mm), respectively.

### 3.5. SCB (Semi-Circular Bending) Fracture Test

A common issue with asphalt mixtures that may severely reduce their durability is cracking, especially at lower and moderate temperatures. Numerous propagation processes, such as fatigue, reflective (bottom-up), and thermal (top-down) mechanisms, can cause cracking [10]. Many techniques, including indirect tensile testing, disk-shaped compact tension, single-edge notched beam (SENB), and semi-circular bending (SCB) tests, have been used to evaluate the fracture performance of asphalt mixtures. Due to its ease of use, dependability, and robust connection with field performance data, SCB is considered as one of the most popular of these [34].

The SCB test evaluates the resistance of asphalt mixes to intermediate-temperature fractures according to ASTM D8044 [35] guidelines. This test utilizes Marshall specimens with a diameter of 101.6 mm and an air void content of 7 ± 1%. Each semi-circular specimen is symmetrically notched at depths of 25 mm, 32 mm, and 38 mm. Four specimens were tested at each notch depth. The tolerance for notch depth is ±1.0 mm, while the width of the notch is maintained within 3.0 ± 0.5 mm range.

A universal testing machine (UTM) fitted with a 3-point bending test was used to perform the SCB fracture testing. Prior to the testing, samples were placed in environmental chambers with a target temperature of 25 ºC for 4 hours. Loading rate was set at 0.5 mm/min. Cracking resistance of the asphalt mixes was evaluated using several methodologies and indices, including the flexibility index and fracture energy based on linear elastic fracture mechanics principles, and the critical J-integral (Jc) based on non-linear elastic fracture mechanics principles. The fracture energy ($G_f$) and flexibility index (FI) were calculated by Eqs. (2) and (3) respectively, as demonstrated in Fig. 3:

$$G_f = \frac{Wf}{A} \qquad (2)$$

$$FI = \left[\frac{G_f}{\text{absolute (m)}}\right] * 0.01 \qquad (3)$$

where A is the ligament's unit area, $W_f$ is the area under the load versus displacement curve at the inflection point, and m is the

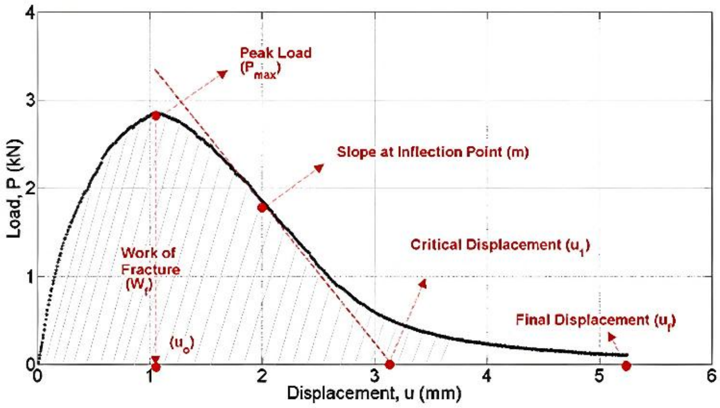


Fig. 3 Typical outcomes of the SCB test load-displacement curve [36].

To find out the intermediate temperature cracking resistance, Kasser et al. calculated cracking resistance index (CRI) as [37]:

$$CRI = \frac{G_f}{Pmax} \qquad (4)$$

$P_{max}$ is the maximum load as determined by the load vs displacement curve. The formula is used to compute the critical J-integral (that is, the release rate of critical strain energy) in kJ/m$^2$ [38]:

$$Jc = \frac{-1}{b}\left(\frac{dU}{da}\right) \qquad (5)$$

Where U is (strain energy) (i.e., the region under the load vs displacement curves up to the maximum load); and a and b are the sample notch lengths and thicknesses, respectively.

## 4. RESULTS AND DISCUSSION

### 4.1. Analysis Methods

The Minitab 21.1 software [39] was utilized to execute analysis of variance (ANOVA) with α: 0.05 significance level. The fundamental parameters were the types of binders and the compaction efforts (CE). An ANOVA test is realized to assess the impact of CE on the properties of asphalt mixtures having various levels of zeolite incorporations with various compaction efforts. Thus, permanent deformation-Kim test at 60

°C, and semicircular bending-SCB test at 25 °C for mixes, including natural zeolite-NZ and synthetic zeolite-SZ were considered the dependent variables, whilst various CE (i.e., 35-50-75 Marshall blows) were chosen as independent factors. Statistical analyses were realized to find out significant factors as shown in Tables 5, 6, 7 and 8. Therefore, groupings were denoted by letters such as A, B, C, etc. in these tables to indicate their similarities or differences. While groups labeled with distinct letters have substantial differences in their mean values, groups sharing the same letter do not exhibit significantly different mean values. For example, group A's mean value differs greatly from other groups, such as group B, in terms of both lower and higher values. There is no discernible difference in the mean values of groups that share letters, such as groups A and AB. Furthermore, percent contributions of the parameters were determined to find the effectiveness degree of selected parameters on the mechanical performances. In case of a value becomes higher, the effect of the parameter was considered significant on the resulting performances.

### 4.2. Deformation Strength Assessment Via Kim Test

The Kim tests were utilized to assess the rutting resistances, Table 6 and Fig. 4 presents the Kim test results of the SZWMA and NZWMA mixtures. The statistical significance of the deformation strength ($S_D$) with higher compaction efforts was analyzed using one-way variance analysis (ANOVA), and the results were presented in Table 6. Table 7 implies that the variations in $S_D$ for the NZWMA mixes was significant difference for all compaction efforts (CE). For example, the $S_D$ variation of the NZWMA mixes obtained 1.756 MPa (10.345 MPa at 75 blows/face (B/F), 8.589 MPa at 50 B/F); 2.454 MPa (10.345 MPa at 75 blows/face (B/F) 7.891 MPa at 35 B/F); 0.698 MPa (8.589 MPa for NZWMA mixes at 50 B/F, 7.891 MPa for SZWMA mixes at 35 B/F). Similarly, the change in $S_D$ for the SZWMA mixes was the significant difference for all CE as can be seen in Table 6. For example, the $S_D$ variation of the SZWMA mixes obtained 0.761 MPa (7.567 MPa at 75 blows/face (B/F) and 6.806 MPa at 50 B/F); 1.661 MPa (7.567 MPa at 75 blows/face (B/F), 5.906 MPa at 35 B/F); 0.9 MPa (6.806 MPa for NZWMA mixes at 50 B/F and 5.906 MPa for SZWMA mixes at 35 B/F). These results showed that the influence of CE on deformation strength is substantial, which is a favorably impacts on the deformation of NZWMA and SZWMA mixes. Furthermore, no significant difference in $S_D$ value was found between NZWMA obtained at 35 and SZWMA at 75 CE (i.e. the Kim tests ranked the NZWMA mixes tested at 35 compaction efforts (CE) as similar to SZWMA mixes obtained at 75 CE in terms of $S_D$). This outcome indicated that the NZWMA mixes need less compaction efforts than SZWMA mixes.

Fig. 4 illustrates that an increase in the CE for NZWMA and SZWMA mixes enhances the $S_D$. At similar CE, NZWMA mixes showed higher $S_D$ than SZWMA mixes. Specifically, NZWMA mixes exhibited an increase in $S_D$ by 33.5% for 35 CE, 26.0% for 50 CE, and 37.0% for 75 CE. Based on these findings, NZWMA mixes demonstrated greater resistance to permanent deformations (higher $S_D$) across all compaction efforts (CE) compared to SZWMA mixes. The higher rutting resistance of NZWMA mixes can be attributed to NZ's ability to reduce the viscosity of the binder, allowing it to penetrate deeply into aggregate surfaces and improve adhesive bonding between aggregate and binder compared to SZ. This results in a higher stiffness of the NZ/asphalt binder at elevated temperatures (60°C). The Kim test results show NZWMA at 50 blows/face outperforms SZWMA at the same effort, consistent with Valdes et al. [4] who reported high rutting resistance for natural-zeolite WMA at reduced mixing temperatures, and with Yousefi et al. [40] who observed improved rutting performance with zeolite additives. Visscher et al. [15] also support differing behaviors of NZ vs. SZ regarding optimal compaction.

All $S_D$ values satisfied the minimum requirements (>3.20 MPa) according to Korean Ministry of Land, Infrastructure, and Transport guidelines [41]. Therefore, it is possible to satisfy this value using 35 B/F for NZWMA and SZWMA mixtures.

Table 6: Parameters of Kim test results and the calculations of $S_D$.

| No. of blows | D, mm | r, mm | y, mm | P, kN | $S_D$, MPa |
|---|---|---|---|---|---|
| SZWMA | | | | | |
| 35 | 30 | 7.5 | 2.089 | 2.959 | 5.906 |
| 50 | | | 2.116 | 3.437 | 6.806 |
| 75 | | | 2.463 | 4.053 | 7.567 |
| NZWMA | | | | | |
| 35 | 30 | 7.5 | 2.136 | 3.997 | 7.890 |
| 50 | | | 2.355 | 4.532 | 8.589 |
| 75 | | | 1.654 | 4.832 | 10.346 |

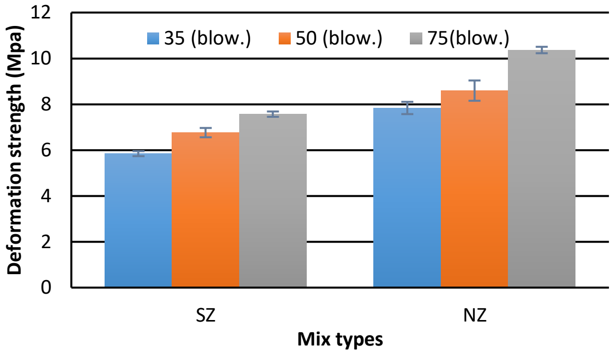


Fig. 4 The deformation strength in Kim test of NZWMA and SZWMA mixtures.

Table 7: Statistical analyses of deformation strength in Kim test of NZWMA and SZWMA mixes at various CE.

| Mix types ×Blows | N | Mean | StDev* | Grouping** | | | | | COV%*** |
|---|---|---|---|---|---|---|---|---|---|
| NZ75 | 3 | 10.3458 | 0.1398 | A | | | | | 1.35 |
| NZ50 | 3 | 8.589 | 0.442 | | B | | | | 15.49 |
| NZ35 | 3 | 7.891 | 0.268 | | | C | | | 11.65 |
| SZ75 | 3 | 7.5670 | 0.1160 | | | C | | | 7.76 |
| SZ50 | 3 | 6.806 | 0.203 | | | | D | | 11.41 |
| SZ35 | 3 | 5.906 | 0.1091 | | | | | E | 13.53 |

(*)StDev: standard deviation; (**) Means that do not share a letter are significantly different, (***)COV: coefficient of variance.

### 4.3. SCB (Semi-Circular Bending) Test Results

$P_{max}$, $G_f$, FI, CRI, and Jc were found through the use of SCB tests to study the intermediate temperature performance of different mixes. Fig. 5 illustrates the highest load of the various mixes at different notch sizes. $P_{max}$ indicated the strength of the asphalt mix, corresponding to the highest load recorded at the SCB tests. As expected, increases in the notch lengths reduce the Pmax values, resulting from the reduced ligament area of asphalt mixes as the notch lengths further increases. In most circumstances, the difference in Pmax values among NZWMA and SZWMA mixes' combinations was obtained significant statistically, in the SCB test at 75 blows/face and 25 mm notch, the mean Pmax for NZWMA was 0.229±0.024 kN versus 0.221±0.019 kN for SZWMA (only ~3.5% difference). At 38 mm notch and 75 blows/face, the mean $P_{max}$ was 0.155±0.018 kNnfor NZWMA and 0.134±0.022 kN for SZWMA (~13.5% difference), but ANOVA shows no statistical significance. Hence, these specific cases indeed yield no significant difference, as noted in Table 8. At all notch sizes and all CE, the results showed that the NZWMA mixes have higher $P_{max}$ values with respect to the SZWMA mixtures. NZWMA mixtures showed a 17.5%, 13.6%, and 15.7% increase in Pmax value at 25 mm notch size than the SZWMA mixes for 35, 50, and 75 CE, respectively. Likewise, NZWMA mixtures showed a 23.9%, 23.0%, and 15.0% increase in $P_{max}$ value at 32 mm notch size than the SZWMA mixes for 35, 50, and 75 CE, respectively. Whereas, the average $P_{max}$ value of NZWMA mixes at 38 mm notch size increase by 10.6%, 7.7%, and 3.6%, respectively.

It was also found that the NZWMA mixtures' $P_{max}$ values were greater than the SZWMA mixtures at the same optimum binder content. Additionally, an improvement in material toughness (toughness is equal to stress times strain) is indicated by an increase in $P_{max}$ values. Since asphalt mixtures are susceptible to low-temperature cracking and thermal fatigue, greater toughness aids in preventing cracks from forming and spreading. Meanwhile, the result further supports that NZWMA mixtures using the same OAC would achieve higher performance than SZWMA mixtures. NZWMA mixtures exhibit higher $P_{max}$ values than SZWMA mixtures. This may be attributed to: (1) the fact that NZ contains 18-22 percent water by weight, which makes the mixture more workable and compatible at lower temperatures by interacting with the binder, and/or (2) the increased stiffness of NZ in comparison to asphalt binder.

Moreover, Table 8 implies that the change in Pmax for the NZWMA mixes was an insignificant difference at all CE and all notch sizes, except for NZWMA mixes obtained for 25 mm and 38 mm notch sizes at 75 CE, which are different from those obtained at 35 and 50 CE (i.e., the SCB tests ranked the NZWMA mixes obtained at 32 mm notch sizes for all CE, and at 25 mm and 38 mm notch sizes for 35 and 50 CE, as similar in terms of Pmax). Similarly, the same statistical analysis results were obtained with SZWMA mixtures. They indicated that the increases in the compaction efforts from 35 to 50 B/F give similar $P_{max}$ of NZWMA and SZWMA mixes with irrespective in notch size. For the combination effects of both notch sizes and compaction efforts, $P_{max}$ results Fisher comparisons were cited in Table 8.

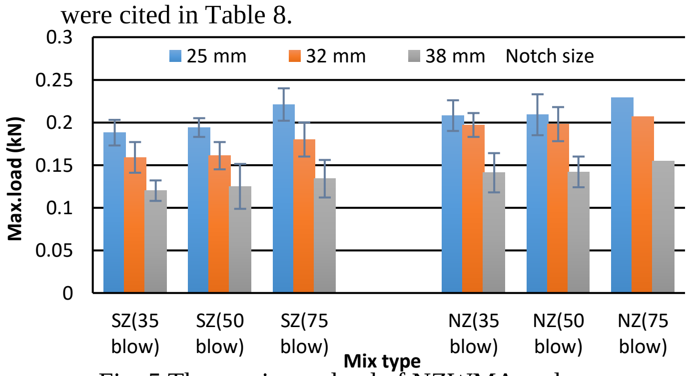


Fig. 5 The maximum load of NZWMA and SZWMA mixes.

Table 8: Statistical analyses of maximum load ($P_{max}$) of NZWMA and SZWMA mixes.

| Mix types*notch size*Blows | N* | Mean | StDev* | Grouping | | | | | | | COV% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NZ 38 75 | 3 | 0.155 | 0.018 | | | | | E | F | | 11.62 |
| SZ 38 75 | 3 | 0.134 | 0.022 | | | | | | F | G | 16.42 |
| NZ 38 50 | 3 | 0.209 | 0.023 | A | B | C | | | | | 11.00 |
| NZ 38 35 | 3 | 0.208 | 0.009 | A | B | C | | | | | 4.33 |
| NZ 32 75 | 3 | 0.207 | 0.020 | A | B | C | | | | | 9.66 |
| NZ 32 50 | 3 | 0.198 | 0.014 | | B | C | | | | | 7.07 |
| NZ 32 35 | 3 | 0.197 | 0.011 | | B | C | | | | | 5.58 |
| SZ 25 50 | 3 | 0.194 | 0.011 | | B | C | | | | | 5.67 |
| SZ 25 35 | 3 | 0.188 | 0.015 | | | C | D | | | | 7.98 |
| SZ 32 75 | 3 | 0.180 | 0.020 | | | C | D | E | | | 11.11 |
| SZ 32 50 | 3 | 0.161 | 0.016 | | | | D | E | F | | 9.94 |
| SZ 32 35 | 3 | 0.159 | 0.018 | | | | D | E | F | | 11.32 |
| NZ 25 75 | 3 | 0.229 | 0.024 | A | | | | | | | 10.48 |
| SZ 38 50 | 3 | 0.125 | 0.0263 | | | | | | F | G | 21.04 |
| NZ 25 50 | 3 | 0.142 | 0.018 | | | | | | F | G | 12.68 |
| NZ 25 35 | 3 | 0.141 | 0.017 | | | | | | F | G | 12.06 |
| SZ 25 75 | 3 | 0.221 | 0.019 | A | B | | | | | | 8.60 |
| SZ 38 35 | 3 | 0.120 | 0.012 | | | | | | | G | 10.00 |

(**) Means that don't exchange letters share a letter are substantially different (i.e., groups are defined by letters like A, B, C, etc., to denote their similarities or differences); (*)N and StDev: Number of samples and standard deviation, respectively. SZ: synthetic zeolite & NZ: natural zeolite; groups labeled with distinct letters exhibit significant differences in their mean values, while groups sharing the same letter do not exhibit significant differences in their mean values.

On the other hand, fracture energy is a commonly utilized parameter to assess the fracture behaviors of asphalt mixes, evaluating the fracture tolerance of the binder, mixture, and intermediate interstitial components [42], [43]. Fig. 6 illustrates the fracture energy ($G_f$), a linear parameter used to evaluate fracture behavior. The findings suggest that as the notch size increases, the fracture energies of NZWMA and SZWMA mixes decrease, attributed to the reduced effective ligament area with larger notches [44]. Across all three notch sizes and compaction efforts (CE), NZWMA mixtures consistently showed slightly higher $G_f$ values compared to SZWMA mixes. Specifically, at the 32 mm notch size, NZWMA mixtures exhibited a 17.9%, 10.2%, and 9.6% increase in Gf value over SZWMA mixes for 35, 50, and 75 CE, respectively. Similarly, the average Gf values of NZWMA mixes at the 38 mm notch size increased by 4.8%, 39.8%, and 27.4%, respectively. In contrast, SZWMA mixtures showed a 14.6% and 27.3% increase in Gf value at the 25 mm notch size compared to NZWMA mixtures at 50 and 75 CE, respectively.

Results also indicated that increases in the compaction efforts give higher $G_f$ values for both NZWMA and SZWMA mixes tested at all

Moreover, notch size in most circumstances, the difference in Gf values among NZWMA and SZWMA mixes' combinations was obtained significant statistically, except for SZWMA mixes obtained for 25*75, 38*75, 32*50, and 38*35 (notch size*Blows) which are not different to NZWMA mixes obtained at 32*75, 25*75, 25*50, and 38*35 (notch size*Blows), respectively (i.e., statistically are insignificant). Similarly, the same statistical analysis results were obtained with SZWMA mixtures.

Moreover, Table 9 indicates that the change in $G_f$ for the NZWMA mixes showed an insignificant difference at 50 B/F CE for 38 mm and 32 mm notch sizes (i.e., the SCB tests ranked the NZWMA mixes obtained at 38 mm notch size for 50 CE and at 32 mm notch size for 50 CE similarly in terms of $G_f$). Likewise, NZWMA mixtures 2550, 2535, and 3235 showed the same $G_f$ values. Similarly, same statistical analysis results were obtained with SZWMA mixtures at 2535, 3235, and 3850. These results indicate that the increases in the compaction efforts from 35 to 50 B/F give similar Gf values for NZWMA and SZWMA mixes regardless of notch size. For the combined effects of both notch sizes and compaction efforts, $G_f$ results and Fisher comparisons are provided in Table 9.

Table 9: Statistical analyses of fracture energy ($G_f$) of NZWMA and SZWMA mixes.

| mix types*notch size*Blows | N | Mean | StDev | Grouping | | | | | | | | COV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NZ 38 75 | 3 | 1485.59 | 34.0 | A | | | | | | | | 2.29 |
| NZ 32 75 | 3 | 1400.52 | 32.0 | | B | | | | | | | 2.28 |
| SZ 25 75 | 3 | 1363.34 | 28.0 | | B | | | | | | | 2.05 |
| SZ 32 75 | 3 | 1277.86 | 23.0 | | | C | | | | | | 1.80 |
| SZ 25 50 | 3 | 1236.17 | 21.0 | | | C | D | | | | | 1.70 |
| NZ 38 50 | 3 | 1217.94 | 23.0 | | | | D | | | | | 1.90 |
| NZ 32 50 | 3 | 1208.61 | 30.0 | | | | D | | | | | 2.48 |
| SZ 38 75 | 3 | 1165.28 | 26.0 | | | | | E | | | | 2.23 |
| NZ 25 75 | 3 | 1151.64 | 28.0 | | | | | E | | | | 2.43 |
| SZ 32 50 | 3 | 1096.57 | 27.0 | | | | | | F | | | 2.46 |
| NZ 25 50 | 3 | 1078.71 | 33.0 | | | | | | F | | | 3.06 |
| NZ 25 35 | 3 | 1070.88 | 29.0 | | | | | | F | | | 2.71 |
| NZ 32 35 | 3 | 1063.64 | 31.0 | | | | | | F | | | 2.91 |
| SZ 25 35 | 3 | 910.04 | 13.00 | | | | | | | G | | 1.43 |
| SZ 32 35 | 3 | 902.17 | 16.00 | | | | | | | G | | 1.77 |
| SZ 38 50 | 3 | 870.80 | 13.00 | | | | | | | G | | 1.49 |
| NZ 38 35 | 3 | 750.16 | 22.0 | | | | | | | | H | 2.93 |
| SZ 38 35 | 3 | 715.57 | 19.0 | | | | | | | | H | 2.66 |

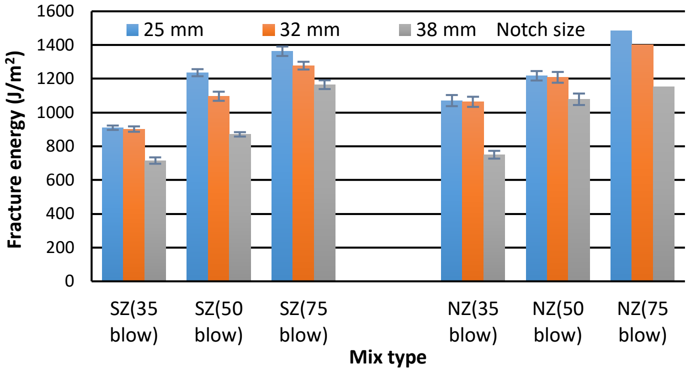


Fig. 6. The fracture energy of NZWMA and SZWMA mixtures.

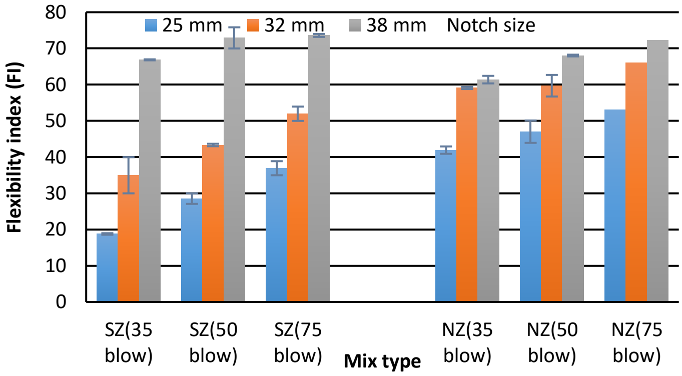


Fig. 7. The flexibility index of NZWMA and SZWMA mixtures.

Fig. 7 illustrates the FI results of various mixes at different notch sizes. A higher FI indicates a mix with higher resistance to crack propagation. The findings revealed that NZWMA mixes at all CE and notch sizes performed better in terms of FI values than the SZWMA mixtures, except for the 38 mm notch size, which showed slightly lower FI values. The minimum FI value was found in SZWMA mixes obtained at 35 CE, while the maximum FI value was found in SZWMA mixes obtained at 75 CE and 38 mm notch size. Furthermore, the FI values of SZWMA mixes obtained at 50 and 75 CE seem identical. A similar finding was observed for NZWMA mixes obtained at 50 and 75 CE. This indicates that the effect of notch size on the FI of zeolite-WMA mixtures is very small and can be neglegted. The high FI values observed in this study reflect that the effect of zeolite addition and specific binder characteristics; for instance, Dao et al. [45] reported FI up to 58.6% for WMA with Zycotherm compared to about 12% for HMA, and other literature shows wide FI variability (COV ~25–34%) due to test conditions, notch depths, and binder properties. Therefore, our elevated FI values align with the upper ranges reported, particularly with zeolite additives that enhance energy absorption during fracture and increase FI. Furthermore, despite FI differences compared to studies without zeolite or with different test setups, other performance parameters (fracture energy, deformation strength) support high stiffness and durability, increasing the validity of our findings.

Fig. 8 illustrates the cracking resistance index (CRI) values of various mixes at different notch sizes, revealed that the CRI value of NZWMA and SZWMA mixes increases with an increase in the notch sizes. The maximum CRI value was found at SZWMA mixes obtained at 75 CE followed by NZWMA mixes obtained at 50 CE, and the minimum CRI value was found at NZWMA mixes obtained at 35 CE. Furthermore, SZWMA mixes obtained at 50 CE showed almost same CRI values to those for NZWMA mixtures obtained at 75 CE.

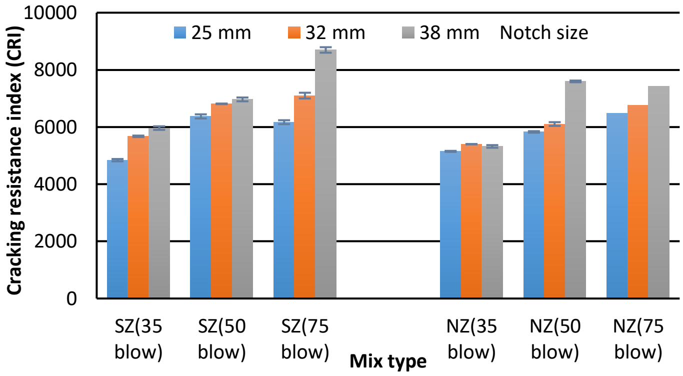


Fig. 8. The CRI (cracking resistance index) of NZWMA and SZWMA mixes.

Fig. 9 shows the critical J-integral values of various NZWMA and SZWMA mixes. There is no general agreement on the minimum Jc value to determine the fatigue cracking of the asphalt mixtures. Meanwhile, 0.5-0.65 Jc value can be regarded as the minimum acceptable values for Jc [46]. In general, both NZWMA and SZWMA mixes are predicted to reduce fatigue resistance. This might be related to the Jc calculation, which use pre-peak absorbed strain energy. While, zeolite might make the combination more elastic and stiffer during this phase, before the tenacity of the mixture is lost in the post-peak periods.

However, the findings depicted the that fact all the SZWMA mixes showed higher Jc values than NZWMA mixtures, indicated more resistance to fatigue cracking, which could be attributed to the calculation of Jc.

Fig. 9 indicates that all NZWMA and SZWMA mixes (except for SZWMA mixes with

35 CE and NZWMA mixes with 35 CE and 50 CE) have Jc values higher than the minimum acceptable value for Jc of 0.5-0.65. The SZWMA mixes obtained at 50 and 75 CE, and NZWMA mixes obtained at 75 CE showed the Jc values more than 0.5. The Jc value of SZWMA mixes obtained at 50 CE, SZWMA mixes obtained at 75 CE, and NZWMA mixes obtained at 50 CE are 0.56, 0.62 and 0.55, respectively. The maximum Jc value was found at SZWMA mixes obtained at 75 CE, followed by SZWMA mixes obtained at 50 CE, and then by NZWMA mixes obtained at 75 CE. The results implied that these mixes are more resistant to the fatigue cracking than the other NZWMA and SZWMA mixes. Furthermore, the Jc value of SZWMA mix at 50 CE seems similar to that of NZWMA mix at 75 CE.

According to the research's overall findings, SZWMA and NZWMA mixes can be produced at 50 and 75 CE, respectively. For example, SZWMA mixtures obtained at 50 CE result in the highest CRI and FI values, a Jc value greater than 0.5, and $S_D$ value greater than 3.2 MPa. Similarly, NZWMA mixes obtained at 75 CE lead to the maximum increase in CRI and FI values, a Jc value greater than 0.5, and SD value greater than 3.2 MPa. Therefore, in the selection of the optimum WMA mixtures, it is necessary to consider the CE and desired performance properties. Regarding the parameters used to determine the rutting resistance and fracture potential of asphalt mixes, it should be noted that these parameters are related to the rutting and fatigue performance of asphalt mixes in different aspects.

Higher Jc in SZWMA at 75 blows/face partially agrees with Visscher et al. [15], who observed certain synthetic additives can enhance binder stiffness relevant to early-stage fatigue indicators, and follows the J-integral framework of Kaseer et al. [37]. It shows NZWMA can reach $J \geq 0.5$ at moderate compaction, whereas SZWMA requires higher compaction for similar fatigue performance.

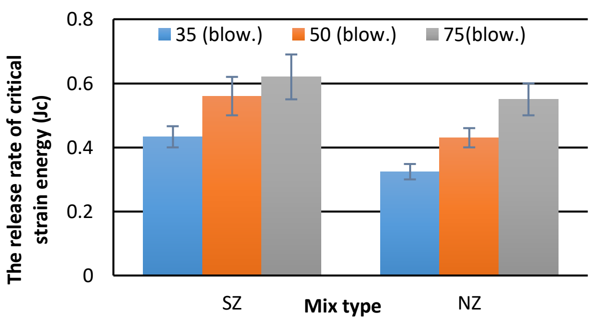


Fig. 9 Critical J-integral of NZWMA and SZWMA mixes.

## 5. CONCLUSIONS

This study aimed to assess how different compaction efforts (CE) impact the deformation strength (rutting resistance), intermediate-temperature cracking, and fatigue resistance of warm-mix asphalt (WMA) containing natural zeolite (NZWMA) and synthetic zeolite (SZWMA). The key findings can be summarized as follows:

1. Optimal Compaction Efforts: Through extensive analysis of various mixtures, it is obvious that both NZWMA and SZWMA mixes, each incorporating 5% zeolite, consistently outperform conventional mixes in crucial metrics such as deformation strength ($S_D$) in the Kim test, maximum load (Pmax), fracture energy ($G_f$), and critical strain energy release rate (Jc). These results highlight their superior performance in these specific aspects. Optimal compaction efforts are identified in the range of 50 to 75 blows/face, striking a balance to achieve enhanced performance across multiple parameters. This detailed understanding is pivotal for optimizing Warm Mix Asphalt formulations.
2. Statistical Analysis: NZWMA mixes generally exhibited higher rutting resistance with lower cracking and fatigue properties compared to SZWMA mixes at lower compaction efforts (50 blows/face). Notably, the production of NZWMA mixes also resulted in time and fuel consumption savings compared to SZWMA mixes.
3. Effect of Compaction Efforts: Both NZWMA and SZWMA mixtures showed increased in $S_D$, Pmax, $G_f$, and Jc values with higher compaction efforts. However, statistically significant differences in deformation strength and semi-circular bending parameters were observed across various compaction effort levels.
4. The performances of asphalts were significantly affected by zeolite incorporations, and the influence of natural zeolite was found much more than the influence of synthetic zeolite.

In conclusion, incorporating compaction efforts in the production of NZWMA and SZWMA mixtures has demonstrated promising outcomes, including meeting minimum specifications for deformation strength in the Kim test and Jc, while potentially leading to cost efficiencies. These findings underscore the importance of optimizing compaction efforts to enhance the performance and sustainability of warm-mix asphalt mixtures.

## 6. FUTURE STUDIES

Based on the results of this study, the following future studies are suggested:

1. Additional investigation is needed to determine the performance of warm asphalt mixtures that incorporate other types of mineral filler such as hydrated lime, Portland cement, marble waste….etc.
2. Further studies necessary to take at the potential effects of varying temperatures and loading rates on the fracture potential of warm mixes. With an emphasis on low-temperature performance, this analysis will help provide a thorough understanding of how the material behaves under different stress circumstances.

## 7. ACKNOWLEDGMENTS

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# التقييم والتحليلات الإحصائية لمقاومة التخدد، التشقق، والكلل للمزجات الاسفلتية الدافئة


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***الملخص***

*يتم إنتاج المزجات الاسفلتية الدافئة (WMA) في درجات حرارة أقل من المزجات الاسفلتية الساخنة (HMA)، مما يشير إلى انخفاض جهود الرص. قامت هذه الدراسة بتقييم مقاومة WMA للتخدد والتشقق والكلل في ظل ثلاث جهود رص (35، 50، و75 ضربة / وجه) باستخدام فحوصات كيم والانحناء نصف الدائري لقياس قوة التشوه وطاقة الكسر ودليل المرونة ومعامل الكلل. تم تحسين الاسفلت الأصلي بدرجة اختراق 40/50 بنسبة 5٪ زيولايت طبيعي (NZ) و 5٪ زيولايت صناعي (SZ) من وزنه لإنتاج NZWMA و SZWMA. خضعت اثنتان وسبعون عينة مرصوصة بمارشال لتحليل إحصائي لتحديد جهد الرص (CE) الأمثل. النتائج الرئيسية: (1) يتطلب NZWMA 50 ضربة / وجه و SZWMA 75 ضربة / وجه لتلبية الحد الأدنى لقوة التشوه 3.2 ميجا باسكال (فحص كيم) ومعامل الكلل J ≥ 0.5 (معدل طاقة الانفعال الحرج)؛ (2) عند جهد رص 50 ضربة/وجه، وفّرت مزجات NZWMA وقتاً وجهداً مقارنة بمزجات SZWMA، مع استيفائها لمتطلبات الأداء؛ (3) أظهرت مقاومة التخدد والتشقق والكلل اتجاهات ثابتة مع زيادة معامل القدرة على التحمل (CE) لكلا المزجتين. تُظهر النتائج كفاءة مزجة NZWMA تحت رص معتدل، مما يوفر مزايا عملية في إنتاج الأسفلت من خلال موازنة الأداء وتوفير الجهد. تُقدّم هذه الدراسة رؤىً حول تحسين معامل القدرة على التحمل (CE) لتقنيات WMA، مع التركيز على إمكانيات مزجة NZWMA في تطبيقات الرصف المستدامة.*



***الكلمات الدالة:***

*مزجات اسفلتية دافئة، دليل المرونة، دليل التشققات، طاقة الكسر، فحص كيم، والانحناء نصف الدائري.*