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Sustainable High-Performance Concrete Using Zeolite Powder: Mechanical and Carbon Footprint Analyses

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Abstract: This study investigates environmentally friendly high-performance concrete (HPC) by partially replacing cement and silica sand with zeolite powder. The replacement levels included 10%, 20%, and 30% for cement and up to 50% for silica sand. The optimal mix achieved 85 MPa compressive strength, 6 MPa tensile strength, and 7.8 MPa flexural strength with a 30% cement replacement, reducing the carbon footprint to approximately 659.72 kg CO_2/m^3. These findings demonstrate the potential of zeolite powder to enhance sustainability in HPC without compromising essential mechanical properties, promoting eco-friendly practices in construction.

Keywords: mechanical characteristics; high-performance concrete; zeolite powder; silica sand; carbon footprint; cement

1. Introduction

High-performance concrete (HPC) stands at the forefront of modern construction materials, offering exceptional mechanical strength, durability, and resilience [1–5]. Its unique properties make it an ideal choice for critical structural elements, including bridges, high-rise buildings, and offshore installations [6–9]. However, achieving an optimal HPC performance requires innovative approaches, and researchers have turned their attention to supplementary cementitious materials (SCMs) as a means of enhancing concrete properties [10–13].

HPC surpasses conventional concrete in terms of compressive strength, flexural strength, and resistance to cracking. It can withstand heavy loads, seismic forces, and harsh environmental conditions [14–17]. HPC exhibits superior durability, minimizing the risk of deterioration due to chemical attacks, freeze–thaw cycles, and abrasion [18–21]. Structures built with HPC have extended service lives, reducing maintenance costs and environmental impact [14,15,22–24].

The carbon footprint of concrete is a critical factor in assessing its environmental impact, especially given the construction industry's substantial contribution to global CO_2 emissions [25]. Cement, the primary binder in concrete, is particularly notorious for its high carbon footprint. This is due to the energy-intensive processes involved in its production, including the calcination of limestone. As the world pushes towards more sustainable practices, reducing the carbon footprint of concrete has become a key objective.

One approach to achieving this goal is through the partial replacement of cement and other concrete components with supplementary cementitious materials (SCMs), such as zeolite powder. Zeolite is a naturally occurring aluminosilicate mineral known for its pozzolanic properties, which can contribute to the formation of additional calcium silicate hydrate (C-S-H) gel in the concrete matrix. This not only enhances the mechanical properties of the concrete but also reduces its overall carbon footprint by decreasing the amount of cement required. Shafighfard et al. explored high-performance alkali-activated concrete (HP-AAC) as a sustainable, cementless alternative, emphasizing its low carbon emissions

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and energy efficiency [26]. They developed machine learning models to accurately predict HP-AAC's compressive strength, utilizing 538 experimental datasets and achieving a high predictive accuracy. Their work supports sustainable construction through advanced modeling and optimized material performance.

Zeolite, a naturally occurring aluminosilicate mineral with a three-dimensional crystalline structure, offers significant potential for sustainable construction applications [27]. Known for its abundance and widespread availability, zeolite is an appealing candidate for use in eco-friendly concrete formulations. This mineral exhibits pozzolanic behavior, whereby it reacts with calcium hydroxide ($Ca(OH)_2$) produced during the cement hydration process, leading to the formation of additional calcium silicate hydrate (C–S–H) gel [28,29]. The unique structural characteristics of zeolite, including its high surface area and considerable pore volume, allow it to adsorb excess water, thereby refining the microstructure of the concrete [30,31]. This quality helps in reducing voids and enhancing the density and integrity of the concrete. Zeolite's multifaceted benefits make it a promising alternative for advancing sustainable construction practices and reducing the environmental footprint of concrete production [6].

Concrete mixtures with zeolite, used as a mineral additive replacing 5% to 35% of cement, were tested by Canpolat et al. [32] for their strength properties. Fly ash was also added at 5% by cement weight in some specimens. The highest compressive strength at 28 days was noted in specimens containing 20% zeolite. When zeolite and fly ash were combined, optimal compressive strength was found with 10% to 25% zeolite and 5% fly ash. Yılmaz et al. [33] conducted experiments with concrete specimens incorporating 5%, 10%, 20%, and 40% zeolite. The compressive strength was assessed after 1, 2, 7, and 28 days of curing. The findings indicated that, after 24 h of curing, concrete specimens with zeolite additives exhibited lower compressive strength compared to the control specimens. This pattern persisted after 2 and 7 days of curing. However, after 28 days, the compressive strength of specimens with 5% zeolite increased by 6.8% compared to the control. For other specimens, the compressive strength increases were 15.9% for 10% zeolite, 22.3% for 20% zeolite, and 4.1% for 40% zeolite. Nagrockiene and Girskas [29] observed that incorporating a 10% zeolite additive into concrete specimens led to an increase in compressive strength by up to 13.3%. This further improved to 15.0% after 28 days of curing. Nas and Kurbetci [34] examined the influence of natural zeolite on various properties of concrete. These properties included compressive and flexural strength, capillary water absorption, rapid chloride permeability, high-temperature resistance, and freeze–thaw durability. They found that substituting natural zeolite in the binder led to a decrease in the capillary coefficient of the concrete. Specifically, replacement ratios of 10% and 15% were identified as the most effective for reducing the capillary action in concrete mixtures.

In 2023, Bahmani et al. [6] investigated the mechanical properties and microstructure of ultra-high-performance fiber-reinforced concrete (UHPFRC) samples that included natural zeolite as a partial cement replacement. The study used steel, polypropylene, and synthetic macro-fibers (barchip) as fibrous reinforcements. They cast 110 UHPFRC prism specimens and subjected them to four different curing conditions (wet, autoclave, heat, and combined curing involving steam, autoclave, and water). The investigation focused on compressive and flexural strength, fracture energy, and flexural toughness indices. Additionally, X-ray diffraction (XRD) and scanning electron microscopy (SEM) tests were conducted to analyze the concrete's microstructure. The results indicated that UHPFRC mixtures containing natural zeolite achieved a minimum compressive strength of 100 MPa. Furthermore, the average compressive strengths were 125 MPa (heat treatment), 162 MPa (autoclave treatment), and 130 MPa (combined curing).

Previous research has demonstrated that increasing the percentage of zeolite replacement in ultra-high-performance concrete (UHPC) or high-performance concrete (HPC) leads to a reduction in the formation of calcium silicate hydrate (C-S-H) while concurrently increasing the production of calcium hydroxide (CH). This shift in the hydration reaction can adversely affect the overall performance of the concrete. Specifically, a decrease in

C-S-H, which is crucial for providing strength and durability, can result in weakened mechanical properties. Additionally, the increased CH may disrupt the bond between the cement matrix and aggregates, compromising the structural integrity and performance of the concrete. These findings highlight the importance of optimizing zeolite replacement percentages to achieve a balance that maintains both the microstructural quality and the mechanical properties of UHPC/HPC.

The selection of zeolite replacement percentages for cement was informed by previous research [6]. However, the decision not to use higher percentages, such as 50% zeolite as a substitute for silica sand, was influenced by concerns regarding its low workability and inadequate bonding between the cement and aggregates.

While previous research has explored the effects of zeolite powder as a cement substitute, the simultaneous replacement of both cement and silica sand with zeolite powder remains unexplored. The primary objective of the study was to examine the feasibility of developing environmentally friendly HPC through the partial replacement of cement and silica sand with zeolite powder. Various replacement levels for both cement (10%, 20%, and 30%) and silica sand (ranging from 10% to 50%) were systematically investigated. The study focuses on the environmental benefits and mechanical properties achieved through such substitutions. The exploration included analyzing the resultant concrete's compressive strength, tensile strength, bending strength, density and carbon footprint. Figure 1 shows the flow chart of the research steps.

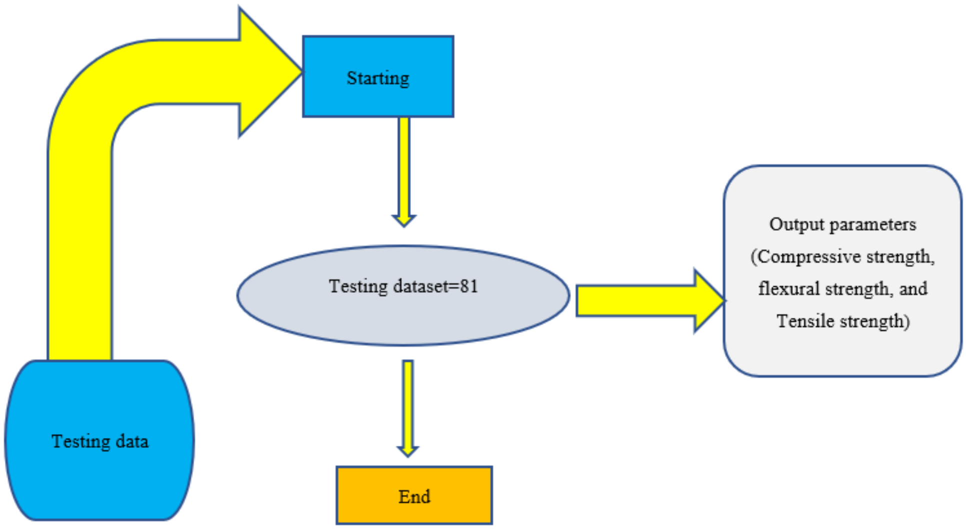

Figure 1. The flow chart of research steps.

While prior research has investigated the substitution of cement with zeolite, this work uniquely examines the simultaneous replacement of silica sand, thereby contributing to a significant reduction in the carbon footprint and material consumption in HPC formulations. Additionally, the study comprehensively evaluates the mechanical properties and environmental impact of each mix design, providing a balanced assessment of performance and sustainability. This approach supports the development of eco-friendly construction materials that maintain high structural standards, addressing a critical need in the field of sustainable engineering.

2. Materials

In the present study, cement type I, also known as Ordinary Portland Cement (OPC), was utilized as the primary binder. This type of cement was chosen for its widespread use and proven reliability in producing high-quality concrete. The OPC used in the experiments was carefully selected to ensure a consistent and reliable chemical composition, as it forms the foundation for the concrete's structural integrity. The selection of Portland cement type 1 was informed by prior research [6]. Zeolite powder and silica sand played crucial roles in the experimental setup as substitute materials for traditional cement and silica sand [9]. The zeolite powder, known for its pozzolanic properties, was used to partially replace the cement, aiming to enhance the sustainability and performance of the resulting concrete mixtures. In this research, natural clinoptilolite zeolite was used based on previous research [6].

Silica sand, sourced from the Chirok mine sand factory, was used for its fine particle size, being smaller than 150 microns. It underwent rigorous chemical analysis to confirm its suitability and purity for use in the concrete mixtures. The size of the silica sand and zeolite powder used in this research was according to the previous research [6]. The particle size plays a key role on the mechanical properties [35]. The chemical compositions of the materials used in the study are presented in Table 1.

Table 1. Chemical compositions of the materials used in the study (%).

Chemical Compositions: % by Weight	ASTM C150 Limits	Cement	Zeolite
Aluminum oxide (Al_2O_3)		-	11.0
Silicon dioxide (SiO_2)		22.0	68.5
Iron oxide (Fe_2O_3)		3.0	0.7
Calcium oxide (CaO)		64.0	0.6
Magnesium oxide (MgO)	$\leq$6.0	1.0	-
Sulfur trioxide (SO_3)	$\leq$3.5	1.0	-
Na_2O	-	-	2.8
K_2O	-	-	4.4
Loss on ignition (LOI)	$\leq$3.0	-	12
Moisture content		-	-

To achieve a consistent water-to-cement ratio and ensure uniformity in the concrete mix, superplasticizer materials were employed. Specifically, AURAMIX 4450, a high-range water reducer based on polycarboxylate ether, was utilized for its remarkable properties [36]. This superplasticizer not only complies with ASTM C494 standards [37], ensuring it meets the necessary performance criteria for construction materials, but it is also recognized for its effectiveness in enhancing the fluidity of concrete. Increased fluidity allows for improved workability, which is crucial in achieving a uniform distribution of fibers throughout the concrete mixture. This uniformity is vital for optimizing the material's mechanical properties and overall performance. Consequently, the application of AURAMIX 4450 significantly contributes to the ease of mixing and placing the concrete, resulting in a higher-quality product that meets the desired engineering specifications. During this research, the samples underwent standard water treatment for a duration of 28 days.

The mixture proportions for the concrete designs are detailed in Table 2. This table outlines the various compositions used in the experiments, with distinct symbols indicating different mix designs. For example, 'HPC' denotes the base mix design without any zeolite substitution. Variations such as HPC (10%Z), HPC (20%Z), and HPC (30%Z) correspond to mixtures where 10%, 20%, and 30% of the cement was replaced with zeolite, respectively. Additionally, mixtures labeled HPC (10%ZP), HPC (20%ZP), HPC (30%ZP), HPC (40%ZP), and HPC (50%ZP) represent the substitution of 10%, 20%, 30%, 40%, and 50% of the silica sand with zeolite, respectively. Zeolite powder percentage was selected according to previous research [6]. These various formulations were developed to systematically evaluate the impact of zeolite substitution on the performance characteristics of HPC. The choice of a cement-to-aggregate ratio of 1:0.91 and a water-to-binder ratio of 0.21 was informed by prior research [6].

Table 2. The mixture proportions in the present study (kg/m^3).

Designation	Cement	Zeolite Powder	Silica Sand	Zeolite Powder	W/B	SP
HPC	1050	-	961	-	0.21	42
HPC (10%Z)	945	105	961	-	0.21	44
HPC (20%Z)	840	210	961	-	0.21	47
HPC (30%Z)	735	315	961	-	0.21	49
HPC (10%ZP)	945	105	96	865	0.21	47
HPC (20%ZP)	945	105	192	767	0.21	49
HPC (30%ZP)	945	105	288	673	0.21	51
HPC (40%ZP)	945	105	384	578	0.21	54
HPC (50%ZP)	945	105	480.5	480.5	0.21	56

The target slump of the concrete samples was carefully maintained at a consistent level across all mixing designs by adjusting the amount of superplasticizer to achieve a slump of approximately 200 mm. This careful calibration was essential to ensure the uniform workability and performance of the concrete across different batches. To provide a visual representation of the mixing process and the resultant material consistency, an image of the samples post-mixing is included in Figure 2. This figure illustrates the effectiveness of the mixing design and demonstrates the uniform texture and homogeneity of the concrete mixture, which are critical factors in achieving optimal performance in the final application. The image serves not only as documentation of the mixing process but also as evidence of the successful integration of the superplasticizer, contributing to the desired slump and overall workability of the concrete. The foundational mixing design was derived from previous research indicating that a low water-to-binder (w/b) ratio combined with a superplasticizer yields optimal results [6,38,39]. This study demonstrated that this mixing approach achieves superior mechanical properties and enhanced durability.

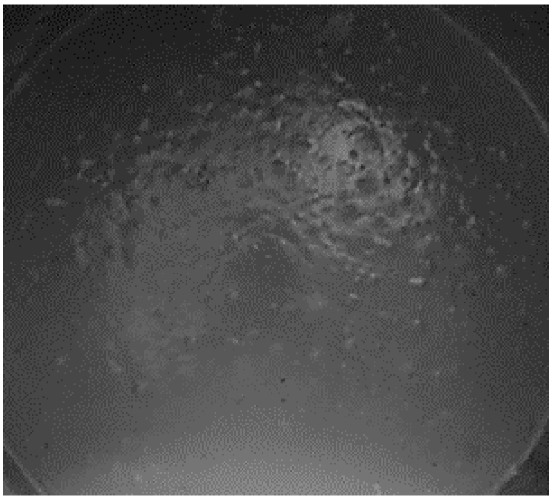

Figure 2. Image of the samples post-mixing.

3. Test Setup

3.1. Compressive Strength

To assess the compressive strength of high-performance concrete (HPC), a hydraulic jack with a significant capacity of 2000 kN was employed. This powerful tool is vital for delivering the substantial forces that are necessary to adequately evaluate the material's strength when subjected to compressive forces. The compressive strength tests were meticulously conducted following the ASTM C39 standards [40], which ensures that the methodology aligns with established industry protocols for concrete testing. For this assessment, cylindrical samples were precisely prepared, measuring 100 mm in diameter and 200 mm in height (Figure 3a). These carefully crafted samples provide uniformity in dimensions, which is essential for facilitating consistent and reliable test results that accurately reflect the material's performance.

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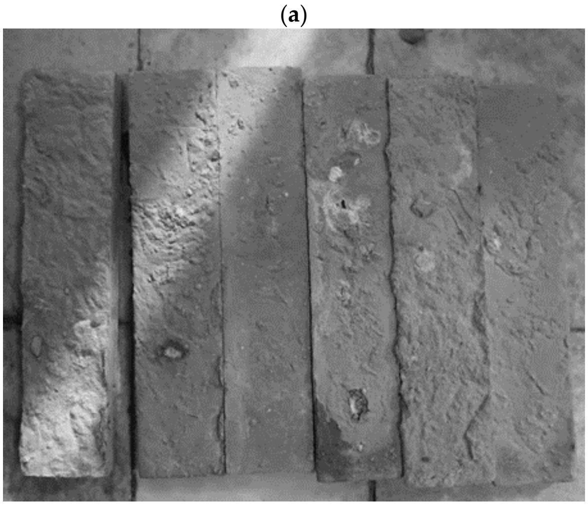


(**b**)

Figure 3. Image of the samples before testing: (**a**) compressive and tensile strength, and (**b**) flexural strength.

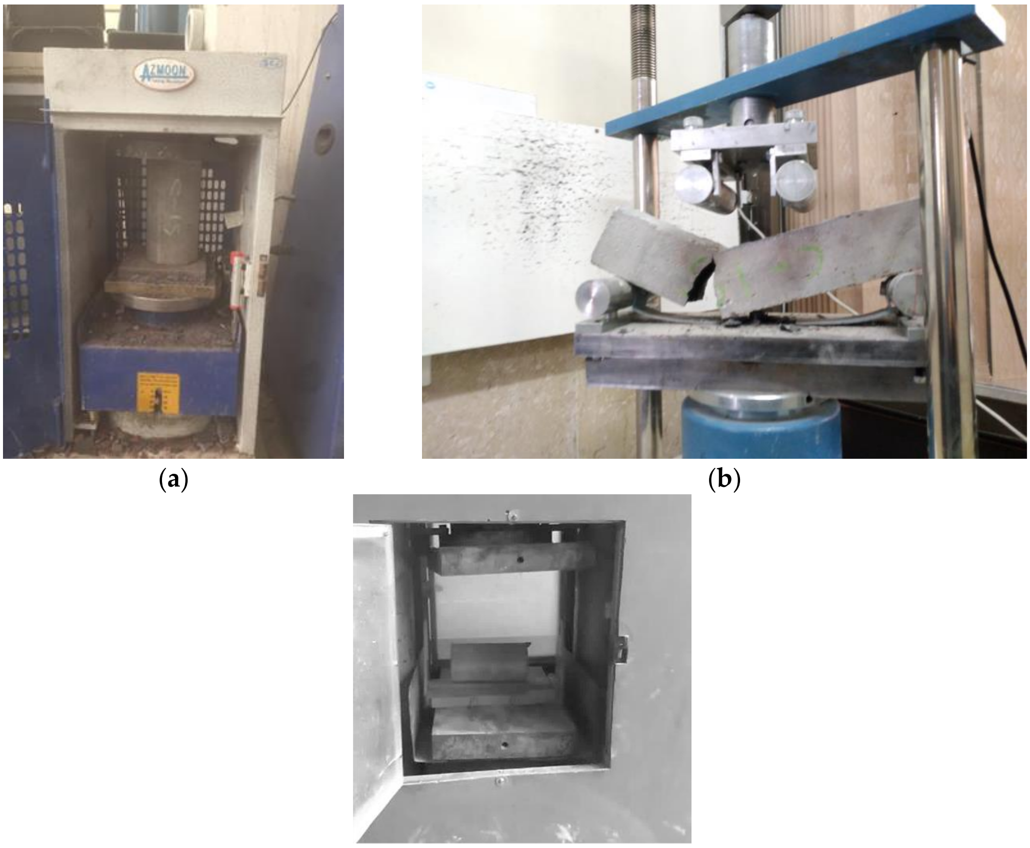
3.2. Tensile Strength

In addition to assessing compressive strength, the tensile strength of the HPC was determined using the Brazilian test method, a widely recognized technique in the field of concrete evaluation. This method, as outlined in ASTM C469 [41], is specifically designed to assess the tensile properties of concrete by applying a diametral compressive load to cylindrical specimens. During this test, tensile stress is induced in a direction perpendicular to the applied load, allowing for a comprehensive understanding of the material's behavior under tension. Consistent with the compressive strength tests, cylindrical samples measuring 100 mm in diameter and 200 mm in height were utilized for the tensile strength evaluations. This uniformity helps ensure comparability and reliability across different measurements, contributing to the overall validity of the findings.

3.3. Four-Point Flexural Strength

To further evaluate the flexural strength of the concrete, the four-point flexural test was conducted in strict adherence to ASTM C78 standards [42]. This involved placing HPC specimens with dimensions of 350 mm in length, 70 mm in width, and 70 mm in height in a specially designed four-point bending setup (Figure 3b). These specimens were subjected to progressively increasing loads applied through an ELE testing device capable of exerting forces up to 50 kN. To accommodate any potential discrepancies in sample dimensions in relation to standard specifications, the loading speed was meticulously adjusted during the testing process. This adjustment proved critical in ensuring that the first crack developed within the specimens occurred between 30 and 60 s after loading commenced. Such a thoughtfully designed setup not only enhances the accuracy of the measurements obtained but also guarantees a uniform distribution of bending stress across the specimen. This approach enables precise assessments of both flexural strength and the overall structural response of the concrete when subjected to bending loads, ultimately reinforcing the significance of these strength evaluations in determining the material's suitability for various applications.

The test setup is depicted in Figure 4, illustrating the configurations for (a) compressive strength testing, (b) four-point flexural strength testing, and (c) tensile strength testing. The research involved an examination of nine different mix designs and the execution of three main experiments, each conducted with three repetitions. This resulted in a total of 81 trials, and the reported results represent the averages of these three repetitions.



(**a**) (**b**) (**c**)

Figure 4. Test setup: (**a**) compressive strength, (**b**) four-point flexural strength, and (**c**) tensile strength.

3.4. Carbon Footprint Analysis

The construction industry is a significant contributor to global carbon emissions, with concrete production alone responsible for approximately 8% of worldwide CO_2 emissions [43–48]. HPC, while offering superior strength, durability, and longevity, often requires a high cement content [49,50]. Cement production is particularly carbon-intensive, as it involves energy-heavy processes and releases substantial CO_2 during clinker formation. Consequently, reducing the carbon footprint of HPC has become a critical focus in sustainable construction [51,52].

Lowering the carbon emissions associated with HPC not only addresses environmental impacts but also aligns with global goals for reducing greenhouse gas emissions [53].

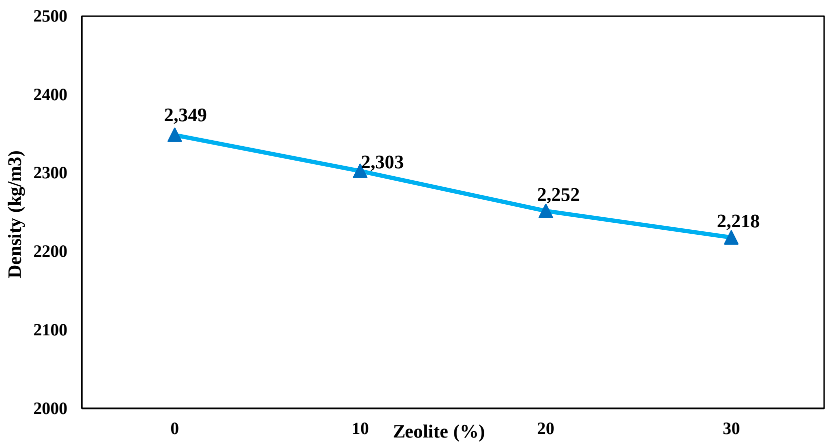
Innovations in material substitutions, such as the use of supplementary cementitious materials (SCMs) like fly ash, slag, and zeolite, have shown promise in reducing cement usage without compromising HPC performance. These SCMs provide a dual benefit: they enhance certain mechanical and durability properties of HPC while decreasing its carbon footprint by offsetting cement [54,55].

As sustainability gains importance in construction, the development and adoption of low-carbon HPC formulations become essential. By integrating alternative materials and optimizing mix designs, it is possible to achieve the high-performance attributes of HPC while significantly minimizing environmental impacts. The shift towards carbon-reduced HPC supports long-term sustainability goals and contributes to eco-friendly infrastructure development, benefiting both the construction industry and society [56,57].

4. Results

4.1. Density Results

Figure 5a presents the density measurements for concrete samples that were formulated with varying percentages of zeolite as a substitute for traditional cement, specifically at levels of 10%, 20%, and 30%. The data clearly illustrate a discernible trend: an increase in the proportion of zeolite leads to a corresponding decrease in the overall density of the concrete samples. This phenomenon can be primarily explained by the intrinsic properties of zeolite, which possesses a lower density compared to conventional cement.



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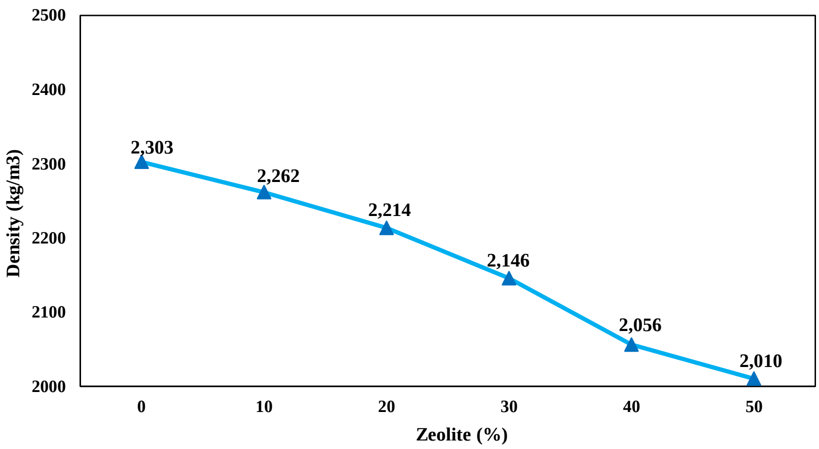


(**b**)

Figure 5. Density results: (**a**) samples incorporating varying zeolite percentages (10%, 20%, and 30%) as a replacement for cement; (**b**) samples incorporating varying percentages of zeolite replacement with silica sand.

Significantly, the samples with a 30% zeolite replacement exhibited a pronounced reduction in density, quantified at approximately 130 kg/m^3 in specific weight. This notable decrease not only reflects the lighter nature of zeolite but also hints at its potential advantages in engineering applications where weight considerations are critical. By incorporating zeolite into concrete formulations, there is a promising opportunity to enhance sustainability. The lower density of the resultant concrete can lead to a reduced material usage and lower transportation costs, thus aligning with eco-friendly construction practices. These findings align with prior research [6].

On the other hand, Figure 5b further explores density outcomes for concrete samples where zeolite is utilized to substitute varying proportions of silica sand, with replacement levels ranging from 0% to 50%. The results indicate a consistent and systematic decrease in density as the proportion of silica sand replaced by zeolite increases. Specifically, a shift from 0% to 50% zeolite replacement corresponds to an approximate 13% reduction in density across the sample set.

This trend can be attributed to several factors, including the increased porosity of the matrix and the introduction of voids within the concrete structure. Zeolite, being a lighter and more porous material compared to denser silica sand, displaces the traditional aggregate and creates air pockets within the concrete. These voids not only contribute to a reduction in weight but can also enhance the insulating properties of the concrete, making it potentially advantageous in various construction scenarios.

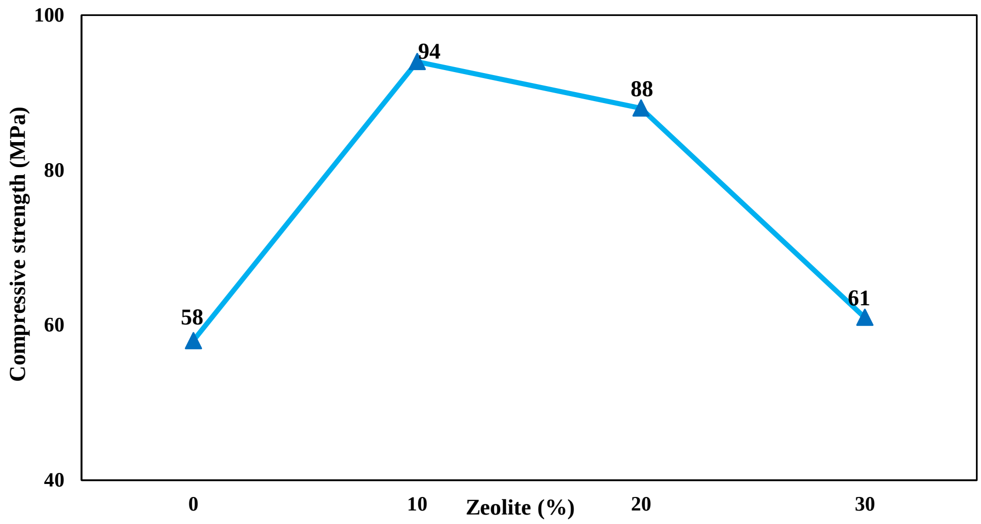
Collectively, these findings underscore the multifaceted benefits of utilizing zeolite as a partial replacement for both cement and silica sand in concrete mixes. By effectively reducing the density of concrete, zeolite offers a sustainable alternative that aligns with modern construction demands while promoting environmentally friendly practices. This approach could lead to innovative concrete formulations that are lighter, more efficient, and conducive to a sustainable building industry.

4.2. Compressive Strength Results

The image of the sample after the compressive strength test is shown in Figure 6. Figure 7a illustrates the compressive strength outcomes for concrete samples with varying percentages of zeolite substituting cement. The data reveal that a 10% zeolite replacement provides the highest compressive strength, peaking at 94 MPa. This enhancement can be attributed to several factors. Firstly, at this substitution level, zeolite's pozzolanic reaction with calcium hydroxide, a byproduct of cement hydration, improves particle packing and increases the formation of calcium silicate hydrates (C-S-H), which contributes to the overall strength of the concrete. Secondly, as the zeolite content rises above 10%, its benefits start to diminish. This is likely due to the excessive amount of zeolite disrupting the cementitious matrix's cohesion, leading to weaker interfacial bonds and a reduced number of cementitious phases. As a result, samples with 20% and 30% zeolite show decreased compressive strength, indicating that too much zeolite can hinder the development of a robust matrix. Therefore, a 10% zeolite substitution optimally balances strength improvement and maintaining the structural integrity of the concrete. These findings align with prior research [6].

Figure 7b provides the compressive strength results for samples with varying levels of zeolite as a substitute for silica sand. The trend shows a consistent decline in compressive strength as the zeolite content increases from 0% to 50%. Specifically, at a 10% substitution, the compressive strength decreases by 9% compared to the base sample. This reduction grows to 17% at 20% zeolite, 32% at 30%, 39% at 40%, and reaches a significant 52% at the 50% substitution level. The decrease in strength is likely due to the altered microstructure of the cementitious matrix when zeolite replaces silica sand. Zeolite's unique characteristics, including its porous nature, may lead to less effective particle packing and weaker interparticle bonds, thereby reducing the overall strength of the concrete.

Figure 6. The image of the sample after the compressive strength test.



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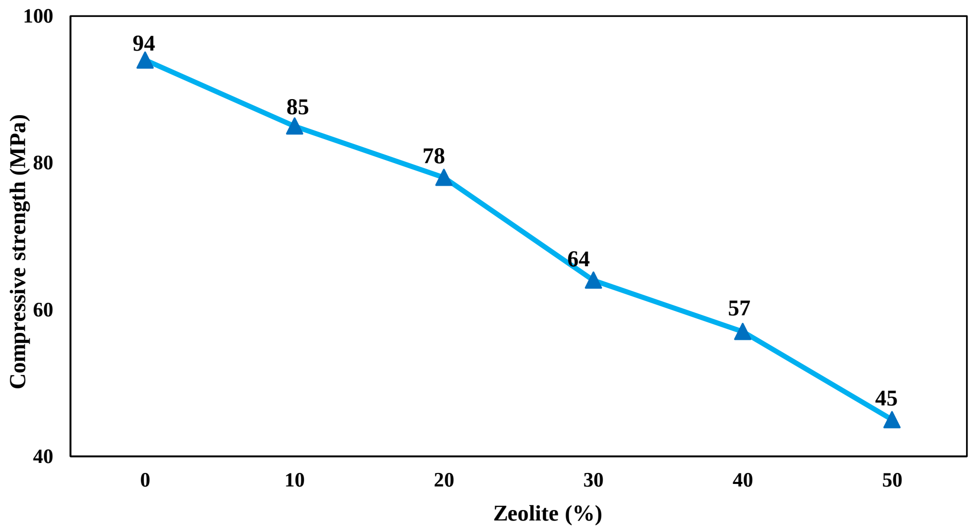
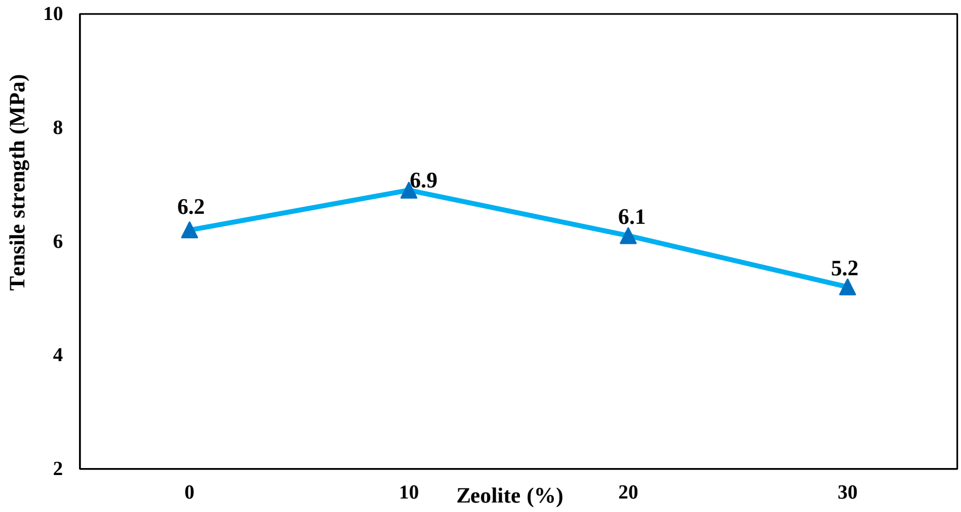


(**b**)

Figure 7. Compressive strength results: (**a**) samples incorporating varying zeolite percentages (10%, 20%, and 30%) as a replacement for cement; (**b**) samples incorporating varying percentages of zeolite replacement with silica sand.

4.3. Tensile Strength Results

Figure 8a presents the tensile strength results for concrete samples with varying percentages of zeolite as a substitute for cement. The analysis indicates that the highest tensile strength of 6.9 MPa is achieved at a 10% zeolite substitution. This enhancement can be attributed to the pozzolanic reaction between zeolite and cementitious materials, which improves the tensile properties by forming additional calcium silicate hydrates (C-S-H). However, as the zeolite content increases beyond 10%, a gradual reduction in tensile strength is observed. Specifically, for each 10% increment in zeolite content, the tensile strength decreases by approximately 1.7 MPa. This reduction in strength can be explained by the potential disruption of the matrix microstructure by zeolite particles, which affects interparticle bonding and overall cohesion. Beyond the 10% substitution level, excessive zeolite may impede the formation of strong C-S-H bonds, leading to weaker tensile properties. Therefore, while zeolite substitution offers environmental advantages, its impact on tensile strength should be carefully considered in the concrete mix design to avoid compromising structural integrity. These findings align with prior research [6].



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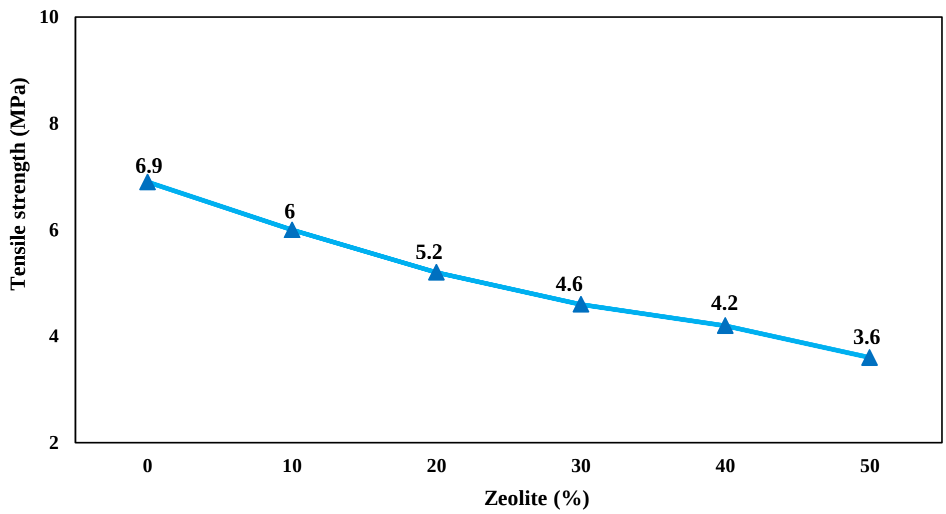


(**b**)

Figure 8. Tensile strength results: (**a**) samples incorporating varying zeolite percentages (10%, 20%, and 30%) as a replacement for cement; (**b**) samples incorporating varying percentages of zeolite replacement with silica sand.

The tensile strength results for samples with varying percentages of zeolite replacing silica sand are illustrated in Figure 8b. The trend indicates a consistent decline in tensile strength as the zeolite content increases from 0% to 50%. This decline can be linked to the interaction of zeolite, which contains significant quantities of SiO_2 and Al_2O_3, with cement through pozzolanic reactions. At a 10% zeolite substitution, the tensile strength decreases by 13% compared to the base sample. The reduction becomes more pronounced with a higher zeolite content: a 24% decrease at 20%, 33% at 30%, 39% at 40%, and a substantial 48% reduction at a 50% substitution level. The weakening of tensile strength is likely due to changes in the microstructure of the cementitious matrix caused by zeolite particles, which affect interparticle bonding and hydration. Additionally, the increased porosity associated with a higher zeolite content contributes to weaker interfacial bonds. Thus, while zeolite offers potential environmental benefits, its effect on tensile strength should be meticulously evaluated when replacing silica sand to ensure the desired performance characteristics of the concrete are maintained.

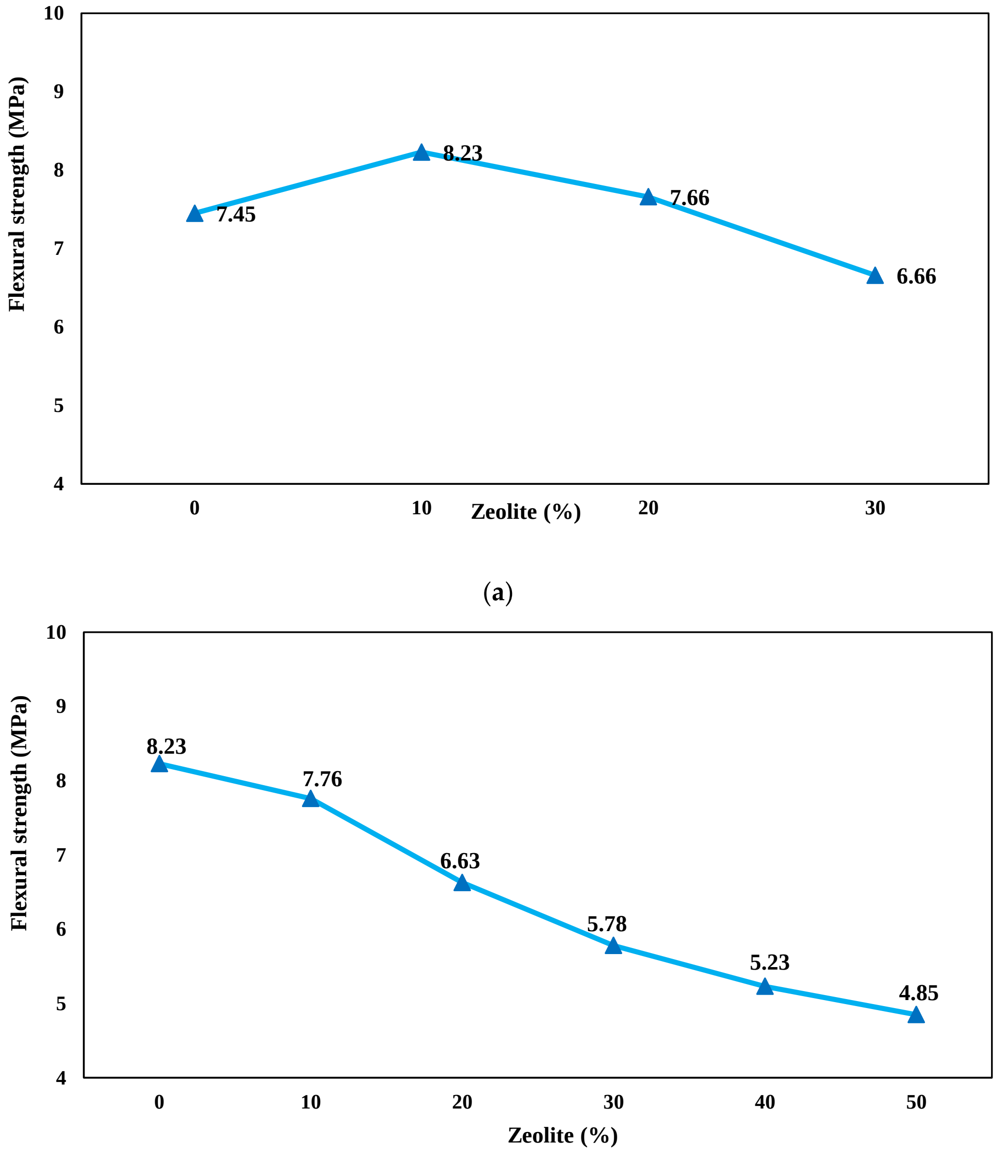
4.4. Flexural Strength Results

The modulus of rupture, also known as flexural strength, can be determined using Equation (1) according to the ASTM C78 standard. This equation relates the rupture modulus ((f_r)) in megapascals (MPa) to the load ((P)) applied to the specimen, the span width ((b)) in millimeters, the average specimen height ((d)), and the span length ((L)). The formula is as follows:

$$f_r = {}^{PL}/_{bd^2} \tag{1}$$

The image of the sample after the flexural strength test is shown in Figure 9. Figure 10a illustrates the flexural strength results of concrete samples where varying percentages of zeolite were used as a substitute for cement. The optimal zeolite content for cement replacement was found to be 10%, achieving the highest bending strength of 8.2 MPa. This improvement is likely due to the pozzolanic reaction between zeolite and cementitious materials, which enhances the flexural properties of the mix. However, as the zeolite replacement increased from 10% to 30%, the bending strength exhibited a decline of 1.6 MPa. This decrease can be attributed to the alteration of the cementitious matrix's microstructure by zeolite particles, which affects interparticle bonding and overall cohesion. At higher replacement levels, the presence of excessive zeolite could impede the formation of strong calcium silicate hydrate (C-S-H) bonds, leading to a reduced strength. The flexural strength results for samples with zeolite replacing silica sand are shown in Figure 10b. Increasing the zeolite powder replacement from 0% to 50% led to a noticeable decline in tensile strength. This reduction in strength may result from the different bonding characteristics of zeolite compared to silica sand, which affects material cohesion. Additionally, the porous nature of zeolite could result in weaker interparticle interactions, contributing to lower strength. Specifically, the compressive strength reductions for samples containing 10%, 20%, 30%, 40%, and 50% zeolite powder as a substitute for silica sand were 6%, 19%, 29%, 36%, and 41%, respectively, compared to the control sample. These findings underscore the need for careful consideration of zeolite's impact on concrete mix design to balance its environmental benefits with its influence on structural properties.

Figure 9. The image of the sample after the flexural strength test.



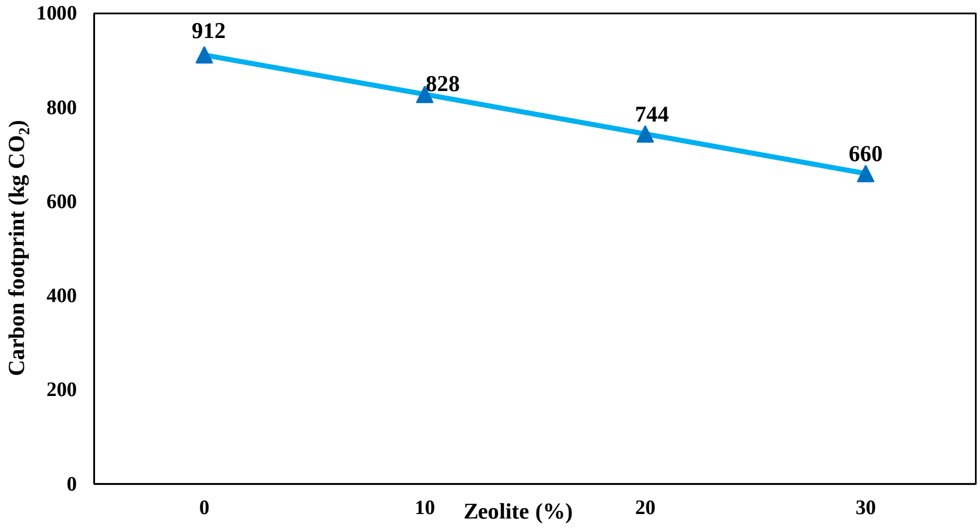
(**a**)

(**b**)

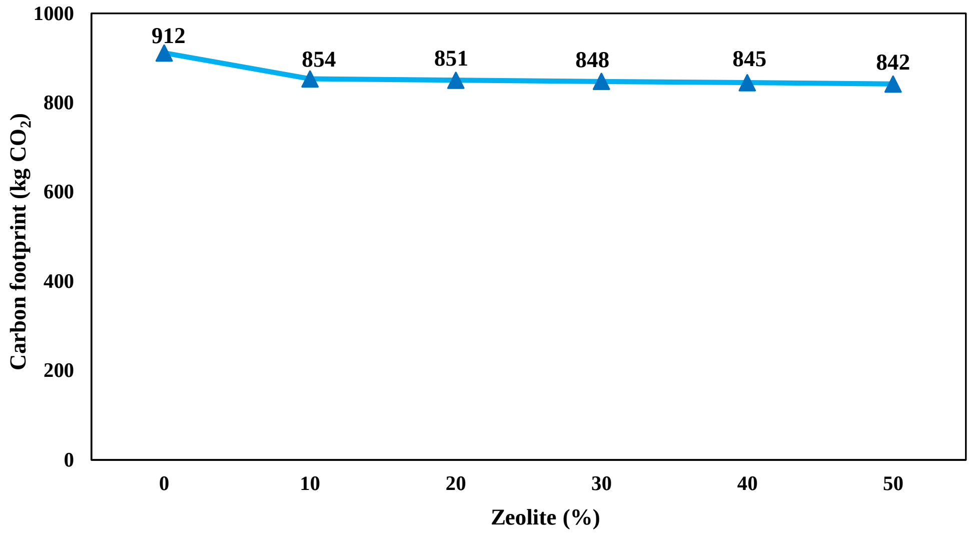
Figure 10. Flexural strength results: (**a**) samples incorporating varying zeolite percentages (10%, 20%, and 30%) as a replacement for cement; (**b**) samples incorporating varying percentages of zeolite replacement with silica sand.

4.5. Carbon Footprint Results

The carbon footprint of the various concrete mix designs is presented in Figure 11. The results reveal significant differences in carbon emissions, depending on the proportion of cement and silica sand replaced with zeolite powder. The mix designs with higher levels of cement replacement, such as HPC (30%Z), HPC (20%Z), and HPC (10%Z), demonstrate the lowest carbon footprints, with HPC (30%Z) achieving the most significant reduction at 659.72 kg CO_2 per cubic meter.



(**a**)



(**b**)

Figure 11. Carbon footprint results: (**a**) samples incorporating varying zeolite percentages (10%, 20%, and 30%) as a replacement for cement; (**b**) samples incorporating varying percentages of zeolite replacement with silica sand.

This reduction is primarily due to the decreased use of cement, which is the largest contributor to the carbon footprint of concrete. By replacing 30% of the cement with zeolite, this mix design effectively lowers its carbon emissions without compromising the concrete's performance, as indicated by the mechanical properties discussed in the manuscript.

On the other hand, mix designs that involve the replacement of both cement and silica sand with zeolite, such as HPC (50%ZP) and HPC (40%ZP), show slightly higher carbon footprints, although they are still lower than the base mix design without any zeolite substitution. These designs are advantageous as they not only reduce cement usage but also offer the potential to lower the density of the concrete, which can be beneficial for specific applications where weight is a critical factor.

It can be noted that changes in particle size can significantly affect the pozzolanic activity and workability of the mix; finer particles may enhance reactivity and improve bonding with the cement matrix, while coarser particles might reduce these effects. Additionally, differences in mineralogy could influence the chemical interactions within the concrete, potentially altering strength development and durability.

5. Conclusions

In this study, the feasibility of developing environmentally friendly HPC was explored by incorporating zeolite powder as a partial substitute for both cement and silica sand. This investigation included varying replacement levels: 10%, 20%, and 30% of cement with zeolite powder, and 10% to 50% replacement of silica sand with zeolite powder. The objective was to assess whether zeolite could serve as a viable alternative in concrete mix formulations while maintaining or enhancing the mechanical properties required for HPC.

To evaluate the effectiveness of zeolite substitution, a series of mechanical tests were conducted to measure key properties, including compressive strength, tensile strength, bending strength, and specific gravity. The outcomes of these tests provided valuable insights into the impact of zeolite on the concrete mix:

- The incorporation of zeolite powder resulted in significant alterations to the key properties of the concrete samples. Notably, replacing 30% of cement with zeolite powder led to a reduction in density by approximately 130 kg/m^3. Additionally, increasing the substitution of silica sand with zeolite from 0% to 50% resulted in an approximate 13% decrease in specific weight, indicating that zeolite effectively contributes to producing a lighter concrete mix.
- The findings show that substituting up to 50% of silica sand with zeolite powder not only meets but exceeds the minimum mechanical specifications for high-performance concrete (HPC). The compressive strength achieved was 85 MPa, with tensile and flexural strengths of 6 MPa and 7.8 MPa, respectively. This highlights that zeolite not only maintains the mechanical properties of the concrete mix but also has the potential to enhance them, thus establishing its viability as a crucial component in fulfilling the performance standards required for HPC.
- The substitution of 10% of cement with zeolite powder also fulfilled the necessary mechanical specifications. This observation suggests that zeolite supports the attainment of high strength while offering a sustainable alternative to traditional cement in the production of HPC. By reducing reliance on conventional materials, this study promotes the advancement of environmentally friendly construction practices and materials.
- The results indicate that a 30% replacement of cement with zeolite powder achieved the most significant reduction in carbon emissions, resulting in a total carbon footprint of approximately 659.72 kg CO_2 per cubic meter. This mix design not only minimizes the environmental impact but also upholds the essential mechanical properties for HPC, including a compressive strength of 94 MPa. Therefore, it emerges as a highly viable option for sustainable construction practices.

The Limitations of This Work

While this study successfully demonstrates the potential of utilizing zeolite powder as an environmentally friendly alternative in the production of high-performance concrete (HPC), several limitations must be acknowledged.

- Limited Replacement Levels: The study explored specific replacement levels (10%, 20%, and 30% for cement; 10% to 50% for silica sand) and may not capture the full potential of zeolite as a substitute. Future research could explore additional percentages to optimize performance.
- Scope of Mechanical Properties: Only compressive strength, tensile strength, flexural strength, and specific gravity were assessed. Other crucial factors, such as durability, shrinkage, and creep, were not evaluated and are essential for real-world applications.
- Laboratory Conditions: Tests were conducted in controlled laboratory settings, which may not fully replicate field conditions like varying temperatures, humidity, and curing practices that can affect concrete performance.

- Environmental Impact of Zeolite: While zeolite's sustainability benefits were highlighted, the environmental impact of sourcing and processing zeolite itself was not evaluated. A comprehensive life-cycle assessment of all materials would provide a more balanced view.
- Economic Feasibility: The cost-effectiveness of using zeolite in large-scale concrete production was not analyzed, which is essential for determining the practicality of this material substitution in industry.

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