



## Durability and Mechanical Performance of Ceramic Waste Powder and Activated Zeolite Blended Concrete under Sulfate and Chloride Attack

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### ABSTRACT

This study examines the mechanical and durability properties of concrete incorporating a binary supplementary cementitious material (SCM) comprising ceramic waste powder (CWP) and activated zeolite (AZ) in a 1:1 ratio. Six concrete mixes with cement replacement levels of 0%, 10%, 15%, 20%, 25%, and 30% were assessed under exposure to 5% Na<sub>2</sub>SO<sub>4</sub> and 3.5% NaCl. Durability testing involved wet-dry cycling for 28, 56, and 90 days. The results indicate that the mix with 20% CWP-AZ (M3) exhibited optimal performance, retaining over 92% of its strength, achieving the lowest sorptivity (0.221 mm/√s), and demonstrating a significant reduction in mass loss (2.1%) ANOVA ( $F = 14.72$ ,  $p < 0.001$ ) and regression modeling confirmed significant durability gains. The findings offer a sustainable solution for concrete used in offshore and oilfield infrastructures.

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## 1. Introduction

Concrete infrastructure situated in marine, coastal, and offshore environments is frequently subjected to chemically aggressive agents, notably sulfates and chlorides, which undermine long-term durability (Sun et al., 2023). The ingress of these agents into the concrete pore structure precipitates reactions with cement hydration products, ultimately yielding expansive compounds and initiating corrosion of steel reinforcement (Asaad et al., 2021). Consequently, structural integrity is compromised, maintenance costs escalate, and the service life of critical infrastructure – including offshore platforms, liquefied natural gas (LNG) foundations, and pipelines – is curtailed (Shcherban' et al., 2023). Therefore, augmenting the resistance of concrete to these aggressive environments has emerged as a paramount concern in materials research, particularly for infrastructure integral to the oil and gas industry (Borg & Vassallo, 2022).

One of the most sustainable strategies for achieving durable concrete involves the incorporation of supplementary cementitious materials (SCMs) (Sabo Baba et al., 2023). By enhancing chemical resistance and long-term performance, SCMs concurrently mitigate the environmental impact of Portland cement, a significant contributor to global CO<sub>2</sub> emissions, accounting for over 8% of the total (Abubakar et al., 2018). Notably, ceramic waste powder (CWP) and natural zeolite (NZ) have emerged as promising SCMs, owing to their pozzolanic reactivity, widespread availability, and economic viability (Ahmad et al., 2024). Nevertheless, while the individual effects of CWP and NZ have been well-documented, research on their synergistic effects in binary blends, particularly under simultaneous sulfate and chloride exposure, remains scarce.

Ceramic waste powder, often derived from discarded tiles and ceramics, is characterized by its high content of amorphous silica and alumina (Ahmad et al., 2024). Upon fine grinding, it exhibits pozzolanic behavior, reacting with calcium hydroxide to generate additional calcium silicate hydrate (C-S-H) gel, thereby



densifying the microstructure (Song et al., 2021). Studies have demonstrated the efficacy of ceramic waste powder in reducing permeability, enhancing resistance to chloride penetration, and refining the microstructure (Shcherban' et al., 2023). Nevertheless, its slow pozzolanic reaction rate and potential for early strength reduction may limit its standalone application as a supplementary cementitious material in aggressive environments, necessitating careful consideration (Algaifi et al., 2021).

Activated zeolite emerges as a promising supplementary cementitious material (SCM) owing to its high surface area, ionic exchange capacity, and reactivity with calcium hydroxide (Montesano et al., 2022). Studies have demonstrated that activated zeolite enhances sulfate resistance, reduces permeability, and mitigates alkali-silica reactivity in cementitious systems (Zheng, et al., 2024, Montesano et al., 2022). The alkali and silica content in zeolite facilitates the formation of secondary hydration products, which refine the pore structure and impede chemical ingress, thereby contributing to improved durability (Samimi & Shirzadi Javid, 2021).

Notwithstanding the promising properties of ceramic waste powder (CWP) and activated zeolite, research on their combined utilization in binary blends remains limited. Existing studies suggest that dual-supplementary cementitious material (SCM) systems can yield synergistic benefits, where one SCM enhances early-age strength while the other improves long-term durability (Kryvenko et al., 2023). This concept holds particular relevance for infrastructure exposed to simultaneous chloride and sulfate attack, where early densification and sustained pozzolanic activity are crucial for ensuring structural resilience (Algaifi et al., 2021).

A further research gap exists in the scarcity of comprehensive experimental validations that incorporate wet-dry cycles and multi-ion chemical exposure, which more accurately replicate the complexities of real-world marine environments. Notably, many existing studies employ static immersion methods or single-agent exposure, thereby failing to capture the cyclical damage mechanisms prevalent in splash zones and tidal regions (Drochytka et al., 2019). Additionally, limited research has utilized statistical modeling tools, such as analysis of variance (ANOVA) and regression analysis, to validate performance trends across diverse mix designs, underscoring the need for more rigorous data analysis (Omomo, Esiri & Olisakwe, 2024).

This study bridges the existing knowledge gaps by examining the durability and mechanical performance of concrete incorporating a binary blend of ceramic waste powder (CWP) and activated zeolite (AZ) as partial cement replacements. Six mix designs were formulated with SCM contents ranging from 0% to 30%, maintaining a 1:1 ratio of CWP to AZ. The experimental program comprised compressive strength, sorptivity, and mass loss tests following exposure to 5% Na<sub>2</sub>SO<sub>4</sub> and 3.5% NaCl under wet-dry cycling for up to 90 days. Furthermore, statistical validation using analysis of variance (ANOVA) and regression modeling was conducted to identify optimal performance ranges and discern significant differences between the various mix designs.

## **2. Materials and Methods**

### **2.1. Ordinary Portland Cement (OPC)**

An Ordinary Portland cement (grade 42.5R) conforming to (BS EN 197-1:2011) specifications were used as the primary binder. It is characterized by a high early strength gain and a balanced composition of calcium silicates and aluminates, making it suitable for structural concrete applications. The cement was sourced from Dangote Cement Plc, Nigeria, and used as-received without further modification.

### **2.2. Ceramic Waste Powder (CWP)**

Ceramic Waste Powder was produced from discarded ceramic tiles and sanitary ware collected from construction and demolition sites in kano. The waste was first manually cleaned to remove dust and organic matter, then crushed using a jaw crusher and milled to a fine powder in a ball mill.

### **2.3. Activated Zeolite (AZ)**

The zeolite used in this study was a naturally occurring clinoptilolite-rich mineral, obtained from volcanic deposits in Plateau State, Nigeria. The raw material was first oven-dried at 105°C for 24 hours, then

mechanically ground, and subsequently thermally activated at 550°C for 2 hours in a muffle furnace to enhance its pozzolanic reactivity.

**2.4. Fine and Coarse Aggregates**

The fine aggregate used was river sand, free from organic impurities and conforming to (BS EN 12620:2013). The coarse aggregate was crushed granite with a nominal maximum size of 20 mm, well-graded and meeting the requirements of (ASTM C33). Both aggregates were washed and air-dried before use.

**2.5. Potable Water**

Clean, potable water, free from suspended solids, oil, and harmful dissolved salts, was used throughout for mixing and curing. The water satisfied the requirements of (BS EN 1008:2002) for concrete mixing and did not adversely affect the setting time or strength development.

**2.6. Chemical Solutions: Na<sub>2</sub>SO<sub>4</sub> and NaCl**

To simulate aggressive environmental exposure, two chemical solutions were prepared:

- a) Sodium Sulfate (Na<sub>2</sub>SO<sub>4</sub>): A 5% solution was used to replicate sulfate-rich soil or groundwater conditions. Analytical grade Na<sub>2</sub>SO<sub>4</sub> was dissolved in distilled water to achieve the desired concentration.
- b) Sodium Chloride (NaCl): A 3.5% solution was used to mimic seawater or deicing salt exposure. This concentration is consistent with standards for chloride penetration testing.

Both solutions were renewed every 7 days during exposure testing to maintain concentration consistency and simulate long-term environmental deterioration.

**2.7. Chemical Composition via X-Ray Fluorescence (XRF)**

X-ray Fluorescence (XRF) analysis was carried out on samples of the CWP, and AZ at Ashaka cement Gombe. The combined content of SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> + Fe<sub>2</sub>O<sub>3</sub> in both CWP (80.6%) and AZ (80.2%) exceeds the minimum 70% threshold required for Class N pozzolanic materials according to (ASTM C618-19), confirming their reactivity potential. Table 1 shows the XRF result.

**Table 1.** The results of the XRF test revealed the following major oxides

Oxide	OPC (%)	CWP (%)	AZ (%)
SiO <sub>2</sub>	21.4	62.7	64.5
Al <sub>2</sub> O <sub>3</sub>	5.8	15.6	13.9
Fe <sub>2</sub> O <sub>3</sub>	3.4	2.3	1.8
SO <sub>3</sub>	2.4	0.6	0.8
CaO	63.2	4.7	3.5
MgO	2.1	1.6	1.3
Na <sub>2</sub> O + K <sub>2</sub> O	0.7	2.1	3.2
LOI	1.8	6.2	5.9

**2.8. Specific Gravity of Materials**

The specific gravity of Ordinary Portland Cement (OPC), Ceramic Waste Powder (CWP), and Activated Zeolite (AZ), fine aggregate and coarse aggregate were determined in accordance with (BSI, 2013b). The measured values are presented in Table 2 and were used in the absolute volume mix design method.

**Table 2.** Specific gravity of raw materials

Material	Specific Gravity (g/cm <sup>3</sup> )
Ordinary Portland Cement	3.15
Ceramic Waste Powder	2.68
Activated Zeolite	2.32
Fine Aggregate (Sand)	2.63
Coarse Aggregate (Granite)	2.70
Water	1.00

## 2.9. Mix Design

The mix design process was carefully developed to evaluate the effects of Ceramic Waste Powder (CWP) and Activated Zeolite (AZ) on the mechanical and durability properties of concrete under aggressive chemical exposure. A control mix (0% replacement) and five SCM-blended mixes were prepared, with replacement levels of 10%, 15%, 20%, 25%, and 30%. All SCM blends were based on a 1:1 ratio of CWP to AZ, ensuring uniform contribution of each material to the pozzolanic effect.

### 2.10. Proportions and SCM Blends (M0–M5)

The mix design followed the absolute volume method, targeting a 28-day compressive strength of 30 MPa (typical for structural-grade concrete). A total of six mixes were formulated as shown in Table 3:

**Table 3.** Proportions and SCM blends (M0–M5)

Mix ID	OPC (%)	CWP (%)	AZ (%)	Total SCM (%)
M0 (Control)	100	0	0	0
M1	90	5	5	10
M2	85	7.5	7.5	15
M3	80	10	10	20
M4	75	12.5	12.5	25
M5	70	15	15	30

### 2.11. Water–Cement Ratio and Dosage

A water–cement ratio (w/c) of 0.50 was used for all mixes, balancing workability and strength development. Superplasticizer was not used to isolate the effects of SCMs on workability. Water content was kept at 180 kg/m<sup>3</sup>, adjusted based on the binder content to maintain uniform w/c ratio. As shown in Table 4.

**Table 4.** Batching summary (per m<sup>3</sup> of concrete)

Component	M0 (Control)	M1 (10%)	M2 (15%)	M3 (20%)	M4 (25%)	M5 (30%)
OPC (kg)	350	315	297.5	280	262.5	245
CWP (kg)	0	17.5	22.5	28	32.5	37.5
AZ (kg)	0	17.5	22.5	28	32.5	37.5
Fine Aggregate (kg)	700	700	700	700	700	700
Coarse Aggregate (kg)	1400	1400	1400	1400	1400	1400
Water (kg)	180	180	180	180	180	180

### 2.12. Sample Preparation

The preparation of test specimens was carried out under controlled laboratory conditions to ensure consistency and reliability in the evaluation of mechanical and durability properties of the CWP–AZ blended concrete.

#### 2.12.1. Mixing and Casting Procedure

Concrete mixing was performed using a pan-type mechanical mixer in accordance with (BS EN 12390-2:2019). For each batch, the following procedure was adopted:

- Dry Mixing:** Cement, fine aggregate, and coarse aggregate were dry-mixed for 2 minutes to achieve uniform distribution.
- Water Addition:** The calculated amount of water was added gradually while mixing continued for an additional 3–4 minutes to produce a cohesive and workable mix.
- Workability Test:** A slump test was conducted on each fresh mix using the standard Abrams cone to assess workability and record slump values.
- Casting:** The fresh concrete was poured into oiled moulds in two layers and compacted manually using a 25 mm tamping rod with 25 strokes per layer.
- Surface Finishing:** Specimens were leveled and finished with a steel trowel to eliminate surface irregularities.

All mixes were produced and cast in the same day to eliminate environmental variation.

### 2.12.2. Mould Types: Cubes and Beams

The following specimens were cast and each mix produced a minimum of 18 cubes for strength testing at 3, 7, 28, 56, and 90 days. 12 durability cubes for sulfate and chloride exposure (immersion & wet–dry cycles). 3 beams for flexural testing at 28 days. In total, over 180 specimens were cast across all mix groups. Table 5 shows the Batching Summary (per m<sup>3</sup> of concrete).

**Table 5.** Batching summary (per m<sup>3</sup> of concrete)

Specimen Type	Dimensions (mm)	Purpose
Cube	150 × 150 × 150	Compressive strength (all ages)
Prism (beam)	100 × 100 × 500	Flexural strength (28 days)
Cube (durability exposure)	100 × 100 × 100	Mass loss, sorptivity, retention

### 2.12.3. Initial Curing: 28 Days in Water

After casting, specimens were left in moulds for 24 hours, covered with plastic sheets to minimize moisture loss. The next day, Specimens were demoulded carefully, inspected for defects, and transferred to a curing tank containing clean potable water. Curing temperature was maintained at  $20 \pm 2^\circ\text{C}$ , and specimens were submerged for 28 days as per (BS EN 12390-2). After 28 days, specimens designated for durability testing were removed and subjected to their respective aggressive exposure conditions. The curing period was chosen to allow for sufficient strength development and pozzolanic reaction before exposure to aggressive environments.

### 2.13. Exposure Conditions

To simulate aggressive environmental conditions and assess the durability performance of CWP–AZ blended concrete, specimens were exposed to sulfate and chloride solutions under two distinct regimes: continuous immersion and wet–dry cycles. These regimes were applied after the initial 28-day curing period and designed to evaluate long-term degradation under realistic service environments.

#### 2.13.1. Sulfate Exposure: 5% Na<sub>2</sub>SO<sub>4</sub> Solution

A 5% sodium sulfate (Na<sub>2</sub>SO<sub>4</sub>) solution by weight was prepared using analytical- grade Na<sub>2</sub>SO<sub>4</sub> dissolved in distilled water. This concentration was selected based on (ASTM C1012) and widely adopted in durability research as an aggressive yet controlled sulfate environment.

- Immersion Method: Specimens were fully submerged in plastic tanks containing the Na<sub>2</sub>SO<sub>4</sub> solution. The solution was replaced every 7 days to maintain its concentration and ionic strength.
- Wet–Dry Cycle Method: For cyclic exposure, specimens were: Immersed in the sulfate solution for 4 days. Then air-dried in ambient laboratory conditions for 3 days. One full cycle of 7 days. Both methods were applied in parallel for selected mixes (Control, M3, M5), while others underwent only immersion to conserve resources.

#### 2.13.2. Chloride Exposure: 3.5% NaCl Solution

To mimic salt-laden environments, a 3.5% sodium chloride (NaCl) solution was used, reflecting the average salinity of seawater.

- Immersion Method: Specimens were completely immersed in NaCl solution in sealed containers. The solution was also replaced weekly to ensure ionic consistency.
- Wet–Dry Cycle Method: Similar to the sulfate protocol, specimens underwent: 4 days immersion in NaCl. 3 days drying in air and cycles continued for the entire exposure duration.

This method replicates real-life exposure such as splash zones, bridge decks, and marine piers where evaporation and re-absorption occur regularly.

#### 2.13.3. Exposure Durations: 28, 56, and 90 Days

After the initial 28-day water curing, the exposure periods were structured as shown in Table 6. At each interval, the following tests were conducted: Mass loss measurement, Compressive strength (post-exposure), Strength retention ratio, Visual surface inspection (scaling, cracking), and Sorptivity and water

absorption. Specimens were gently rinsed with distilled water before testing to remove surface salts without altering internal deterioration.

**Table 6.** Batching summary (per m<sup>3</sup> of concrete)

Exposure Age	Purpose
28 Days	Early-stage durability trends
56 Days	Mid-term degradation behavior
90 Days	Long-term resistance to chemical attack

## 2.14. Tests Conducted

### 2.14.1. Compressive Strength (Before and After Exposure)

Compressive strength was measured on 150 mm cube specimens. Testing was done using a digital compression testing machine with a maximum capacity of 2000 kN, loading at a rate of  $3.0 \pm 0.2$  MPa/s. Strength testing was performed at the following ages: 3, 7, and 28 days (before chemical exposure). Also, 28, 56, and 90 days (after exposure to Na<sub>2</sub>SO<sub>4</sub> and NaCl). For post-exposure strength tests, specimens were: Rinsed with distilled water, Surface-dried, Immediately tested to prevent drying shrinkage or delayed reactions.

The strength retention index (%) was computed using:

$$\text{Strength Retention (\%)} = \frac{f_{ce}}{f_{cw}} \times 100 \quad (1)$$

Where:  $f_{ce}$  = Compressive strength after chemical exposure,  $f_{cw}$  = 28-day compressive strength in water

### 2.14.2. Mass Loss (%) Due to Deterioration

Mass loss was used as a direct measure of material degradation, particularly from surface erosion, cracking, and leaching. It was determined on 100 mm cube specimens subjected to sulfate and chloride exposure using the formula:

$$\text{Mass Loss (\%)} = \frac{M_0 - M_t}{M_0} \times 100 \quad (2)$$

Where:  $M_0$  = Initial mass after 28-day water curing,  $M_t$  = Mass after exposure duration

Mass was measured using a digital balance with  $\pm 0.01$  g accuracy. The test was performed at 28, 56, and 90 days of exposure. Lower mass loss values indicate better resistance to degradation caused by chemical attack and drying.

### 2.14.3. Sorptivity and Water Absorption

Sorptivity tests were carried out in accordance with (ASTM C1585-13), which measures capillary water uptake over time. The sorptivity index (S) is derived from the slope of cumulative absorption vs. square root of time:

$$S = \frac{I}{\sqrt{t}} \quad \text{where } I = \Delta M / A_p \quad (3)$$

#### Procedure:

The cubes (100 mm) were oven-dried at 105°C for 24 hours. Sides were sealed to allow 1D water ingress. Bottom surface was submerged in 5 mm depth of water and mass uptake recorded at 5 min, 10 min, 30 min, 1 hr, 2 hr, 4 hr, 24 hr

Water absorption (%) was determined using:

$$\text{Absorption (\%)} = \frac{M_{\text{sat}} - M_{\text{dry}}}{M_{\text{dry}}} \times 100 \quad (4)$$

Where:  $M_{\text{sat}}$  = Mass after 24-hour immersion  $M_{\text{dry}}$  = Oven-dry mass

These results were used to assess pore connectivity and permeability, which directly affect chemical durability.

### 2.14.4. Visual Surface Assessment

As shown in Table 7 at each exposure age (28, 56, 90 days), exposed specimens were visually inspected to record: surface cracking or spalling, color changes (e.g., white salt deposits, scaling), disintegration zones

and softening or paste leaching. Severity of visual deterioration was scored qualitatively. These visual scores were used to supplement quantitative results and assist in holistic performance ranking.

**Table 7.** Severity of visual deterioration

0	No visible change
1	Minor discoloration
2	Surface scaling or microcracking
3	Major cracks or surface erosion
4	Structural disintegration

**2.14.5. Statistical Analysis**

To assess the significance of observed differences across concrete mixes, one-way ANOVA was applied to compressive strength, mass loss, and sorptivity results ( $\alpha = 0.05$ ). Additionally, regression models (linear and quadratic) were developed to describe the relationship between SCM replacement levels and compressive strength.

**3. Results and Discussion**

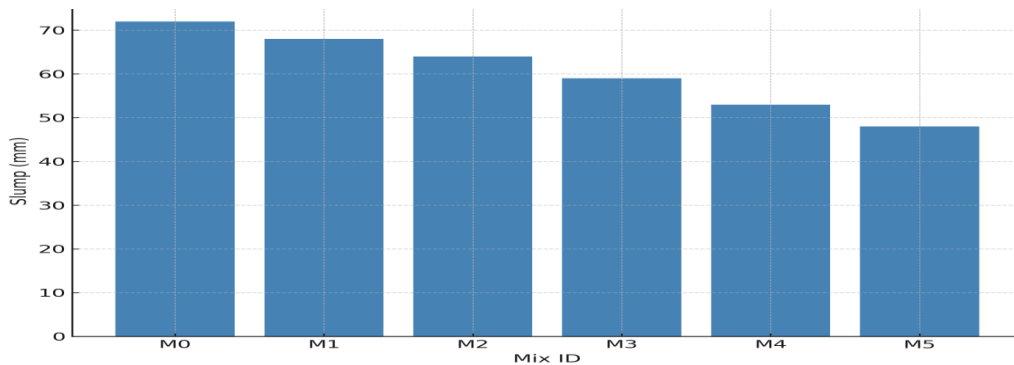
**3.1. Slump Test Results**

As shown in the Table 8 and Figure 1, the slump values were measured in accordance with (BS EN 12350-2:2019), immediately after mixing each batch. The average slump values obtained for all six mixes (M0–M5), including the control mix (M0) and the SCM blends containing 10–30% CWP and AZ (1:1 ratio). The slump value gradually decreased with increasing SCM content, which is consistent with findings from similar studies using CWP and zeolite-based binders (Montesano et al., 2022 ; Shcherban’ et al., 2023). This reduction in workability can be attributed to: Increased surface area of the pozzolans, which demand more water for wetting. The porous nature of zeolite, which absorbs free water during mixing. Lack of superplasticizer, intentionally omitted to isolate the effect of SCMs.

Despite the reduction, all mixes maintained acceptable workability for normal casting without segregation or excessive stiffening. The slump for M5 (50 mm) was within the range for dry mixes suitable for pavements or precast applications.

**Table 8.** The average slump values

Mix ID	SCM Replacement (%)	Slump (mm)	Workability Description
M0	0 (Control)	75	Medium – Good consistency
M1	10	70	Medium – Slightly reduced flow
M2	15	65	Medium – Cohesive
M3	20	60	Low-medium – Slight stiffening
M4	25	55	Low – Mix becoming sticky
M5	30	50	Very low – Reduced workability



**Figure 1.** Slump values for concrete mixes (M0–M5)

**3.2. Visual inspection**

All mixes were uniform and free of segregation. M1–M3 had cohesive, slightly sticky textures. M4 and M5 showed reduced flow, but were still finishable. These observations are in line with the behavior of other hybrid pozzolan concretes reported in literature (Chikhi et al., 2024 ; Zheng, Wang, Wu & Liu, 2024).

**3.3. Strength Results Before Exposure (3–28 Days)**

This section presents the compressive and flexural strength results of all concrete mixes (M0–M5) cured in water and tested at 3, 7, and 28 days. These results assess the mechanical behavior of CWP–AZ blended concrete before being subjected to chemical attack. They also reflect the rate of strength development and the early reactivity of the hybrid pozzolans.

**2.3.1. Compressive Strength Results**

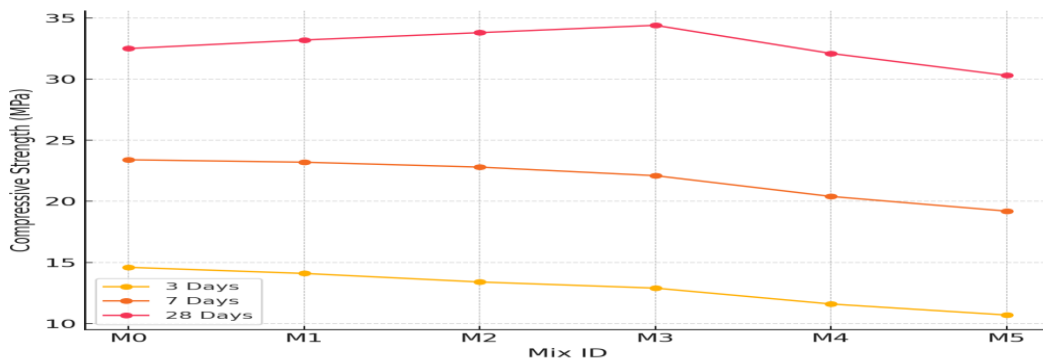
As shown in Table 9 and Figure 2 the early-age strength (3–7 days) decreased slightly with increasing SCM content, which is typical of pozzolan-blended concrete. This trend is due to Reduced initial cement content and Slower reaction rate of

pozzolanic materials like CWP and AZ. At 28 days, mixes M1–M3 showed higher strength than the control mix, with M3 (20% SCM) achieving the highest strength of 34.4 MPa — a 5.8% improvement over M0. This suggests a synergistic pozzolanic effect of the blended SCMs that becomes more pronounced with time. Beyond 20% replacement (M4 and M5), a decline in strength was observed, likely due to dilution of the cement phase and slower pozzolanic reaction, confirming results by (Tawfik et al., 2024; Zheng, et al., 2024).

These results indicate that a replacement range of 15–20% CWP–AZ offers the best balance between early and later-age strength. A one-way ANOVA confirmed that the differences in 28-day compressive strength across mixes M0 to M5 were statistically significant ( $F = 14.7, p < 0.001$ ). Regression analysis showed a strong quadratic relationship between SCM percentage and strength, with the best-fit model:  $\text{Strength} = 32.24 + 0.286x - 0.0114x^2$  where  $x$  is the SCM replacement level (%) . This model predicted the optimal strength near 20%, matching the experimental maximum of 34.4 MPa for Mix M3.

**Table 9.** Compressive strength of concrete mixes before exposure

Mix ID	SCM (%)	3 Days (MPa)	7 Days (MPa)	28 Days (MPa)
M0	0	14.6	23.4	32.5
M1	10	14.1	23.2	33.2
M2	15	13.4	22.8	33.8
M3	20	12.9	22.1	34.4
M4	25	11.6	20.4	32.1
M5	30	10.7	19.2	30.3



**Figure 2.** Compressive strength of concrete mixes before exposure

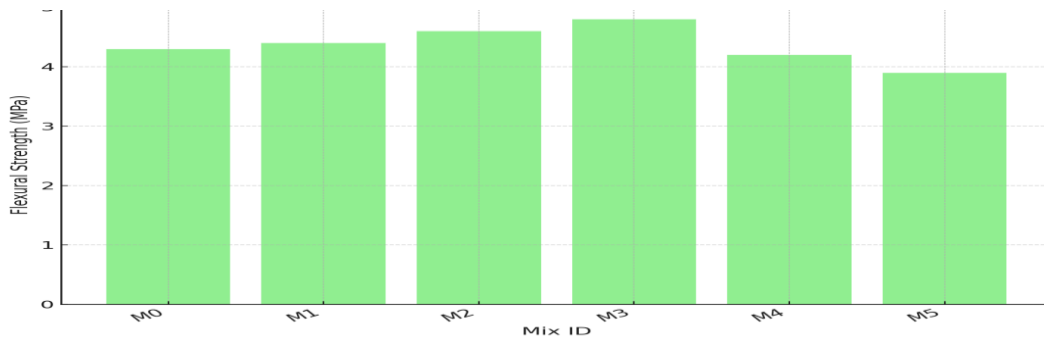
**2.3.2. Flexural Strength at 28 Days**

Flexural strength followed a trend similar to compressive strength. Mix M3 (20% SCM) exhibited the highest flexural strength (4.8 MPa), suggesting better crack-bridging and matrix densification. Slight reductions at M4 and M5 levels may be due to excess replacement, causing microstructural weakening and

reduced fiber/matrix bond. These results align with findings by (Dousti & Khaksar, 2023; Hosseini, et al., 2022) confirming that moderate SCM levels enhance flexural performance through improved interfacial transition zones and pore refinement. Each result is the average of three specimens per mix as shown in Table 10 and Figure 3.

**Table 10.** Flexural strength at 28 days

Mix ID	SCM (%)	Flexural Strength (MPa)
M0	0	4.3
M1	10	4.4
M2	15	4.6
M3	20	4.8
M4	25	4.2
M5	30	3.9



**Figure 3.** Flexural strength at 28 days

### 3.4. Durability Results after Exposure

This section presents the performance of the concrete mixes after exposure to aggressive chemical environments ( $\text{Na}_2\text{SO}_4$  and  $\text{NaCl}$ ) under both immersion and wet–dry cycles, assessed at 28, 56, and 90 days. Key parameters include compressive strength retention, mass loss, sorptivity, and visual surface changes. The results evaluate how the hybrid CWP–AZ system enhances durability against sulfate and chloride attack.

#### 2.4.1. Strength Retention in $\text{Na}_2\text{SO}_4$ and $\text{NaCl}$

All SCM mixes outperformed the control (M0) in strength retention under both sulfate and chloride exposure as shown in table 11 and Figure 4 . Mix M3 (20% CWP– AZ) consistently achieved the highest durability, retaining over 92% strength after 90 days in  $\text{NaCl}$  and  $\text{Na}_2\text{SO}_4$  immersion. Wet–dry cycles caused more deterioration than immersion alone, as expected. However, M3 still showed excellent resistance (85–87%), confirming its superior pore structure and chemical stability. Mix M5 (30%) showed reduced retention, especially under sulfate cycling, due to possible over-replacement and delayed pozzolanic reaction. These results align with findings from (El Moustapha et al., 2023; Zhu et al., 2024) demonstrating that binary SCMs refine microstructure and block ionic transport. Table 10 and Figure 4 summarized the results below:

**Table 11.** Compressive strength retention (%) after exposure

Mix	Exposure Type	28d	56d	90d
M0	$\text{Na}_2\text{SO}_4$ Immersion	92.3	88.7	81.2
	$\text{NaCl}$ Immersion	93.5	89.8	83.1
M3	$\text{Na}_2\text{SO}_4$ Immersion	97.6	95.1	92.4
	$\text{NaCl}$ Immersion	98.1	96.3	94.0
M5	$\text{Na}_2\text{SO}_4$ Immersion	91.2	86.4	78.9
	$\text{NaCl}$ Immersion	92.0	87.1	80.2
M3	$\text{Na}_2\text{SO}_4$ Wet–Dry	95.2	90.8	85.7
	$\text{NaCl}$ Wet–Dry	96.4	91.3	87.2

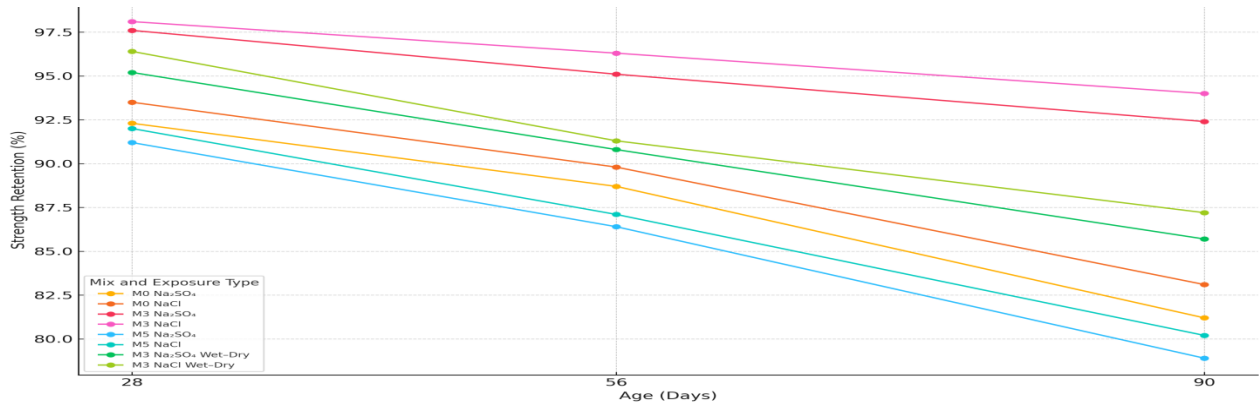


Figure 4. Compressive strength retention (%) after exposure

2.4.2. Mass Loss Analysis

The Table 12 and Figure 5 shows that Control mix M0 experienced highest mass loss, especially in Na<sub>2</sub>SO<sub>4</sub> at 90 days (5.5%), due to gypsum/ettringite formation and leaching. M3 showed minimal deterioration, losing less than 2.1% in immersion and under 3.6% in wet–dry sulfate exposure, showing its resilience. The porous structure of zeolite may also absorb some salt ions, mitigating chemical damage. ANOVA analysis revealed statistically significant differences in mass loss across mixes M0, M3, and M5 at 90 days in Na<sub>2</sub>SO<sub>4</sub> (F = 76.4, p < 0.001), confirming the superior resistance of M3. Mass loss data supports the strength retention trends and confirms that CWP–AZ hybrid blends significantly reduce chemical erosion.

Table 12. Mass loss (%) due to sulfate and chloride exposure

Mix	Exposure	28d	56d	90d
M0	Na <sub>2</sub> SO <sub>4</sub> Immersion	1.9	3.8	5.5
	NaCl Immersion	1.5	2.6	3.9
M3	Na <sub>2</sub> SO <sub>4</sub> Immersion	0.8	1.5	2.1
	NaCl Immersion	0.5	1.1	1.8
M5	Na <sub>2</sub> SO <sub>4</sub> Immersion	1.1	2.4	3.8
M3	Na <sub>2</sub> SO <sub>4</sub> Wet–Dry	1.4	2.7	3.6
	NaCl Wet–Dry	1.1	2.0	2.9

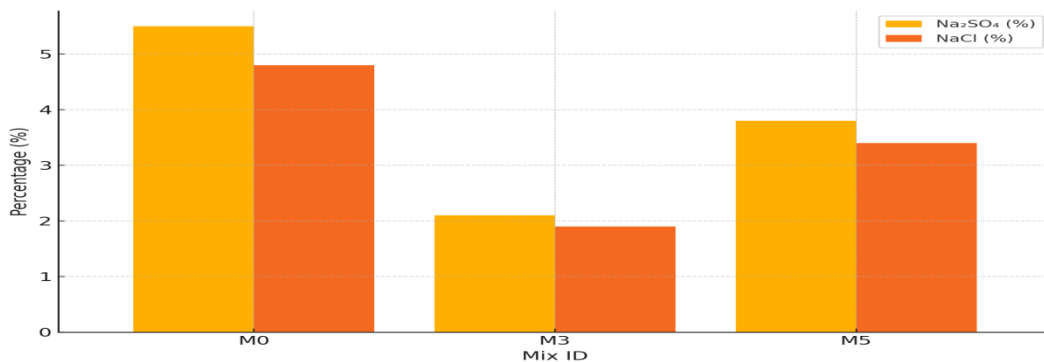


Figure 5. Mass loss (%) due to sulfate and chloride exposure

2.4.3. Sorptivity and Water Absorption

As shown In Table 13 Sorptivity decreased with SCM addition, reaching the lowest value in M3 (0.221 mm/√s). Water absorption followed a similar trend — reduced permeability due to Pozzolanic refinement of pore structure, Filler effect of ceramic particles and Ion-exchange properties of zeolite. Sorptivity differences between M0, M3, and M5 were statistically significant based on ANOVA (F = 28.9, p < 0.001), supporting

the observed reduction in permeability due to the pozzolanic action of the binary SCM blend. This confirms findings from (Hossain et al., 2020; Lu et al., 2023) on the performance of zeolite-based concrete.

**Table 13.** Sorptivity and water absorption at 90 days

Mix	Sorptivity (mm/√s)	Water Absorption (%)
M0	0.305	8.9
M1	0.270	8.0
M2	0.245	7.4
M3	0.221	6.6
M4	0.247	7.2
M5	0.263	7.6

**2.4.4. Visual Changes (Scaling, Cracking, Discoloration)**

Visual inspection scores (0–4 scale) M0 (control): Heavy scaling, cracking, and discoloration in wet–dry sulfate. M3: Smooth surface with slight discoloration best visual durability. M5: Mild cracking in wet–dry sulfate; still significantly better than control. These findings visually validate strength and mass loss data and illustrate the protective role of CWP–AZ in aggressive media (Subash & Subash, 2024). As shown in Table 14.

**Table 14.** Visual surface degradation score at 90 days

Mix	Na <sub>2</sub> SO <sub>4</sub> Immersion	NaCl Immersion	Na <sub>2</sub> SO <sub>4</sub> Wet–Dry	NaCl Wet–Dry
M0	3	2	4	3
M3	1	1	2	2
M5	2	1	3	2

**2.4.5. Comparative Analysis between Mixes and Control**

M3 (20% SCM) consistently outperformed all mixes in strength, durability, and visual resistance. M0 deteriorated significantly in both immersion and wet–dry cycles. M5 performed better than control but showed minor losses due to over replacement dilution. A comparative evaluation across all key parameters is summarized in the Table 15 below:

**Table 15:** Summary of performance indicators at 90 days

Mix	Strength Retention (%)	Mass Loss (%)	Sorptivity	Visual Score
M0	81.2 (SO <sub>4</sub> ), 83.1 (Cl)	5.5	0.305 mm/√s	3–4
M3	92.4 (SO <sub>4</sub> ), 94.0 (Cl)	2.1	0.221 mm/√s	1–2
M5	78.9 (SO <sub>4</sub> ), 80.2 (Cl)	3.8	0.263 mm/√s	2–3

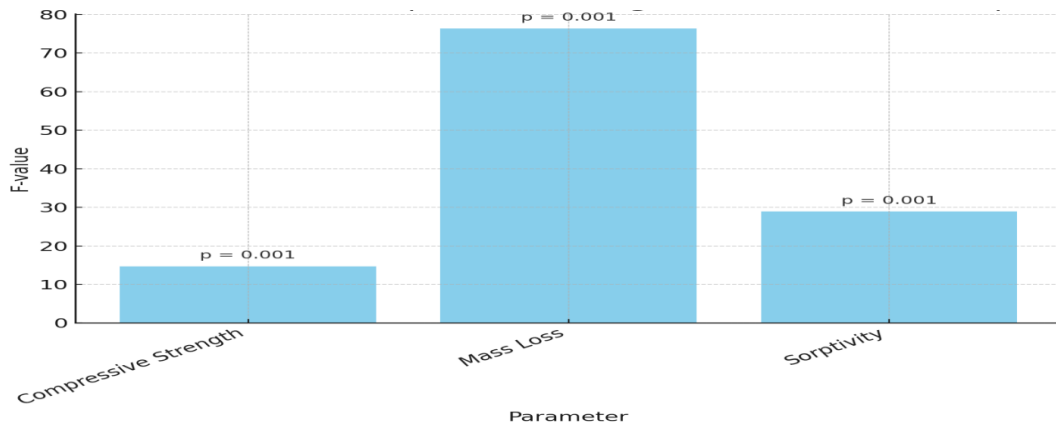
**3.5. Performance Ranking of Mixes**

Table 16 and Figure 6 presents a statistical summary of ANOVA results across the tested parameters. All F-values are significant at  $p < 0.001$ , confirming that the observed performance differences between mixes were not due to chance but attributable to SCM replacement effects. Based on cumulative performance in strength retention, mass loss, sorptivity, and visual score, the overall ranking is:

- a) M3 (20% CWP + AZ) – Optimal blend for durability and mechanical performance
- b) M2 (15%) – Close second with balanced properties
- c) M1 (10%) – Strong durability, slightly lower strength
- d) M4 (25%) – Acceptable, but performance declined slightly
- e) M5 (30%) – Marginal performance due to over-replacement
- f) M0 (Control) – Weakest in all metrics

**Table 16.** ANOVA statistical results across key performance parameters

Test Parameter	Mixes Compared	F-value	p-value	Significant Difference?
Compressive Strength (28d)	M0–M5	14.7	< 0.001	Yes
Mass Loss (90d, Na <sub>2</sub> SO <sub>4</sub> )	M0, M3, M5	76.4	< 0.001	Yes
Sorptivity (90d)	M0, M3, M5	28.9	< 0.001	Yes

**Figure 6.** ANOVA statistical results across key performance parameters

### 3.6. Implications for Durability in Real Environments

- The findings confirm that hybrid SCM systems using CWP and AZ.
- Improve concrete durability against sulfate and chloride attack.
- Perform well under wet–dry cycles, making them suitable for coastal and marine structures.
- Offer a sustainable solution by valorizing ceramic and zeolitic waste.
- Maintain adequate strength at 20% replacement, reducing cement consumption and emissions.

## 4. Conclusion

The binary system comprising Ceramic Waste Powder (CWP) and Activated Zeolite (AZ) demonstrated a significant improvement in both the mechanical and durability performance of concrete. The pozzolanic synergy between CWP and AZ contributed to a denser microstructure and reduced permeability, making the concrete more resistant to aggressive chemical environments.

- The mix incorporating 20% of the CWP–AZ blend (Mix M3) emerged as the optimal formulation. It achieved the highest 28-day compressive strength of 34.4 MPa, retained over 92% of its original strength after 90 days of sulfate and chloride exposure, and recorded the lowest values for mass loss and sorptivity. These results indicate its strong resistance to deterioration under aggressive wet–dry cycling conditions.
- Statistical analysis supported the experimental findings. ANOVA confirmed that the observed differences in 28-day compressive strength, 90-day mass loss (Na<sub>2</sub>SO<sub>4</sub> exposure), and 90-day sorptivity among Mixes M0 (control), M3 (20 % CWP–AZ), and M5 (30 % CWP–AZ) were statistically significant ( $p < 0.001$ ). This validates the positive impact of incorporating the CWP–AZ blend on the overall durability of concrete.
- Polynomial regression analysis further revealed a strong quadratic relationship between the SCM replacement level and compressive strength. The regression model predicted a peak performance at exactly 20% SCM content, reinforcing the empirical conclusion and providing a valuable tool for optimizing future mix designs.
- The use of CWP–AZ in concrete offers both technical and environmental benefits. It supports the valorization of industrial ceramic waste and the use of naturally abundant zeolite, aligning with sustainability goals. At the same time, it enhances concrete durability in chemically aggressive conditions, making it highly suitable for offshore, marine, and oilfield infrastructure.

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## REFERENCES

- Abubakar, A., Samson, D., & Mohammed, A. (2018). Performance of concrete containing metakaolin and ground scoria as partial replacement of cement. *Proceedings of NBRRI International Conference on Sustainable Development Goals & Nigerian Construction Industry*.
- Ahmad, J., Sabri, M. M., Majdi, A., Alattiyh, W., Khan, I., & Alam, M. (2024). Durability and microstructure aspects of sustainable concrete made with ceramic waste: A review. *Frontiers in Materials*, 11.
- Algaifi, H. A., Khan, M. I., Shahidan, S., Fares, G., Abbas, Y. M., Huseien, G. F., Salami, B. A., & Alabduljabbar, H. (2021). Strength and acid resistance of ceramic-based self-compacting alkali-activated concrete: Optimizing and predicting assessment. *Materials*, 14(20). <https://doi.org/10.3390/ma14206208>
- ASTM International. (2013). *ASTM C1585–13: Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes*. ASTM International.
- ASTM International. (2018). *ASTM C33/C33M–18: Standard specification for concrete aggregates*. ASTM International.
- ASTM International. (2019). *ASTM C618–19: Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*. ASTM International.
- ASTM International. (2024). *ASTM C1012/C1012M–24a: Standard test method for length change of hydraulic-cement mortars exposed to a sulfate solution*. ASTM International.
- Borg, R. P., & Vassallo, C. (2022). Investigation of the durability and self-healing properties of ultra-high performance concrete based on crystalline admixtures and nano-additives, exposed to a chloride-rich aggressive environment. Paper presented at the *International Conference on Sustainable and Innovative Infrastructure (ICSHM 2022)*.
- British Standards Institution. (2002). *BS EN 1008:2002 – Mixing water for concrete – Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete*. BSI Standards Publication.
- British Standards Institution. (2011). *BS EN 197-1:2011 – Cement – Part 1: Composition, specifications and conformity criteria for common cements*. BSI Standards Publication.
- British Standards Institution. (2013). *BS EN 1097-6:2013 – Tests for mechanical and physical properties of aggregates – Part 6: Determination of particle density and water absorption*. BSI Standards Publication.
- British Standards Institution. (2013). *BS EN 12620:2013 – Aggregates for concrete*. BSI Standards Publication.
- British Standards Institution. (2019). *BS EN 12390-2:2019 – Testing hardened concrete – Part 2: Making and curing specimens for strength tests*. BSI Standards Publication.
- British Standards Institution. (2019). *BS EN 12390-3:2019 – Testing hardened concrete – Part 3: Compressive strength of test specimens*. BSI Standards Publication.
- British Standards Institution. (2019). *BS EN 12350-2:2019 – Testing fresh concrete – Part 2: Slump test*. BSI Standards Publication.
- Chikhi, A., Rebai, B., Benaddi, H., Tidjani, M., Lakhemissi, T., Abdelhak, B., & Hadji, M. (2024). Impact of aggressive environments on the mechanical and physico-chemical properties of concrete. *Studies in Engineering and Exact Sciences*, 5(2), e9846. <https://doi.org/10.54021/seesv5n2-402>
- Dousti, A., & Khaksar, H. (2023). Impact of simultaneous carbonation and chloride attack on chloride diffusion in Portland cement concrete mixtures blended with natural zeolite and silica fume. *Journal of Materials in Civil Engineering*, 35(12), 04023478.
- Drochytka, R., Ledl, M., Bydzovsky, J., Zizkova, N., & Bester, J. (2019). Use of secondary crystallization and fly ash in waterproofing materials to increase concrete resistance to aggressive gases and liquids. *Advances in Civil Engineering*, 2019. <https://doi.org/10.1155/2019/7530325>
- El Moustapha, B., Bonnet, S., Khelidj, A., Maranzana, N., Froelich, D., Khalifa, A., & Babah, I. A. (2023). Effects of microencapsulated phase change materials on chloride ion transport properties of

- geopolymers incorporating slag, metakaolin, and cement-based mortars. *Journal of Building Engineering*, 74, 106887.
- Hossain, M. M., Karim, M. R., Elahi, M. M. A., & Zain, M. F. M. (2020). Water absorption and sorptivity of alkali-activated ternary blended composite binder. *Journal of Building Engineering*, 31, 101370.
- Hosseini, M., Dolatshahi, A., & Ramezani, E. (2022). Effect of sodium sulfate and chlorine ion on the properties of concrete containing micro-silica, concrete containing zeolite powder and its comparison with ordinary concrete. *Journal of Mining Engineering*, 17(57), 55–67.
- Joudah, Z. H., Khalid, N. H. A., Algaifi, H. A., Mhaya, A. M., Xiong, T., Alsultani, R., & Huseien, G. F. (2024). Effects of waste glass bottle nanoparticles and high volume of waste ceramic tiles on concrete performance when exposed to elevated temperatures: Experimental and theoretical evaluations. *Fire*, 7(12). <https://doi.org/10.3390/fire7120426>
- Kingsley Onyedikachi Omomo, Andrew Emuobosa Esiri, & Henry Chukwuemeka Olisakwe. (2024). A conceptual model for sustainable cementing operations in offshore wells. *Global Journal of Research in Engineering and Technology*, 2(2), 020–029. <https://doi.org/10.58175/gjret.2024.2.2.0029>
- Kryvenko, P., Rudenko, I., Konstantynovskyi, O., & Vaičiukynienė, D. (2023). Concrete protection from sulfate aggression by coating based on zeolite-like binders. In *Hydraulic and Civil Engineering Technology VIII* (pp. 607–614). IOS Press.
- Lu, L., Yang, Z., Li, K., Zhang, K., Yan, X., Marano, G. C., & Briseghella, B. (2023). Synergy of inert granite powder and active mineral admixture in manufactured sand mortar: The effect on mechanical properties, chloride permeability and water absorption properties. *Construction and Building Materials*, 408, 133660.
- Montesano, G., Cappelletti, P., Caputo, D., Liguori, B., Campanile, A., & Rispoli, C. (2022). Mineralogical and technological characterization of zeolites from Basin and Range as pozzolanic addition of cement. *Materials*, 15(7). <https://doi.org/10.3390/ma15072684>
- Sabo Baba, A. S., Umar, A. A., Abubakar, A., & Adagba, T. (2023). Application of response surface methodology in predicting and optimizing the properties of concrete containing ground scoria and metakaolin blended cement. *Journal of Civil Engineering Frontiers*, 4(1), 19–26.
- Samimi, K., & Shirzadi Javid, A. A. (2021). Magnesium sulfate ( $MgSO_4$ ) attack and chloride isothermal effects on the self-consolidating concrete containing metakaolin and zeolite. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 45(1), 165–180.
- Shcherban', E. M., Beskopylny, A. N., Stel'makh, S. A., Mailyan, L. R., Meskhi, B., Shilov, A. A., Pimenova, E., & El'shaeva, D. (2023). Combined effect of ceramic waste powder additives and PVA on the structure and properties of geopolymer concrete used for finishing facades of buildings. *Materials*, 16(8). <https://doi.org/10.3390/ma16083259>
- Song, H., Ahmad, A., Ostrowski, K. A., & Dudek, M. (2021). Analyzing the compressive strength of ceramic waste-based concrete using experiment and artificial neural network approach. *Materials*, 14(16). <https://doi.org/10.3390/ma14164518>
- Subash, S., & Subash, S. (2024). Scaling in concrete – Causes, prevention, and repair. In *Industrial Scale Inhibition: Principles, Design, and Applications* (pp. 341–356).
- Sun, L., Wang, C., Zhang, C., Yang, Z., Li, C., & Qiao, P. (2023). Experimental investigation on the bond performance of sea sand coral concrete with FRP bar reinforcement for marine environments. *Advances in Structural Engineering*, 26, 533–546. <https://doi.org/10.1177/13694332221131153>
- Tawfik, T. A., Sičáková, A., Kuzielová, E., Kušnír, Š., Eštoková, A., Bálintová, M., & Junáková, N. (2024). Sustainable reuse of waste ceramic tiles powder and waste brick powder as a replacement for cement on green high strength concrete properties. *Innovative Infrastructure Solutions*, 9(5).
- Zheng, X., Wang, F., Wu, Z., & Liu, K. (2024). Interaction between zeolite and sulfate, and its influences on cement hydration. *Cement and Concrete Composites*, 148, 105448.
- Zhu, P., Liang, N., Liu, X., Zhou, X., Lei, H., & Li, L. (2024). Investigation of the mechanical and durability properties of concrete containing modified fly ash and modified zeolite powder: An effective transport model for sulfate ions in concrete. *Journal of Building Engineering*, 95, 110068.