

Research Article

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Sustainable road paving: Enhancing concrete paver blocks with zeolite-enhanced cement

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Abstract: The present investigation assesses the impact of zeolite-enhanced sustainable cement (ZESC), a product achieved through the blending and grinding of clinker, gypsum, and varying percentages of natural zeolite (6, 10, and 15%). While the existing research has mainly concentrated on substituting ordinary Portland Cement with natural or synthetic zeolite, a critical research gap persists in using this manufactured cement in nontraditional building materials. Addressing this gap, our investigation assesses the durability and mechanical properties of concrete paver blocks manufactured by ZESC, particularly crucial for road paving applications. Comprehensive evaluations of hardened properties were conducted, including compressive strength, splitting tensile strength, abrasion resistance, and water absorption. In addition, the impact of ZESC on the fresh properties of concrete paver blocks was examined. The findings reveal that a 15% N.Z. inclusion in ZESC production results in an optimal mix design, leading to a remarkable increase in compressive strength and splitting tensile strength by 24 and 25%, respectively. It reduces water absorption and abrasion resistance by 80 and 7.8%, respectively, compared to O.P.C. cement concrete paver blocks. It is noteworthy that the addition of natural zeolite to ZESC mixtures led to an increased water demand. Notably, the integration of natural zeolite significantly reduces the environmental impact of cement production, promoting a sustainable shift by minimizing cement clinker. The study employs microstructural analysis, supported by scanning electron microscopic images, revealing a significant reduction in microcracks and enhanced cohesiveness, particularly at the aggregate-cemented paste interface in ZESC mixes.

Keywords: zeolite-enhanced sustainable cement, concrete paver blocks, mechanistic features, durable qualities

1 Introduction

In the 1960s, interlocking concrete tiles were manufactured inside the borders of the United States for walkways, patios, parking lots, and garages [1]. The paver tiles technology is becoming more popular worldwide because it is effective in terms of quality, cost, surface efficiency, how easy it is to lay, and how much it is worth if it needs to be replaced. These blocks are employed for heavy-load pavements, low-speed, extensively trafficked metropolitan streets, and, more recently, aircraft taxiways, factories, etc. Interlocking concrete tiles are designed to interlock with one another when they are in place [2]. According to Gao et al. and Yaro et al. [3,4], conventional pavement materials can no longer withstand the increasing stress and heavy traffic loads, which causes early pavement deterioration and higher maintenance costs. New materials for road paving are thus required to provide affordable, secure, and long-lasting pavements that can resist expected loads [5].

Recently, extensive studies of modified concrete have been carried out. Researchers test the effect of various active minerals or supplementary cementitious materials, such as silica fume [6,7], fly ash [8], etc. Supplementary cementitious materials used in the construction industry have significantly reduced cement demand, enhanced microstructure properties [9], and have a favorable environmental impact [10]. Supplementary cementitious materials like natural zeolite have shown great potential as additives to concrete, which can significantly improve mechanical properties and durability [11] while helping reduce its permeability [12]. The hydrated alumino-silicates that make up natural zeolite have a strong affinity for cations like ammonium [13].

According to a study conducted by Ahmadi and Shekarchi [14], adding 5, 10, 15, and 20% natural zeolite (clinoptilolite type) to the concrete mixture increased compressive strength of 14, 16, 23, and 25% respectively, compared to the control

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mixture. In addition, Yilmaz et al. [15] investigated the impact of blending clinoptilolite type of natural zeolite with Portland cement, revealing that varying clinoptilolite content influenced plasticity times, early and end strengths, correlating with Blaine values, reactive SiO_2 , and clinoptilolite's ion exchangeability, depending on calcium hydroxide levels.

To improve the effectiveness and benefits of this natural pozzolan, additional research on the formulation and features of new concrete, including natural zeolite to boost mechanical strength was advised [16]. In this regard, a study has demonstrated that natural zeolite reduces water absorption and chloride permeability. Furthermore, it exhibited enhanced compressive strength, chloride durability, and electrical resistivity in comparison to the corresponding characteristics of the control concrete [17]. In recent studies, Gowram and Beulah [18] compared the durability effects of different cementitious materials on high-strength concrete. They found that incorporating 5% natural zeolite and 10% metakaolin yielded the maximum enhancement in durability. For the same percentage of incorporation, Canpolat et al. [19] discovered that the addition of 5% natural zeolite to regular concrete not only improved compressive strength during the initial curing stages but also led to a reduction in the concrete's setting time by substituting cement particles with natural zeolite.

Concurrently, investigations by Mola-Abasi et al. [20] supported the idea that incorporating N.Z. into concrete contributes to enhanced shear strength and peak axial stress. Building upon this, Valipour et al. [21] emphasized the significant impact of N.Z. inclusion at replacement levels of 10, 20, and 30%, revealing substantial increases in the compressive strength for conventional concrete 64.3, 69.7, and 60.3%, respectively. While the prior research has not explored the use of natural zeolite in concrete pavers, Girska et al. [22] attempted to enhance the durability of concrete paving blocks by incorporating 5% synthetic zeolite, demonstrating reduced absorption, increased tensile splitting strength, decreased abrasion, and improved resistance to scaling after freeze–thaw cycles.

Examining the environmental impact of cement production, Abdul-Wahab et al. [23] investigated the role of zeolite (synthetic type) as an additive to enhance efficiency and reduce CO_2 emissions. Their study revealed optimal outcomes with 7% zeolite for zeolite-containing cement and a mix of 10% zeolite and 15% kaolin for zeolite-kaolin cement, showing a significant reduction in both CO_2 emissions and energy usage by replacing a portion of the cement clinker. Another study [24] focused on cement performance, clinker content, and CO_2 emissions, demonstrating that synthetic zeolite could be introduced up to 10% without compromising the produced cement's mechanical behavior,

quality, and performance. These findings underscore the potential of zeolite as a catalyst in cement manufacturing, addressing both performance and environmental sustainability aspects.

Moreover, extending the environmental benefits of incorporating zeolite into concrete, studies by Najimi et al. [25] reveal that the inclusion of natural zeolite positively influences various key aspects, such as water infiltration, chloride ion infiltration, corrosion rate, and drying shrinkage. This emphasizes the dual advantage of using zeolite in concrete production, enhancing sustainability and positively impacting the material's performance and durability.

The existing literature predominantly focuses on the clinoptilolite type of zeolite in cement and concrete research, neglecting the vast diversity of over 70 naturally occurring zeolite types. Recognizing that China, South Korea, Jordan, Turkey, and Japan are key producers of natural zeolites [26], the current research gap highlights the need to explore the potential of other zeolite varieties in cement production.

The present work aims to investigate the addition of Jourdain natural zeolite in cement production with three different percentage replacements from clinker to produce zeolite-enhanced sustainable blended cement. This zeolite type and its impact on the cement industry and concrete production have not been studied yet. In contrast, the most global natural zeolite production is from the clinoptilolite mineral. The chosen research subject addresses a key construction industry demand for sustainable and environmentally friendly practices. Natural zeolite could reduce the environmental impact of cement manufacture. Exploring sustainable construction materials is crucial as global concern for climate change and industry carbon footprints grows. The effects of zeolite-enhanced sustainable cement (ZESC) on the mechanical properties of concrete paver blocks were investigated through compression and split tensile strength tests. In addition, water absorption and abrasion resistance of the concrete pavers were assessed to evaluate the benefits of natural zeolite durability and abrasion resistance. Scanning electron microscopic (SEM) pictures were utilized to examine the microstructure of (ZESC) concrete samples. In this context, the study explored how ZESC contributes to reducing carbon footprints and promoting sustainability in the development of eco-friendly construction materials.

2 Materials and methods

2.1 Materials

- Natural zeolite from al Karak (Amman, Jourdain). Jourdain natural zeolite contains significant minerals such as

Table 1: XRD test result for minerals in the natural zeolite used

Zeolite minerals%	Formula [28]	Content (%)
Phillipsite	$(K, Na, Ca)_{1.2}(Si, Al)_8O_{16} \cdot 6H_2O$	32.9
Chabazite	$CaAl_2Si_4O_{12} \cdot 6H_2O$	13.3
Analcime	$NaAlSi_2O_6 \cdot H_2O$	8.1

Phillipsite, Chabazite, and analcime, as clarified in X-ray diffraction (XRD) analyses in Table 1. Chemical properties are presented in Table 1. This zeolite type and its impact on the cement industry and concrete production have not been studied yet. In contrast, the most global N.Z. production is from the clinoptilolite mineral. N.Zs specific gravity and unit weight were 1.9 and 1,010 kg/m³. The loss on ignition of the N.Z. is 9%, with a grain size ranging from 5 to 1 cm.

- The ZESC investigated in this research is the result of carefully combining and grinding particular components. The formulations combined ordinary Portland clinker, gypsum, and N.Z. following British Standard 197 [27]. The mill used in this research is a laboratory ball mill of 25 kg raw mix capacity. After grinding, the cement was passed through 100 µm and was identified as the primary cement for subsequent concrete pavers production. The formulations labeled ZESC 6, ZESC 10, and ZESC 15 consisted of 6, 10, and 15% natural zeolite mixed with 89, 85, and 80% conventional Portland clinker. In addition, these formulations consistently included 5% gypsum, accurately measured by weight. Table 2 presents the chemical composition of the three ingredients determined through X-ray fluorescence analysis.
- O.P.C. (CEM I 42.5, Lafarge- Tasluja) has been used, which satisfies the requirements set out in EN 197. The chemical and physical parameters are presented in Table 3.
- The coarse aggregate has a maximum size of 12.5 mm, a specific gravity of 2.6, water absorption of 0.48%, a loose density of 1440 kg/m³, and 0.083% sulfate (SO₃) content.

Table 2: Chemical analysis of ordinary Portland clinker, natural zeolite, and gypsum used in this research

Symbol	Clinker (%)	Natural zeolite (%)	Gypsum (%)
CaO	66.68	14.12	32.62
SiO ₂	20.3	40.12	2.77
Al ₂ O ₃	3.078	11.38	0.62
Fe ₂ O ₃	5.27	11.24	0.36
SO ₃	0.367	1.439	38.75
MgO	1.388	5.119	1.2
K ₂ O	0.69	1.27	0.04
TiO ₂	0.28	2.547	0.02

Table 3: Chemical and physical properties of ordinary Portland cement

Chemical compositions (%)	Content
SiO ₂	19.66
Al ₂ O ₃	4.10
Fe ₂ O ₃	5.56
CaO	60.44
MgO	3.49
SO ₃	2.09
Loss on ignition	3.7
Insoluble residue	1.31
Physical properties	
Specific gravity	3.032
Blaine fineness (m ² /kg)	350
Initial setting time (min)	175
Final setting time (min)	295
Compressive strength (MPa)	
2 days	17.2
28 days	42.7

The sand was a well-rounded natural material with a fineness modulus 2.6, specific gravity of 2.7, sulfate (SO₃) content of 0.048%, and water absorption of 2.7%. Sieve analysis fine and coarse aggregate is shown in Tables 4 and 5.

- The superplasticizer (S.P.) was polycarboxylic polymers with a specific gravity of 1.073. The name of the Brand is Hyperplast PC600.

Figure 1 illustrates a schematic overview of the experimental study.

Table 4: Sand grading according to Iraqi specifications [29]

Sieve size (mm)	% Passing	Limit of Iraq specification
4.75	97.4	90–100
2.36	93.2	75–100
1.18	65.6	55–90
0.6	52.3	35–59
0.3	20.2	8–30
0.15	6.4	0–10

Table 5: The grading of coarse aggregate according to Iraqi standards [29]

Sieve size (mm)	Passing (%)	Limit of Iraq specification
20	100	100
14	98	100–90
10	81	85–50
5	5	10–0
2.36	0	—

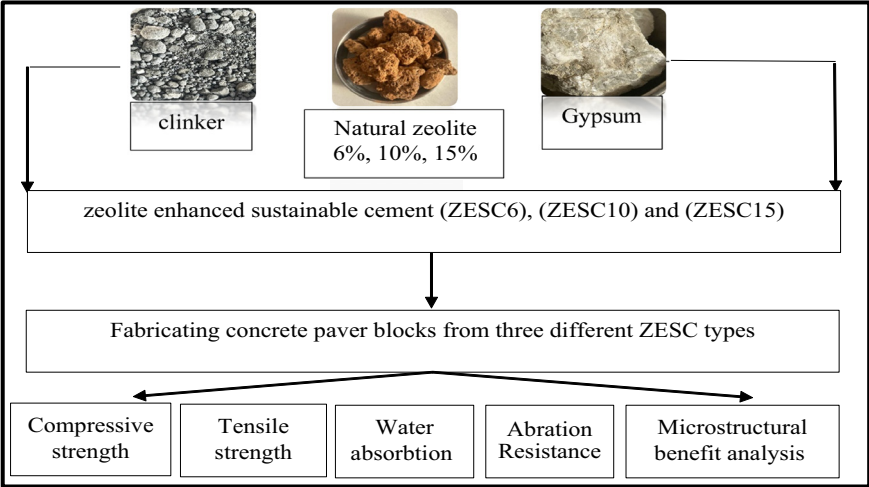


Figure 1: Schematic overview of the work.

2.2 Sample preparation and techniques

The concrete paving tiles and mix preparation procedure are described in detail. Three different varieties of ZESC were employed in the concrete mixtures, and these mixes are compared with reference ordinary Portland cement mix. The thickness and dimensions used to manufacture paver blocks were per Iraqi specifications [30]. Specimens with a length of 200 mm, a width of 100 mm, and a depth of 60 mm were prepared. The size of specimens is shown schematically in Figure 2a. The wooden molds used for manufacturing interlocking concrete tiles are shown in Figure 2b. Mixture specifics are provided in Table 6. All concrete mixtures pass a slump test of 30 mm.

Correct and constant techniques were employed in filling the molds of samples for all mixes, as depicted in Figure 3a. The constituents of the concrete composite utilized in producing paver blocks were accurately quantified and subsequently incorporated into the mixer. Initially, a combination of coarse aggregate and sand was mixed. The

cement was added to the mixer in its dry state. The mixture was subjected to adding 50% of its total water content, which was then thoroughly mixed for 90 s. A superplasticizer and 50% water were introduced into the mixture to ensure thorough homogenization. The mixer was subsequently activated for an additional duration of 30 s. Subsequently, the concrete mixture was extracted from the mixer. The concrete mix in the paver block mold could move the table from one end to the other. After 24 h, the paver blocks were extracted from the molds and assigned designations corresponding to their respective mix I.D.S.,

Table 6: Mix design of concrete paver blocks

Cement type	Cement	Sand	Gravel	S.P	W/C
OPC (ref. pav.)	400	703	973	1	0.41
ZESC 6	400	703	973	1	0.26
ZESC 10	400	703	973	1	0.31
ZESC 15	400	703	973	1	0.34

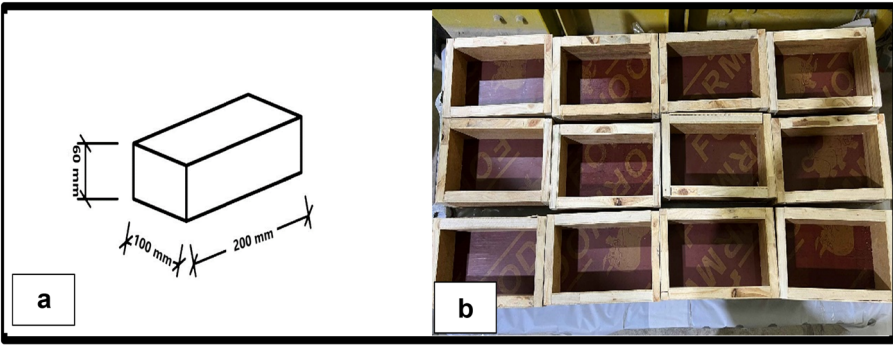


Figure 2: (a) Schematic concrete paver blocks size, (b) wooden molds for paver blocks.

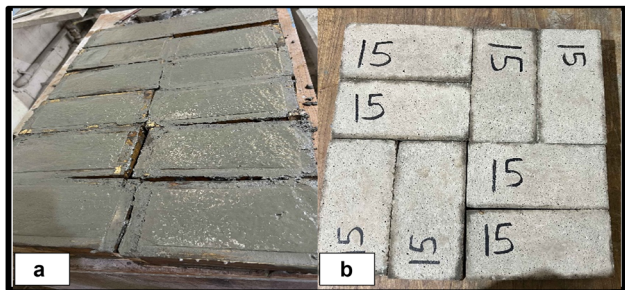


Figure 3: (a) casting concrete paver blocks, (b) paver blocks after demolding.

as depicted in Figure 3b. These blocks were then placed within the curing chamber at 27°C to undergo the curing process until they were ready for testing.

2.2.1 Testing methods of specimens

The investigation of paver blocks has primarily focused on examining their compressive and tensile strengths, and considered the most crucial properties across all paver blocks. The specimens were tested at two specific time intervals, 7 and 28 days after the casting date. Determining the compressive strength for each mixture included calculating the average ultimate compressive stress by the specific contact area of the three cement paver blocks.

The absorption measurement process typically involves desiccating specimens until a uniform mass is achieved, followed by immersion in water and the subsequent determination of the resulting mass increase as a percentage of the initial dry mass. The absorption of three specimens was evaluated after a 28-day cure period in water. Each mixture's water absorption was calculated by averaging the values of three samples.

The experiment involves the abrasion of the top surface of concrete paver blocks using a standardized abrasive

substance. Abrasion testing was performed on concrete paver block specimens at 28 days. The abrasive used for this test comprises fused alumina, sometimes known as corundum. Figure 4a depicts an abrasion test apparatus. The disk's length and diameter were 70 and 200 mm, respectively. The specimen required for this test is 70 mm long, 10 mm wide, and 60 mm thick; the test piece shall be clean and dry. During the test, the corundum-crystalline powder was poured between the disc and the specimen from the powder box, as shown in Figure 4b, and the disc was spun at 75 rpm for 1 min for each specimen. The groove length loss due to wear was then measured from six sites for every mixture, as shown in Figure 4b and c, and averages of these measurements were calculated for each sample. Paving blocks' mechanical and durability properties were assessed following the specified requirements outlined in Table 7. After conducting tests on concrete paver blocks, a comparison was made to assess the compliance of various types of produced pavers with three different standards, namely, the Iraqi, ASTM, and European standards, as shown in Table 8.

3 Results and discussion

3.1 Effect of ZESC on fresh properties of the mixture

The impacts of varying percentages of N.Z. in ZESC production were examined while maintaining consistent proportions of cement, fine aggregates, and coarse aggregates. A comparison was made with the results obtained using Ordinary Portland Cement. The primary focus was to analyze the influence of N.Z. on the properties of the concrete mixtures and, consequently, on the characteristics of the concrete paver blocks.

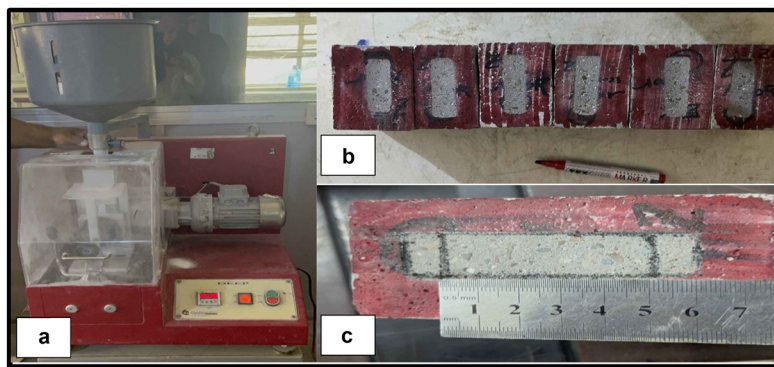


Figure 4: Abrasion test: (a) abrasion apparatus, (b) the tested specimens, (c) the groove length.

Table 7: Test specifications of concrete paving tiles

Properties	Testing specification
Compressive strength (7, 28) days	ASTM C140/2017 [32]
Total absorption (28) days	ASTM C140/2017 [32]
Tensile strength (7, 28) days	ASTM C496, (2004) [33]
Abrasive resistance (28) days	BS EN 1338 [34]

The addition of N.Z. to the ZESC mixtures led to an increased water demand. To address this, a constant percentage of superplasticizers was added to maintain an appropriate water-to-cement ratio. This adjustment was necessary due to N.Z.'s porous nature and the increased surface area [25].

The inclusion of N.Z. significantly impacted the fresh properties of the concrete mixture, primarily owing to the rough and porous structure of natural zeolite. A constant percentage of superplasticizer was used to ensure a consistent slump of (30 + 5 mm), even with variations in the water-to-cement ratio. This observation emphasizes the considerable influence of N.Z. on the water demand of the ZESC mixture, particularly with varying quantities of N.Z. when ZESC 15 is used in the mixture, and the required

water-to-cement (W/C) ratio was 0.34. In contrast, for a ZESC 6 mixture, the W/C ratio was 0.26. This reveals a clear trend: as the proportion of N.Z. replacement in the ZESC production increased, there was a corresponding rise in the water demand for the resulting mixture. These findings are consistent with the prior research, as evidenced in the previous studies [14,31].

3.2 Effect of ZESC on compressive strength of concrete paver blocks

Figure 5 shows the crushing strength of concrete paver blocks after 7 and 28 days of curing in water for ordinary portland cement (OPC) and ZESC paver blocks. Each column on the plot is the average of the results of three different samples for each mix. The failure patterns observed in the tested models are elucidated in Figure 6.

The compressive strength of ordinary Portland cement mix depends on hydration speed. However, adding (N.Z.) to cement production causes several major changes such as N.Z. significantly impacts early hydration. It becomes active when calcium hydroxide is produced. Calcium

Table 8: The specifications standards for concrete paving blocks

Requirements	Iraqi stander No. 1606	Europe (BS EN-1338)	American (ASTM C936)
Compressive strength (average value)	55 MPa: for a high level of load 35 MPa: for medium level of loads	—	55 MPa: min average 50 MPa: min absolute
Water absorption (average value)	≤5%	≤6.0%	≤5.0%
Tensile splitting strength	—	≥3.6 MPa	—
Abrasion resistance	Loss of volume ≤15 cm ³ /50 cm ²	I: groove length ≤20 H: groove length ≤23	Loss of volume ≤15 cm ³ /50 cm ²

High-loading class pavement is used in areas subject to severe surface erosion, such as those used by heavy industry, ports, container yards, heavily trafficked highways, and those carrying heavy loads.

Medium-loading class pavement is suitable for medium-loading vehicles and service areas.

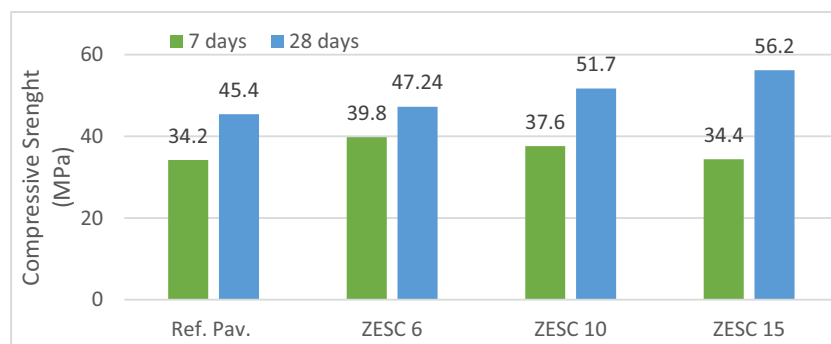
**Figure 5:** Compressive resistance of reference and ZESC pavers mixes after 7 and 28 days.



Figure 6: Compression crushed test specimen of reference ZESC paver mixes.

hydroxide reacts with zeolite's active ingredients, silica, and alumina to form another gel. This phenomenon significantly increases compressive strength compared to conventional cement hydration without Pozzolanic components. Another reason is reduced hydration rate and heat: zeolite inclusion slows cement hydration. This reduces heat generated during hydration, crucial to preventing heat-induced cracks. Decelerated hydration promotes uniform hydration product distribution in cement paste. This uniform distribution reduces cement voids.

All concrete mixtures incorporating ZESC exhibit nearly comparable 7-day strengths. Notably, the 7-day strength of ZESC 6 demonstrates an approximate 16% increase compared to the reference pavement (Ref pav.). However, ZESC 10 showcases a notable 9.9% rise in compressive strength over the reference mix, whereas ZESC 15 demonstrates only a slight 0.5% increase. This boost in strength can help clarify the contrasting findings in the literature, where several

researchers have found that incorporating N.Z. as a cement replacement leads to enhanced concrete compressive strength [14,35–37]. On the flip side, some researchers argue that zeolite has a detrimental effect on concrete compressive strength [25,38,39].

It was clear that all ZESC paver blocks had significantly higher compressive strengths at 28 days when compared to the control concrete paver. ZESC 15 blocks showed especially impressive results. This fits with the findings of Chan and Ji [35], who reported a 14% higher 28-day strength for N.Z. concrete with a 15% replacement level (considered the optimal replacement level) compared to control concrete. In contrast, a 24% increase in compressive strength was observed for the ZESC 15 mix, surpassing the 14%. This dual utilization ensures the homogeneous distribution of N.Z. molecules within the cementitious material, significantly enhancing compressive strength. It is worth noting that a converse effect is reported in studies such as Najimi et al. [25], where a 15% replacement of N.Z. led to a reduction in compressive strength. These insights collectively underscore the importance of the production process and the optimal replacement level. The findings underscore the promise of ZESC 15, showing superior compressive strength at the 28-day mark. ZESC 6 and ZESC 10 showed an increase in compressive strength of 4 and 14%, respectively, compared with the reference mix.

3.3 Effect of ZESC on split tensile strength

The splitting tensile strength of concrete after 7 and 28 days of curing in water for O.P.C. and ZESC mixes is shown in

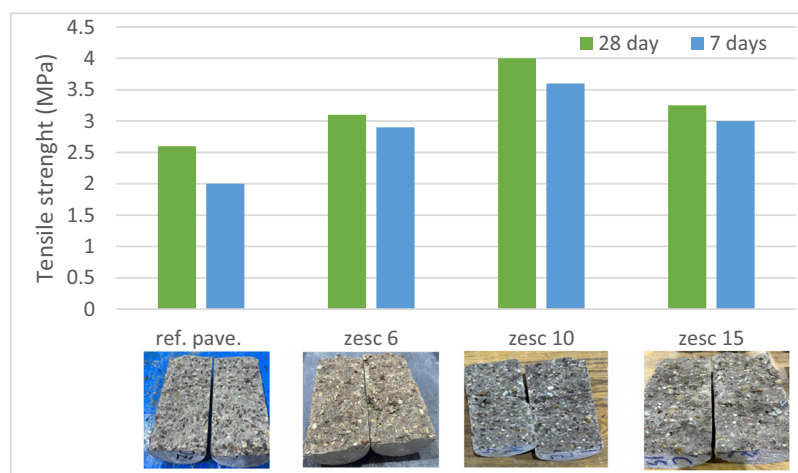


Figure 7: Average split tensile strength of reference and ZESC paver mixes at 7 and 28 days, with specimen failure modes.

Figure 7. Each column on the plot is the average of the results of three different samples for each mix.

The splitting tensile strength of specimens containing ZESC consistently surpassed that of specimens with O.P.C. at the 7- and 28-day mark. Notably, the enhancement of tensile strength due to using ZESC was more substantial than the improvement in compressive strength over the same period. At 7 days, the ZESC 6, ZESC 10, and ZESC 15 exhibited increased tensile strength by (45, 55, and 50%) compared with reference concrete. The 28-day splitting tensile strength of ZESC specimens ranged from approximately 3.1 to 4 MPa, while the reference O.P.C. specimen had a value of about 2.6 MPa. This improvement can be attributed to the densification of the matrix and reduced porosity resulting from the incorporation of N.Z. in blended cement. Notably, ZESC 6 and ZESC 15 exhibited a percentage increase in split tensile strength of 19 and 25%, respectively. ZESC 10 demonstrated a remarkable 53% increase in 28-day tensile strength compared to the reference mix. The observed behavior is primarily attributed to developing secondary calcium–silicate–hydrate (C–S–H) compounds due to Pozzolanic reactions and using calcium hydroxide $\text{Ca}(\text{OH})_2$. In addition, the higher water-to-cement (w/c) ratio of the reference mixture (0.41) compared to the ZESC 10 mix (0.31) suggests that the lower w/c ratio had a positive effect on the transition zone. This was further enhanced by the Pozzolanic reaction, leading to improved transition zone structure through the consumption of $\text{Ca}(\text{OH})_2$ crystals and the formation of secondary C–S–H compounds. The study reveals similar outcomes consistent with the findings of Ramezani pour et al. [40]. However, the results diverge from Tanijaya et al. [38] observations, which noted a 23% reduction in splitting tensile strength with a 10% replacement over 28 days. Conversely, a recent 2023 study [41] focusing on zeolite-mixed pervious concrete demonstrates an initial decrease in splitting tensile strength at 7 days. Notably, 5, 10, and 15% replacements with zeolite led to strength increases of 1.4, 5.6, and 7.88%, respectively, at 28 days only. ZESC 10 mix exhibited the highest percentage increase, suggesting that the optimal zeolite addition percentage for enhanced tensile strength in blended cement is 10%.

3.4 Effect of ZESC on the water absorption of concrete paver blocks

The water absorption of concrete is inherently linked to the pore structure characteristics of the hardened concrete. Aggregates may also possess pores; however, these

pores are often discontinuous. Furthermore, the cement paste surrounds the aggregate particles, serving as only one continuous phase in concrete. Consequently, pores inside the aggregate do not play a role in the water absorption of the concrete. Hence, the impact of the aggregate is relatively insignificant. The hardened cement paste mainly influences the absorption of thoroughly compacted concrete. The results of water absorption of the concrete paver blocks results are presented in Figure 8.

For ZESC 6, ZESC 10, and ZESC 15 paver blocks, water absorption values are (1.11, 1.02, and 0.92%), respectively, while the water absorption of ref. Pav. is 4.5%. On average, the 28-day water absorption of ZESC 6, ZESC 10, and ZESC 15 concrete paver blocks having w/c of 0.26, 0.31, and 0.34 respectively, reduced by 75, 77, and 80%, when compared with reference paver with 0.41 w/c ratio. Using N.Z. to produce blended cement and apply this ZESC in manufacturing concrete paver blocks was brilliant and helpful in reducing the water absorption of the studied paver blocks beyond the border. The facts mentioned earlier can be related to Pozzolanic reactions, which result in enhancements in pore structure and the disconnection of capillary pores. In addition, compared to ordinary Portland cement, ZESC with N.Z. particles has a larger surface area that comes into touch with water molecules. This matter makes the hydration process go faster.

3.5 Effect of ZESC on the abrasion resistance of concrete paver blocks

The overall durability of concrete paver blocks is heavily influenced by the abrasion resistance of the individual components used in their production, as they undergo continuous rubbing, sliding, and skidding. The abrasion resistance of concrete is greatly influenced by several

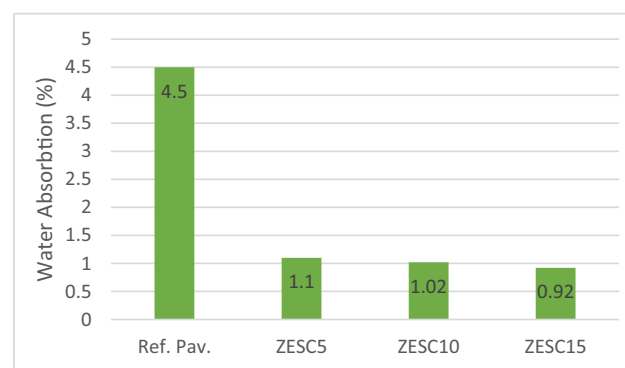


Figure 8: Water absorption for reference and ZESC pavers mix at 28 days.

factors, including compressive strength, surface finishing techniques, curing procedures, aggregate characteristics, cement composition, and testing conditions (such as dry or wet conditions) [42]. A more significant level of abrasion is observed under load; shear forces and normal stresses are generated at the outermost layer of the abraded substance when the abrasive particles acquire relative motion. Scratches and grooves on the specimen surface are created through shear force while abrasive particles are embedded into the surface with applied load. Therefore, a combination of shear and regular forces causes material transfer from the specimen's surface. In this case, the cement-binding interaction between the tiny particles, and the aggregate is just as crucial as the aggregate themselves. Based on this study, the binder material, or cement paste, is a significant way to improve the abrasion resistance of concrete paver blocks. Using N.Z. to produce blended cement enhances the connection of concrete materials. This enhancement reflects on compressive strength, split tensile, and water absorption; consequently, the improvement appears in abrasion resistance. The abrasion resistance of ZESC 6, ZESC 10, and ZESC 15 is shown in Figure 9.

Figure 8 shows that using ZESC reduces groove length in concrete paver blocks. This reduction becomes more pronounced with an increase in the percentage of N.Z. incorporated into the blended cement. For instance, ZESC 15 demonstrates a substantial reduction of 7.8%, while ZESC 6 and ZESC 10 show relatively similar results, with reductions of 5 and 6%, respectively, compared to the reference concrete paver blocks.

The primary reason behind this phenomenon lies in the role of N.Z. in enhancing the bonding between the concrete ingredients. This improved bonding significantly enhances the resistance of concrete paver specimens to abrasion cycles and abrasive materials. According to BSI 1338, the three types of concrete paver with different ZESC comply with a type (I) with groove lengths less than 20 mm.

3.6 Effect of using natural zeolite in enhancing new cement and microstructure development

The research of alternative materials in cement manufacturing has received considerable attention in recent years. This interest is motivated by the need for sustainable, high-performance construction solutions. N.Z. has emerged as a promising choice among these alternatives, providing a range of advantages that go beyond traditional cement formulations. Naturally occurring minerals possess exceptional

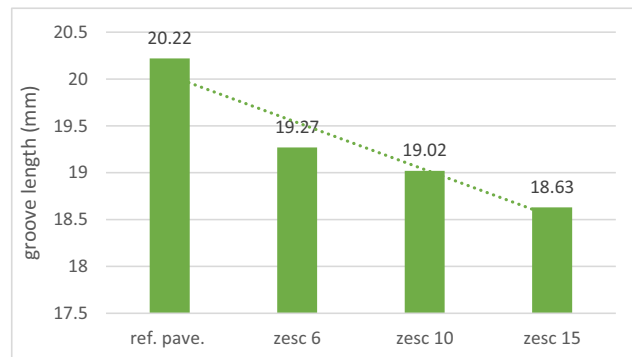


Figure 9: Groove length for reference and ZESC pavers mixes at 28 days.

Pozzolanic characteristics, significantly improving cementitious compounds. One ton of cement produces the same amount of CO₂ emissions. The urgent need to reduce environmental impact makes natural zeolite a breakthrough option. The biggest benefit is its ability to minimize cement clinker significantly. The decrease is a sustainable paradigm shift, not just a pragmatic compromise. The grinding blends unmodified N.Z. into the cement matrix. This technology harnesses natural materials' potential to reduce CO₂ emissions from typical clinker-based cement manufacture by minimizing industrial interventions.

Adding natural zeolite to cement blends provides silica and alumina. This purposeful combination of silica, alumina, and limestone (CaCO₃) produces calcium silicate and calcium aluminum hydrates. Hydrated products change hardened mortar microstructure. As chemical reactions occur, calcium silicate and calcium aluminum hydrates become part of the mortar's microstructure. This inclusion refines pores, greatly improving the hardened mortar's durability and strength. Hydrated products refine pores, strengthening the material against structural degradation and enabling the creation of a more durable concrete structure. A significant decrease in microcracks is visible in the SEM photographs shown in Figure 10, which depict the microstructure of the ZESC 15 mix after 90 days compared with the OPC mix. This decrease is especially remarkable compared to the reference concrete made with OPC. Moreover, the SEM pictures clearly show the top connections of aggregate with cement paste. The increased cohesiveness is seen in the strength of the primary hydration products that surround the aggregate phase. In other words, incorporating natural zeolite enhances the interfacial transition zone between the aggregate and cemented paste phases. This contributes significantly to the dense microstructure and higher compressive strength reported in ZESC 15 mixes compared to reference mixes. The careful analysis of these SEM images presents convincing proof of the beneficial influence of adding

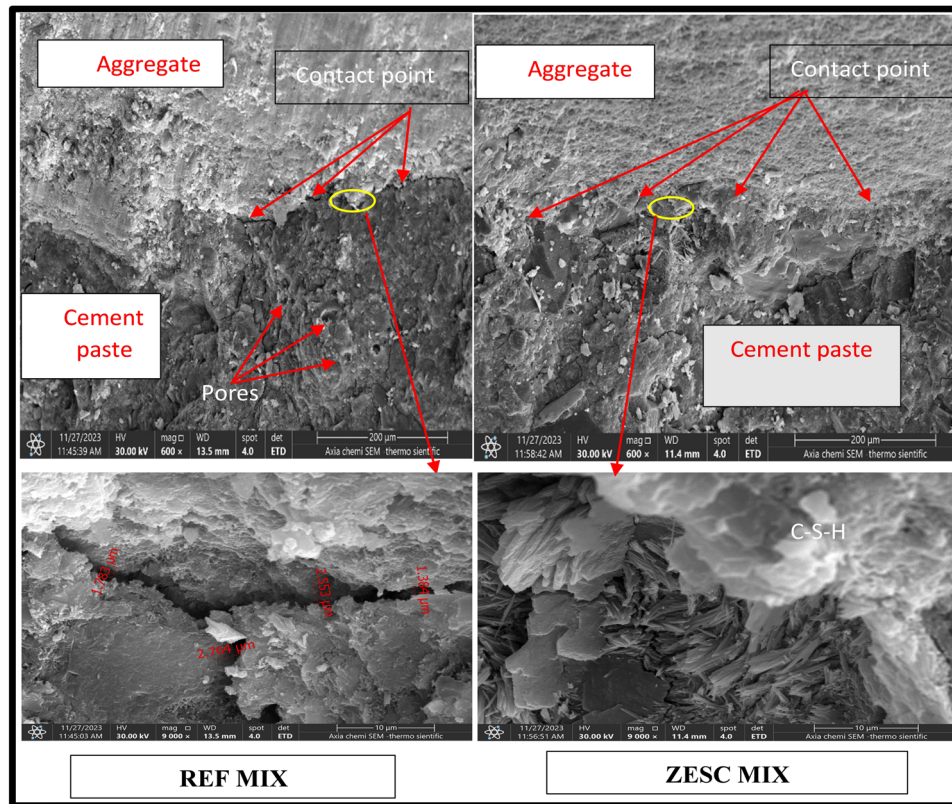


Figure 10: SEM image of reference mix and ZESC 15 mix at (200 and 10 μm) level at 90 days age.

natural zeolite on the cementitious system's microstructural soundness and mechanical characteristics.

3.7 Classification of ZESC pavers blocks

According to the test findings of compressive, tensile strength, water absorption, and abrasion resistance, all concrete

pavers manufactured from ZESC comply with Iraqi, American, and European standards. Due to their unique properties, all ZESC paver samples can be effectively applied in road paving for both medium- and high-loading conditions, showing their distinctive and advantageous properties. Table 9 illustrates the categorization of ZESC concrete paver blocks based on their compressive strength, water absorption, and abrasion resistance. Each paving brick created falls into one of two loading

Table 9: Properties and classification ZESC concrete pavement tiles

Type of mixes	Water absorption (%)	Compressive strength (MPa)	Abrasion resistance (mm)	Classification according to IQ.S 1606, ASTM C936, and EN 1338
Ref. paver	4.5	45.4	20.22	IQS: medium loading ASTM: $\checkmark$ EN: $\checkmark$
ZESC 6	1.1	47.24	19.27	I.Q.S.: medium loading ASTM: $\checkmark$ EN: $\checkmark$
ZESC 10	1.02	51.7	19.02	I.Q.S.: medium loading ASTM: $\checkmark$ EN: $\checkmark$
ZESC 15	0.92	56.2	18.63	I.Q.S.: high loading ASTM: $\checkmark$ EN: $\checkmark$

classes: medium or high. Consequently, ZESC 15 paver blocks are suitable for various paving applications, such as heavy vehicle highways and container parking, subject to harsh conditions and strong abrasion pressures. In contrast, pedestrian and lower-loading automobile roads may be paved with alternative paver blocks (ZESC 6 and ZESC 10).

4 Conclusions

The current investigation employs natural zeolite to create zeolite-enhanced blended cement for enhancing the properties of concrete paver blocks. Based on this experimental evaluation, the following conclusions can be drawn

1. Using ZESC in concrete paver blocks ensures unwavering strength, durability, and sustainability, marking a significant advancement in concrete paving solutions.
2. All concrete blocks produced from ZESC were within the durability requirements stated in BS EN 1338, ASTM 936, for abrasion resistance and water absorption.
3. ZESC incorporation enhances compressive strength by 4, 14, and 24% for ZESC 6, ZESC 10, and ZESC 15, respectively, after 28 days of curing, showing the effectiveness of zeolite in blended cement.
4. ZESC, particularly with 10% zeolite, exhibits a remarkable 53% increase in tensile strength at 28 days, emphasizing the optimal zeolite addition for enhancing the tensile strength of blended cement.
5. The tensile strength of the ZESC 6, ZESC 10, and ZESC 15 was 50, 55, and 45% higher than that of the reference concrete after 7 days, respectively.
6. The tensile strength of the ZESC 6, ZESC 10, and ZESC 15 was 19, 53, and 25% higher than that of the reference concrete after 28 days, respectively.
7. Water absorption in concrete paver blocks decreases to (75, 77, and 80%) for ZESC 6, ZESC 10, and ZESC 15 mixes, respectively, showing the potential of zeolite in minimizing water permeability.
8. Abrasion resistance decreases to 5, 6, and 7.8% for ZESC 6, ZESC 10, and ZESC 15, respectively, indicating improved durability compared to reference concrete paver blocks.
9. Natural zeolite's integration significantly reduces the environmental impact of cement production, presenting a sustainable shift by minimizing cement clinker.
10. The study's microstructural analysis, supported by SEM images, demonstrates a decrease in microcracks and enhanced cohesiveness in zeolite-containing mixes, particularly at the aggregate-cemented paste interface.

The recommendation for future work is to conduct long-term durability studies to assess the performance of concrete paver blocks with ZESC under various environmental conditions and extended service periods.

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