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Performance Evaluation of Sustainable Rigid Pavement Structure and Rehabilitation Decision Making

Tamara Hussein Bani Ata [1] , Asma Thamir Ibraheem [2]

Abstract

Real-life strategies are applied to assess pavement functionality, high-quality performance, and durability throughout its service life. Estimating pavement maintenance and sustainability is difficult. High-performance continuous reinforced concrete pavement (CRCP) structural design and Jordanian natural zeolite (JNZ) as a sustainable supplementary cementitious material (SCM) and unique mixed cement for green manufacturing are researched in this paper. The results obtained from this study showed that replacing cement with JNZ powder at 0%, 10%, 15%, and 20% improved concrete performance. Natural zeolite-mixed cement preserved concrete quality and reduced the use of ordinary Portland cement (OPC) and sulfate-resistant cement (SRC) clinker. After that slab universal testing equipment and Jordanian zeolite-blended cement-reinforced concrete slabs were developed for CRCP performance. Therefore, fresh concrete was tested for partial cement substitution and standard mixture workability. Compressive, tensile, and flexural tests on 7 and 28 days and durability (water absorption) were used to assess concrete strength and natural zeolite's potential to reduce resource consumption and carbon footprint while maintaining structural integrity using Open LCA. Sustainable CRCP structure development improved performance, resource conservation, and carbon footprint over the prior mix, according to EIA (Environmental Impact Assessment) software and chemical tests. This research improves pavement engineering and supports global sustainability goals while informing professionals and governments.

Keywords: Durability, Environmental Impact Assessment (EIA), Rehabilitation, Rigid Pavement and Sustainable

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تقييم أداء هيكل التبليط الصلب المستدام واتخاذ القرارات المتعلقة بإعادة التأهيل

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المستخلص

يتم تطبيق استراتيجيات واقعية لتقييم وظائف الرصف وأداء الرصف عالي الجودة والمتانة طوال فترة خدمته، فمن الصعب تقدير صيانة الرصف واستدامته. هذه الورقة البحثية بحثت في التصميم الهيكلي للرصف الخرساني المسلح المستمر عالي الأداء (CRCP) والزيوليت الطبيعي الأردني (JNZ) كمادة أسمنتية تكميلية مستدامة (SCM) وأسمنت مخلوط فريد من نوعه للتصنيع الأخضر. أظهرت النتائج التي تم الحصول عليها من هذه الدراسة أن استبدال الأسمنت بمسحوق الزيوليت الطبيعي الأردني بنسبة 0% و10% و15% و20% حسّن من أداء الخرسانة. وكذلك حافظ الأسمنت المخلوط بالزيوليت الطبيعي على جودة الخرسانة وقلل من استخدام الأسمنت البورتلاندي العادي (OPC) والأسمنت المقاوم للكبريتات (SRC) الكلنكر. بعد ذلك تم استخدام معدات اختبار عالمية للبلاطات والألواح الخرسانية الأردنية المخلوطة بالزيوليت المخلوط بالأسمنت المسلح وتطوير بلاطات خرسانية لنمذجة أداء CRCP. ولذلك، تم اختبار الخرسانة الطازجة للاستبدال الجزئي للأسمنت وقابلية التشغيل القياسية للخلطة. استُخدمت اختبارات الضغط والشد والانثناء في 7 و28 يومًا والمتانة (امتصاص الماء) لتقييم قوة الخرسانة وقدرة الزيوليت الطبيعي على تقليل استهلاك الموارد والبصمة الكربونية مع الحفاظ على السلامة الهيكلية باستخدام التقييم المفتوح لتقييم دورة الحياة (Open LCA). حيث أدى تطوير الهيكل المستدام للخرسانة الخرسانية المستدامة إلى تحسين الأداء والحفاظ على الموارد والبصمة الكربونية مقارنةً بالمزيج السابق، وفقًا لبرنامج تقييم الأثر البيئي

انتساب الباحثين

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[1] **المؤلف المراسل**

معلومات البحث
تاريخ النشر: تشرين الاول 2025

والاختبارات الكيميائية. يحسّن هذا البحث هندسة الرصف ويدعم أهداف الاستدامة العالمية مع إعلام المهنيين والحكومات.

الكلمات المفتاحية : الديمومة ، تقييم الأثر البيئي (EIA) ، إعادة التأهيل ، الرصف الصلب ، الاستدامة

1. Introduction

The construction sector is facing a variety of challenges, including the need to mitigate environmental impacts while satisfying infrastructure needs. Infrastructure systems that are durable and resilient are essential as urbanization accelerates around the world. CRCP, or continuously reinforced concrete pavement, is one of the best options because it is a very advanced type of rigid pavement known for its continuous steel reinforcement and one-piece structure that makes load distribution and structural integrity better.

The evaluation of long-lasting rigid pavement structures and the decision-making process for their rehabilitation are important topics in civil engineering, especially as traffic volumes rise and common pavement issues arise, such as early wear and tear, and high repair costs. In addition, the conventional concrete mix, which is mainly made of ordinary Portland cement (OPC), has numerous cons despite its pros. The energy-intensive calcination process and the natural CO_2 generated during the chemical transformation of limestone are the main causes of global carbon dioxide emissions related to the production of OPC [1].

The challenges get worse due to an inadequate performance evaluation approach and insufficient rehabilitation frameworks, leading to inefficient resource allocation and unsustainable practices in pavement preservation. So, there is a scientific emphasis on sustainable construction methods and alternative materials used, such as natural zeolite supplementary cementitious materials (SCMs). Jordanian natural zeolite (JNZ), a volcanic mineral with particular pozzolanic characteristics, has attracted interest in improving concrete's mechanical properties, durability, and strength by reacting water with calcium hydroxide. Zeolite is a desirable alternative to cement because of its natural abundance and limited manufacturing needs, which also fit with environmentally friendly construction goals [2,3].

This research aims to fill this gap by evaluating the performance of CRCP using Jordanian natural zeolite to identify an optimal balance between sustainability and structural integrity. Enhancing the use of natural zeolite in CRCP results in modern environmentally friendly pavement construction techniques, thereby reducing carbon emissions and conserving resources in sustainable infrastructure development. However, the specific impacts of JNZ on CRCP behaviour have not been extensively studied and investigated.

1.1 Problem Statement

The conventional techniques of rigid pavement construction and maintenance frequently inadequately meet the complexities of modern transportation requirements and environmental considerations. This lack highlights the pressing necessity for extensive research that assesses the efficacy of sustainable rigid pavements and develops informed rehabilitation practices.

1.2 Significance of the Study

This research significantly improves the conceptual basis of pavement engineering by

integrating principles of sustainability, materials science, and structural performance. It seeks to enhance current understanding and create an essential framework for future research on sustainable practices in civil engineering. The practical applications of this finding are extensive.
It has primarily focused on the unique performance requirements and stress conditions related to continuously reinforced pavements over other previous studies of Jordanian natural zeolite in traditional mixes. The findings of this study have contributed crucial insights into the potential benefits of using JNZ in CRCP for sustainable construction practices. To promote the use of eco-friendly materials in pavement design, this study will assist in developing industry standards and guidelines by investigating the mechanical and durability advantages of zeolite-concrete blend.
Furthermore, this research supports global sustainability goals that seek to reduce the construction sector's carbon footprint. Also, using natural zeolite in CRCP is a big step forward in meeting both environmental and performance goals in pavement technology because people want infrastructures that can last for a long time.

2. Materials and Methodology

This section outlines the materials and methods utilized in this research to assess the performance of sustainable rigid pavement structures and to develop appropriate rehabilitation decision-making strategies.

2.1 Cement

Portland cement CEM I with appropriate limits on composition and high durability is used with certain chemical and physical properties according to (ASTM C150) and (JS No.30 - 2024) specifications for general construction and concrete use .

2.2 Coarse Aggregate

This research used coarse aggregates based on ASTM and Jordanian Standards (JS 2024) specifications defined by the Jordan Standards and Metrology Organization. A typical sample of coarse aggregate was prepared, and the results of experimental testing are presented in Table (1).

Table (1): Coarse aggregates testing for experimental work in the research

Aggregate Test	Test Result	Testing Specification
Absorption %	2.4	ASTM C127
Abrasion %	27	ASTM C131
B.S.G (Dry)	2.552	ASTM C127
B.S.G (SSD)	2.613	ASTM C127
Sulfate Content %	0.042	ASTM C33
Bulk Density kg/m^3	1578	ASTM C29
Chloride Content %	0.019	ASTM C33
Soundness Loss ($NaSO_4$) %	5.0	ASTM C88

2.3. Fine Aggregate

A fine-grained substance with particle sizes less than 5 mm is known as sand. It was used in concrete mixtures according to ASTM C128 standards and requirements for aggregate grading. In this study, it was analyzed by several tests, yielding a fineness modulus of 2.40, a specific gravity of 2.60, an absorption rate of 1%, and a sand equivalent percentage of 76%.

2.4. Jordanian Natural Zeolite (JNZ)

Zeolite is a volcanic inorganic microporous mineral defined by a highly porous structure. Zeolite, with its crystalline aluminosilicate structure, serves as a supplementary cementitious material [4,5]. There is a notable lack of JNZ use in cement and concrete production for infrastructure applications like pavement.

This research examines the characteristics of Jordanian natural zeolite for the production of a sustainable, high-performance CRCP structure using newly blended cement with varying percentages of zeolite. Figure (1) illustrates the collection of JNZ compositions from an actual site in northeastern Jordan.

Figure (1): Field site source of JNZ used in the study

The Quality Directorate laboratory at the Ministry of Energy and Mineral Resources in Jordan verified JNZ properties through XRF analysis. Table (2) tabulates JNZ elements that affect the concrete mixing process, workability, and overall performance.

Table (2) : X-ray fluorescence (XRF) analysis of JNZ

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	CL	LOI	∑
39.7%	10.8%	12.89%	10.97%	9.23%	1.63%	1.39%	0.16%	0.035%	9%	96.42%

3. Sustainable Zeolite Cement and Concrete Production

Jordanian natural zeolite is applied in two principal roles in cement and concrete manufacturing: as a correction ingredient in zeolite-blended cement clinker and as a partial replacement for cement as an additional material. The study's originality is the application of JNZ to modern concrete performance, promoting its sustainability and efficiency in CRCP construction.

A normal concrete mixture was designed, including a control conventional mix with 100% Portland cement. The other design trial involved the replacement of cement weight with JNZ and the production of zeolite-blended cement.

Utilizing JNZ in the cement and concrete mix to assess its performance and effects on the mechanical properties and durability of the developed zeolite-enhanced CRCP, examine its impact on CRCP sustainability under heavy traffic loads, and evaluate the long-term performance with environmental impact considerations as shown in Figure (2).

Figure (2): Natural zeolite grain size grinding for the study.

In the tests of concrete mixes, different amounts of JNZ were added to replace 10%, 15%, or 20% of the Portland cement (CEM I, 42.5 N, ASTM C150). This was done to study the effects of JNZ on concrete properties [6,7]. Mixture designs were assembled and summarized as shown in Table (3).

Table (3): Concrete mixtures design.

Mix No.	Cement Content (kg/m^3)	JNZ Replacement %	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	w/c
1	400	0	946	946	0.45
2	360	10	946	946	0.37
3	340	15	946	946	0.38
4	320	20	946	946	0.4

In contrast, JNZ was used as a correction material in both ordinary Portland and sulfate-resistant cement clinker for the production of zeolite-blended cement and concrete. This innovative study method optimizes the chemical composition of the clinker and enhances the properties of the resulting concrete. JNZ was used during the clinker manufacturing process with specific amounts and homogeneous mixing to adjust the silica, alumina, and other oxide compositions for optimal clinker formation, as illustrated in Figure (3).

Figure (3): Zeolite blended cement production

Four different types of mixtures were made in varying percentages of Jordanian natural zeolite material, with a reference concrete mixture of Portland cement. Plain concrete specimens were produced using a 400 kg/m³ concrete mixture, which contained a specific proportion of weighted coarse aggregate, sand, and cement, combined in a dry state with a designated amount of water as indicated by the water-to-cement ratio in Table (3).

A slump test was performed to assess the workability and consistency of fresh concrete before its setting. The mixture was subsequently collected and poured into molds for cubic, cylindrical, and prismatic specimens for the upcoming concrete testing evaluation. Concrete samples were removed from molds after 24 hours and cured for 7 and 28 days in a water bath, as illustrated in Figure (4) [8].

Figure (4): Plain concrete mix production and sample preparation

Zeolite concrete mixes were formed in the preparation of 150 specimens with a uniform concrete design, including 10%, 15%, and 20% replacement of Portland cement with natural zeolite as newly developed mixtures. The zeolite concrete mixtures were cast into standard molds for curing and slump testing. In addition, zeolite-mixed concrete was created and poured into standard molds for testing after 7 and 28 days of curing to make the concrete last longer and perform better. Figure (5) shows the design of the created zeolite concrete specimen.

Figure (5): Zeolite blended cement specimens design

4. Sustainable Continuously Reinforced Zeolite Concrete Pavement

A design for continuously reinforced concrete pavements (CRCP) utilizing JNZ was implemented by introducing a JNZ-modified concrete mixture into the constructed continuously reinforced slabs to simulate an actual CRCP structure. A systematic design of slab thickness, dimensions, and steel reinforcement was performed to evaluate structural integrity and resistance to failure.

A portable plywood structure of 1 m x 1 m x 0.1 m was constructed based on a laboratory testing configuration featuring continuous longitudinal bars with a diameter of 10 mm and transverse bars positioned every 10 cm across the width. Then, standard and specially designed reinforced concrete slabs were cast with appropriate vibration and cured using water spraying and wet burlap to enhance hydration and strength development, as illustrated in Figure (6).

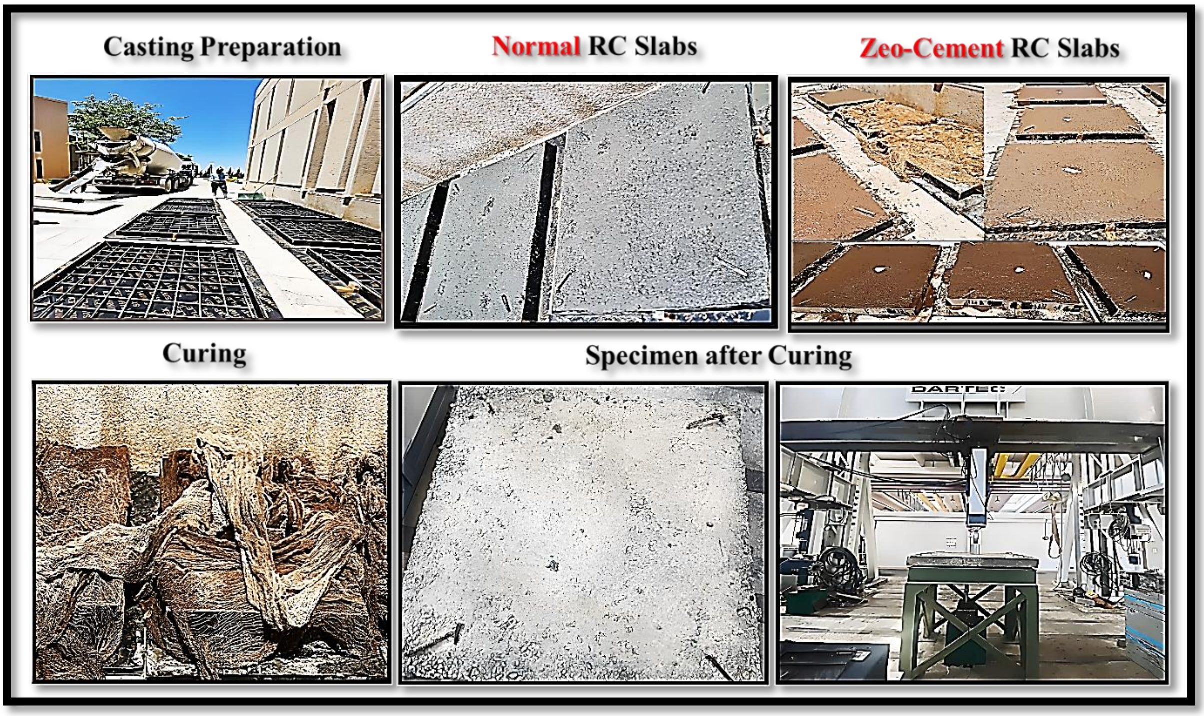

Figure (6): Continuously reinforced zeolite concrete pavement slabs

5. Zeolite Concrete Testing Techniques for Sustainable CRCP

The essential components of any concrete specimen have been analyzed in the assessment of concrete mixtures, focusing primarily on the evaluation of their mechanical properties, particularly compressive, tensile, and flexural strengths. After the casting process, the specimens were examined at 7 and 28 days. The mean ultimate stress of the three concrete specimens with a certain contact area was utilized to calculate the test results for each mixture. This study conducted zeolite concrete tests to evaluate the sustainable CRCP performance, as depicted in a schematic flowchart in Figure (7).

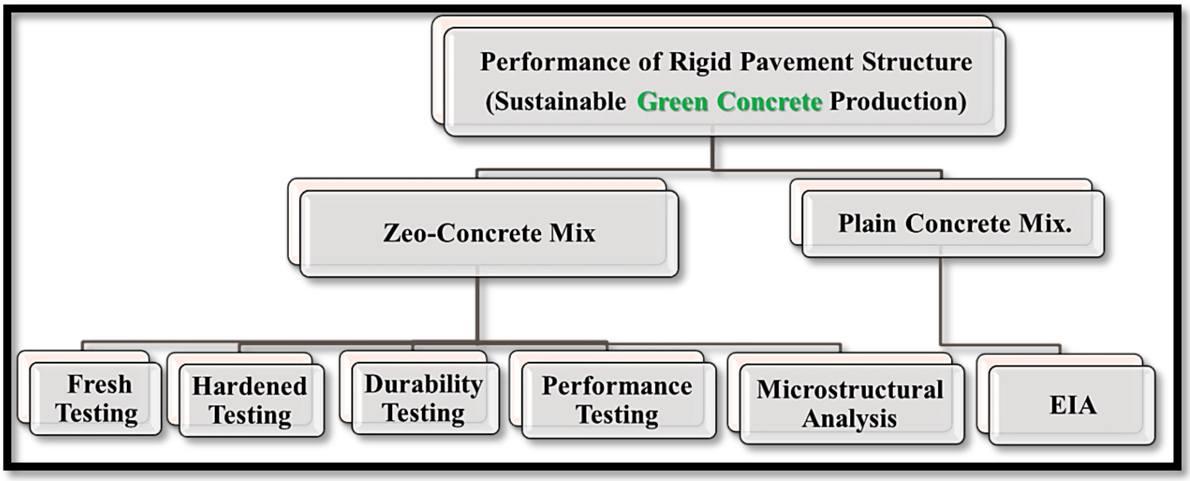

Figure (7): Schematic flowchart of sustainable concrete key tests in study

5.1 Density, Permeability Performance and Setting Time

The weight of compacted concrete in a container with certain dimensions can be utilized to determine the density of fresh concrete by dividing the container's volume by the given mass. The permeability of mixes was evaluated using water absorption to assess durability considerations [9].

The computation of the mass increase from the initially dry mass forms an aspect of the absorption process. The absorption was determined during a 28-day curing time of specimens in water by averaging the absorption values of the samples according to ASTM C642. Samples were dried at 100°C, weighed, immersed in water for 24 hours, and subsequently weighed again to find the proportion of water absorption.

In addition, the initial and final setting times of concrete were assessed using a Vicat apparatus, which recorded the duration required for the concrete to initiate and finish setting, focusing on workability and setting properties, particularly in CRCP based on ASTM C191.

5.2 Concrete Compressive Strength

Concrete specimens of normal and modified concrete mixtures were cast into standard cube molds of 150 mm x 150 mm x 150 mm for compressive strength testing [8,10]. A universal testing machine conducted the test, providing a compression force at a rate of 0.6 MPa/s, as shown in Figure (8).

Figure (8): Compression strength of normal and zeo-concrete test.

5.3 Concrete Tensile and Flexural Strength Tests

Concrete specimens were formed in conventional cylindrical molds measuring 150 mm in diameter and 300 mm in height and then evaluated for tensile splitting strength according to ASTM C496. The third-point loading test is used to check the flexural strength of concrete by bending prisms that are 100 mm x 100 mm x 500 mm and loading them until they break, according to ASTM C78, as shown in Figure (9).

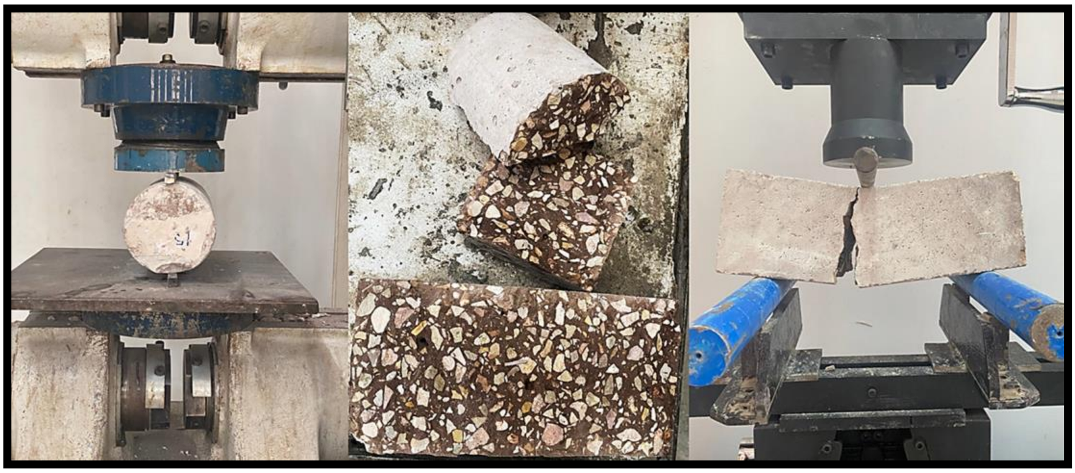

Figure (9): Tensile and flexural strength of zeo-concrete tests

5.4 Integrating JNZ into the Sustainable Future of CRCP

The integration of Jordanian natural zeolite in the design and construction of Continuously Reinforced Concrete Pavements (CRCP) offers a sustainable method for improving the performance and durability of concrete. This section examines the characteristics of natural zeolite, its prospective advantages in CRCP, and a suggested approach for its incorporation.

A 450-kN cell load with a 10-cm diameter was applied vertically to ensure the load was spread evenly across the slab. Additionally, a displacement rate of 2 mm/min was applied to reduce the dynamic effects of sudden loadings by improving the modulus. Strain was recorded until the slabs broke, then the maximum failure load (P, kN) and the sample's cross-sectional area (A, mm²) were utilized to calculate the compressive strength (fc') of the CRCP slab as shown in Figure (10).

Figure (10): Integrating JNZ into sustainable future of CRCP

5.5 Microstructural Development of Zeolite Concrete Blend using SEM

Microstructural analysis is a special method for evaluating the morphological properties of concrete. This study used scanning electron microscopy (SEM) as a proficient method for visualizing the microstructural characteristics of mixes utilizing Nano-SEM images.

The zero-concrete specimens are generally cured and divided to suitable dimensions. The specimens are positioned in the Nano-SEM, which relies on a highly focused electron beam to examine the surface as illustrated in Figure (11) at the Institute of JUST Nanotechnology. The high-resolution images displayed the microstructure, covering pore distribution, particle shape, and inter-aggregate bonding.

Figure (11): Microstructural analysis of concrete mixes using Nano-SEM

5.6 Environmental Impact Assessment (EIA) Study

The Environmental Impact Assessment (EIA) systematically assesses the potential environmental effects of planned work before its execution. The RECIPE 2016, Cumulative Energy Demand (CED), and Environmental Design of Industrial Products (EDIP 2003) methodologies were examined for life cycle assessment utilizing open LCA software.

In this study, the inputs utilized during concrete mix design were used to develop Table (5), which presents the results of the EIA of conventional and specialized zeolite concrete.

6. Results and Discussion

6.1 Fresh Properties, Wet Density and Permeability Performance of Concrete Mixtures

The influence of JNZ on the characteristics of concrete was examined through several trials

involving the replacement of cement proportions in concrete mixtures, in comparison to the standard form. The partial replacement of 10%, 15%, and 20% JNZ significantly influenced the workability and water absorption of the zeolite concrete mixture results after 28 days, as demonstrated in Table (4).

Table (4): Fresh Properties, Permeability and Wet Density of SCP Mixtures.

Design Mix	Slump (mm)	Water Absorption (%)	Wet density (kg/m^3)	Initial – Final Setting Time (min.)
0	25	4	2390	120-180
10% JNZ	35	3.3	2350	123-184
15% JNZ	27	2.5	2290	130-190
20% JNZ	20	2.0	2200	134-194

The findings show that using natural zeolite from Jordan makes a long-lasting, continuously reinforced zeolite concrete pavement with a high slump. Adding natural zeolite made the mixture easier to work with at a 10% replacement level. However, an increased zeolite amount resulted in lower workability, requiring careful handling during placement.

The addition of zeolite greatly lowered the rate of water absorption at all replacement levels. These changes made the concrete durable with less water absorption. While the initial and final setting times get longer with increasing zeolite amounts, the conventional concrete had a normal setting time, but adding zeolite increased them, especially when 20% of the zeolite was used instead of water.

ASTM determined the elastic modulus (E) by measuring the strain in a concrete specimen at a specified stress [8]. JNZ in concrete improves the modulus of elasticity from approximately 29,000 MPa to 35,000 MPa compared to normal concrete. The slight increase in elastic modulus shows that the incorporation of zeolite does not reduce the stiffness of the concrete, preserving overall structural integrity.

6.2 Effect of Using JNZ in Enhancing Modified Concrete Mechanical Properties

The use of Jordanian natural zeolite as a supplemental cementitious material has attracted concern for its ability to improve the mechanical properties of concrete. This section explores the impact of integrating JNZ into modified concrete, emphasizing improvements in compressive strength, flexural strength, and durability. The use of JNZ in concrete can enhance various mechanical properties, resulting in better durability for high-performance CRCP applications. Figure (12) illustrates the impact of integrating JNZ on the compressive strength, resulting in a modified blend after curing in water for 7 and 28 days.

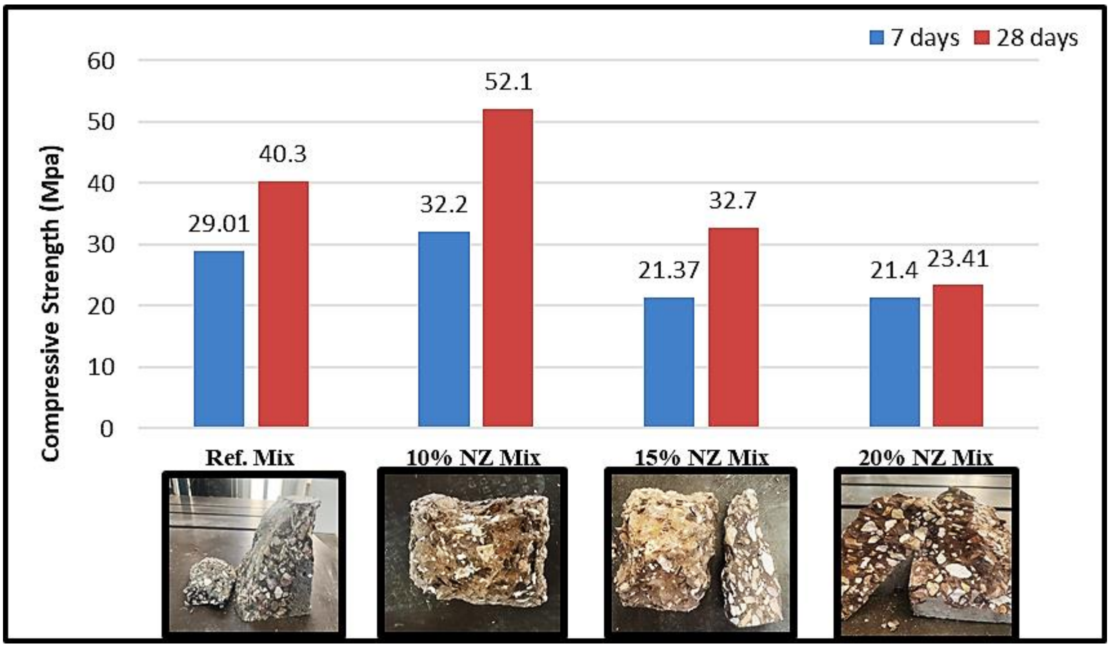

Figure (12): Compressive strength of reference and modified concrete

The strength of the concrete with JNZ was tested at three different percentages, as shown in Figure (13). The modified mixture with 10% JNZ has the highest compressive strength compared to the others. It improves how the particles fit and bond together for preferable performance and strength because of the zeolite material's quality.

Figure (13) shows that the modified zeolite concrete with a 10% substitution has a higher tensile strength resistance. The modified concrete mix containing 10% JNZ exhibited superior values compared to the standard and other mixes after 28 days of curing. It improved high tensile strength by strong adhesion between zeolite particles and cement.

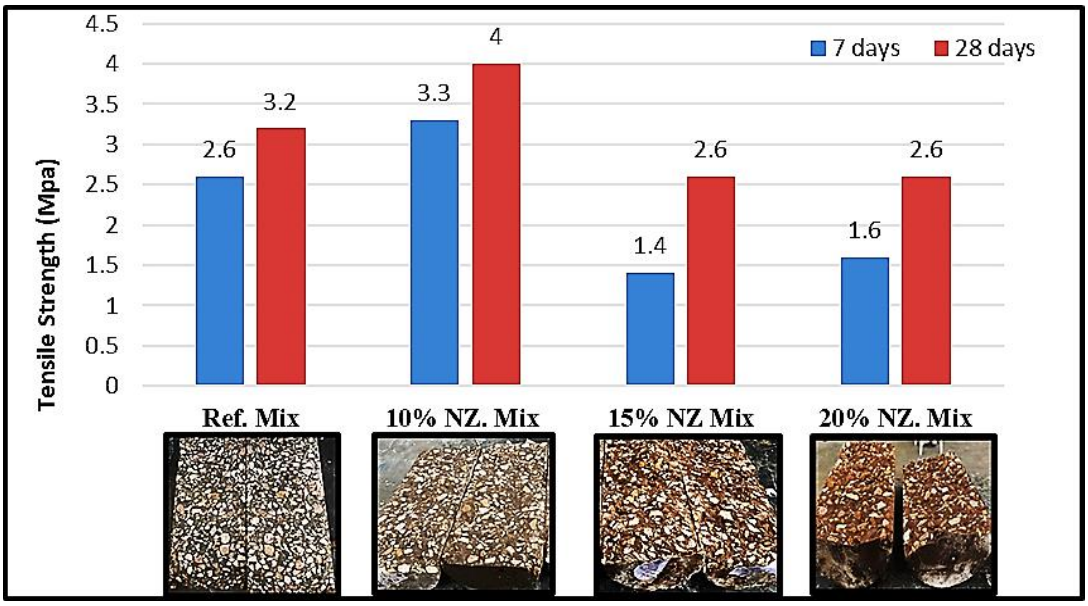

Figure (13): Tensile splitting strength of reference and modified concrete

Figure (14) shows that the concrete containing 10% of natural zeolite provided higher resistance to bending, improved element bonding, and increased ductility. This increase improved load distribution and adhesion between the zeolite particles and cement, strengthening the overall structural integrity.

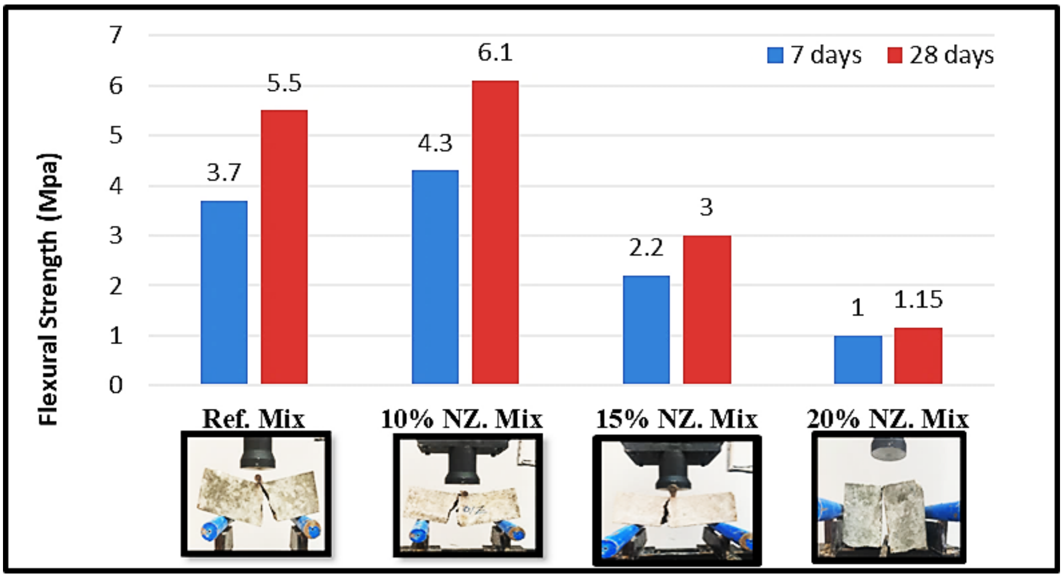

Figure (14): Flexural strength of designed concrete mixes

The results shown in Figure (14) indicate that the concrete incorporating 10% JNZ showed improved resistance to bending, better element bonding, and increased ductility.

6.3 JNZ Blended-Grinding Cement Enhancing Concrete Mechanical Properties

This research looks at how JNZ blended-grinding cement is made from two main types of clinker: ordinary Portland cement (OPC) and sulfate resistance (SRC), as well as gypsum. These two different types of new cement improve the mechanical characteristics and overall efficacy of concrete, making it suitable for various construction applications, such as CRCP runways.

The following charts in Figures (15) and (16) illustrate the mechanical properties of new concrete obtained from both blends, based on the results of various tests conducted on these types of new cement.

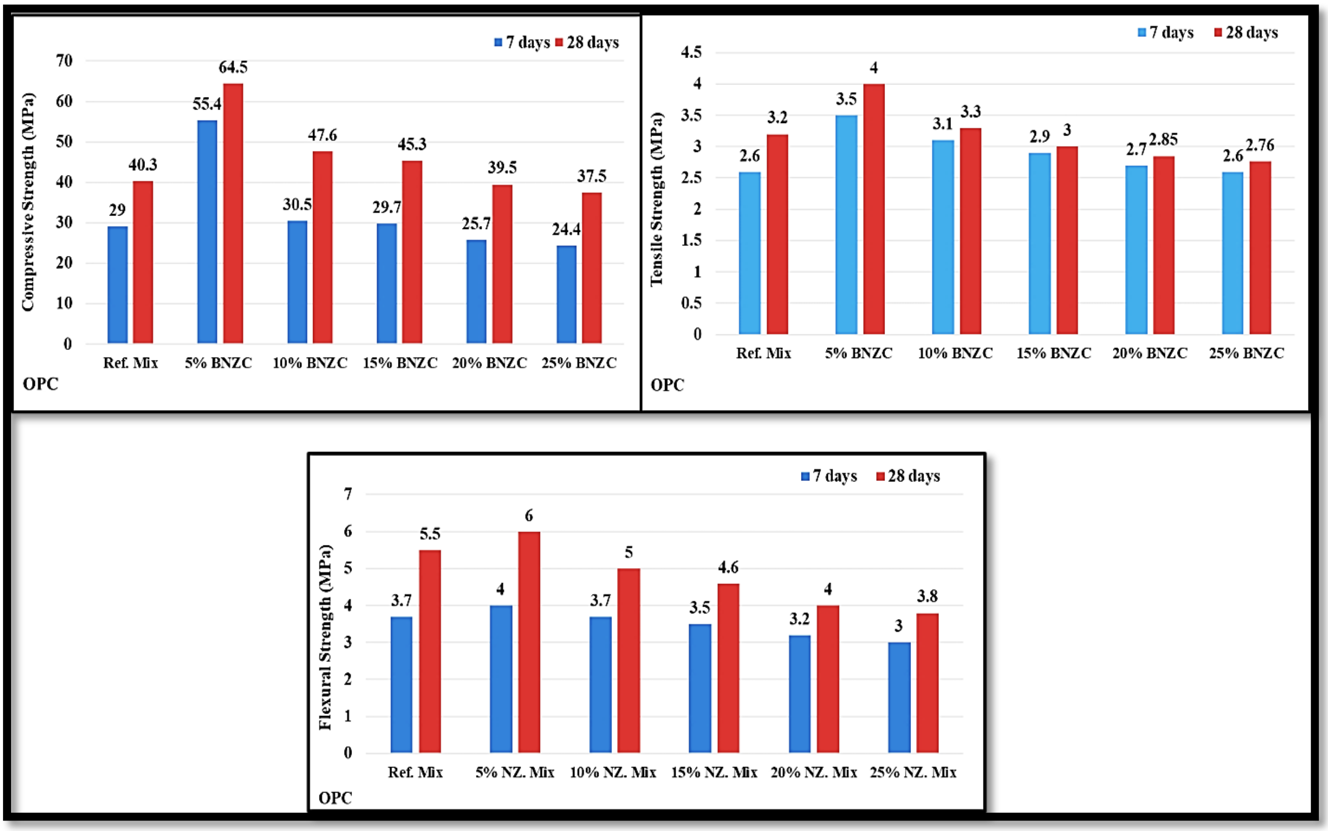

Figure (15) : Compressive, tensile and flexural strengths of blended Zeo-OPC

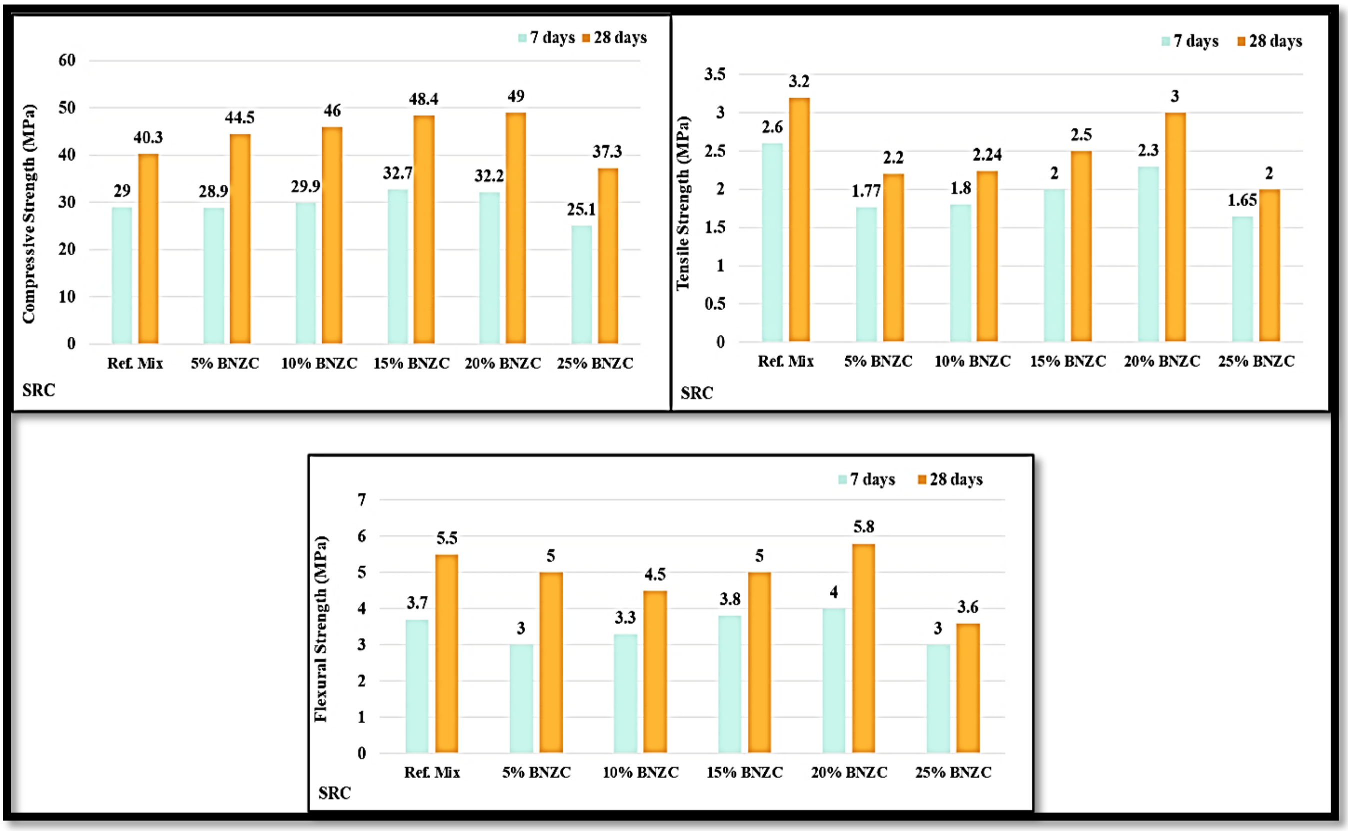

Figure (16): Compressive, tensile and flexural strengths of blended Zeo-SRC

The results show that using 5% zeo-OPC or 20% zeo-SRC in concrete mixtures makes the microstructure denser and increases the compressive strength, which is good for building structures that can hold a lot of weight. These blended mixtures improve particle bonding and increase the tensile strength with low cracking and structural failures. Furthermore, these blended mixtures improved the flexural characteristics, enabling concrete to effectively resist bending forces in components such as slabs.

JNZ blended-grinding cement had a high workability slump value of 70 mm, confirming ASTM C143 compliance due to its fine particle size. Zeolite concrete retains 80-90% of its strength after 6 months, so this result makes the structure long-lasting and durable in a sulfate area, based on ASTM C452.

6.4 Microstructural Analysis of Zeolite Concrete Production

The analysis provided significant information about the microstructural features of the special concrete that had a zeolite blend in it. The SEM at 28 days illustrates a noticeable reduction in microcracks related to the efficient bonding between aggregates and cement. Therefore, this significant phenomenon leads to a dense microstructural composition, reduced porosity, increased compressive strength, and durable characteristics, as evidenced by the Nano-SEM images presented in Figure (17).

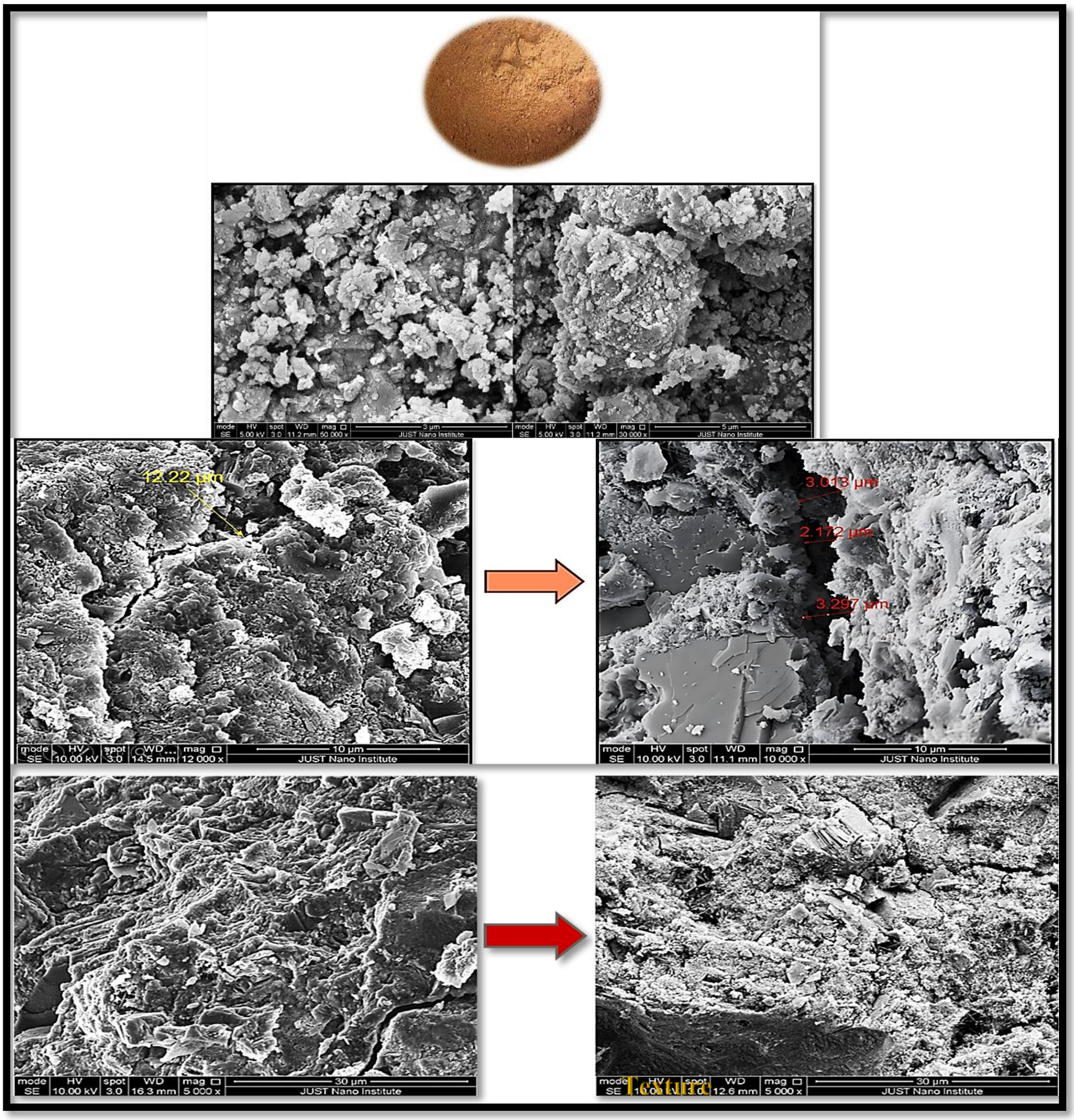

Figure (17): Nano-SEM Images: (a) Reference mix (b) Zeo-concrete (30 and 10 µm) magnification.

6.5 EIA Results: Zeolite in Concrete

Incorporating JNZ into concrete mixtures is anticipated to yield significant environmental benefits, particularly in CO_2 emissions and resource conservation, as evidenced by the comparison with the three selected assessment methods. This evaluation was to identify, predict, and reduce negative environmental impacts while promoting sustainable pavement as shown in Table (5).

Table (5) : Environmental impact assessment (EIA).

Impact Categories	Normal Concrete Mix	Zeolite Concrete Mix	% Improvement
Recipe 2016			
Fossil resource scarcity (kg oil eq)	**1462**	**500**	**65.8**
Global warming (kg CO_2 eq/m^3)	**750**	**400**	**46.7**

Human carcinogenic toxicity (kg 1.4-DCB/m^3)	**1.03**	**0.6**	**41.7**
Mineral resource scarcity (kg Cu eq/m^3)	**15**	**7**	**53.3**
Ozone formation, Human health (kg NOx eq/m^3)	**1.05**	**0.7**	**33.3**
Ozone formation, Terrestrial ecosystems (kg NOx eq/m^3)	**1.35**	**0.5**	**62.9**
Stratospheric ozone depletion (kg CFC^{-11} eq/m^3)	**1.67**	**0.001**	**99.9**
Terrestrial acidification (kg SO_2 eq/m^3)	**2.5**	**1.5**	**40**
Terrestrial ecotoxicity (kg 1.4-DCB)	**0.74**	**0.44**	**40.5**
Cumulative Energy Demand (CED)			
Non-renewable, fossil (MJ/m^3)	**1560**	**1100**	**29.5**
Non-renewable, minerals (MJ/m^3)	**329**	**110**	**66.6**
Renewable, potential (MJ/m^3)	**12**	**5.5**	**54.2**
Renewable, solar (MJ/m^3)	**1.73**	**0.5**	**71.1**
EDIP			
Ecotoxicity soil chronic (m^3)	**0.413**	**0.2**	**51.6**

Conclusions

Upon studying the impact of JNZ on the performance and characteristics of concrete, the following conclusions based on the study's results can be drawn:

1. The improvement of concrete characteristics with Jordanian natural zeolite depends on experimental laboratory studies and tests. Concrete shows low density, with the proportion of JNZ consistently increasing, making it lighter than the conventional mixture.
2. A zeolite concrete mixture with 10% JNZ enhances the characteristics of fresh concrete after 28 days of curing, particularly its workability and setting time, in comparison to other proportions and the standard mix.
3. The modified mixture with 10% JNZ has the highest compressive, tensile, and flexural strengths of 52.1, 4, and 6.1 MPa. Concrete mixtures that incorporate 5% zeo-OPC or 20% zeo-SRC result in a denser microstructure, exhibiting compressive strengths of 64.5 and 49 MPa, tensile strengths of 4 and 3 MPa, and flexural strengths of 6 and 5.8 MPa. These results are indicative of the high loading capacity of CRCP.
4. The use of JNZ in cement production decreases production costs by utilizing locally sourced materials and greenhouse gas emissions and mitigates various ecological effects, including resource consumption, toxicity, and energy consumption.
5. The zeolite concrete mix had a uniform microstructure with few empty spaces, strong bonds, and high mechanical properties, as seen with scanning electron microscopy (SEM).

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