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ORIGINAL ARTICLE

Sulfate Resistance of Green Concrete Incorporating Ceramic Waste Powder and Sugarcane Bagasse Ash

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ABSTRACT – This study investigates the sulfate resistance of green concrete incorporating ceramic waste powder (CWP) and sugarcane bagasse ash (SCBA) as supplementary cementitious materials. The objective was to evaluate the impact of binary CWP–SCBA replacements on the durability and mechanical performance of concrete subjected to prolonged sulfate exposure. Six concrete mixes were developed with varying replacement levels (0–30%) by total binder weight. The experimental program assessed workability, compressive strength, mass change, and strength retention of specimens exposed to a 5% sodium sulfate solution for up to 90 days. The results showed that incorporating CWP and SCBA slightly reduced slump and density but significantly enhanced sulfate resistance compared to the control. The mix containing 15% SCBA and 5% CWP (M5) achieved the lowest mass loss and the highest strength retention (80.3%) after 90 days. This improvement was attributed to the pozzolanic activity and filler effects, which refined the microstructure and reduced permeability. These findings demonstrate that the combined use of ceramic and agricultural waste can improve concrete durability in sulfate-rich environments, supporting sustainable construction and waste valorization. The study recommends the partial replacement of Portland cement with CWP and SCBA as a viable and eco-friendly approach for enhancing concrete longevity in aggressive conditions.

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1.0 INTRODUCTION

The global cement sector accounts for approximately 8% of anthropogenic CO_2emissions, chiefly attributed to limestone calcination and the energy-demanding clinker production process [1]. In response, there has been anincreasing transition towards sustainable techniques in concrete production by partially substituting ordinary Portland cement (OPC) with supplementary cementitious materials (SCMs) sourced from industrial and agricultural waste [2],[3]. These technologies not only mitigate environmental effects but also improve durability in harsh weather conditions [4].

Ceramic waste powder (CWP), a byproduct of the ceramic production and building sectors, is predominantly composed of silica and alumina. When finely ground, it demonstrates pozzolanic activity and can serve as a partial replacement for Ordinary Portland Cement (OPC) [5], [6]. Multiple studies have shown that the inclusion of CWP improves microstructural refinement, decreases permeability, and aids in the formation of long-term strength in concrete [7], [8]. Sugarcane bagasse ash (SCBA), an agricultural byproduct produced from the incineration of sugarcane pulp in boilers, is a promising supplementary cementitious material (SCM). SCBA, abundant in amorphous silica, has been documented to enhance mechanical qualities and reduce harmful chemical reactions in concrete [8], [9]. When utilized in suitable amounts, SCBA can improve the sulphate resistance of concrete by diminishing free calcium hydroxide and optimizing the pore structure [10].

Sulfate attack is a significant type of chemical degradation that impacts concrete structures subjected to sulfate-laden environments, such as coastal areas, saline soils, and wastewater systems. Sulphate ions interact with calcium hydroxide and aluminate phases in cement paste, resulting in the formation of expansive compounds, including gypsum and ettringite, which cause cracking, scaling, and deterioration of mechanical integrity [11], [12]. Enhancing sulphate resistance is essential for guaranteeing the durability of infrastructure in harsh service environments

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Prior studies indicate that incorporating pozzolanic materials, including y ash, metakaolin, and rice husk ash, mitigates sulfate-induced deterioration by restricting calcium hydroxide availability and enhancing matrix density [13], [14]. Blended cements, including those with dual or multiple supplementary cementitious materials (SCMs), exhibit improved performance attributed to synergistic pozzolanic reactions [15]. Nonetheless, few studies have investigated the synergistic effects of ceramic and agricultural waste powders—specifically ceramic waste powder (CWP) and sugarcane bagasse ash (SCBA) —on sulphate resistance and long-term durability [16], [17]. Furthermore, although current studies predominantly examine compressive strength and permeability, factors like mass alteration and strength preservation following prolonged sulphate exposure remain insufficiently explored [18], [19]. These characteristics are essential indications of chemical stability and longevity over time.

This study aims to assess the sulfate resistance of green concrete formulated using binary mixes of ceramic waste powder and sugarcane bagasse ash. The precise objectives encompass assessing the workability, Density, compressive strength, mass variation, and strength retention of concrete mixtures exposed to sodium sulphate during periods of 28, 56, and 90 days. The research seeks to enhance sustainable construction methods by utilizing industrial and agricultural waste, hence increasing the longevity of concrete structures in sulfate-rich regions.

2.0 Materials

2.1 Cement

Ordinary Portland cement (OPC) conforming to BS EN 197-1:2011 [20] was used as the primary binder. It had a specific gravity of 3.14 and a Blaine fineness of 340 m²/kg.

2.2 Ceramic Waste Powder (CWP)

The ceramic waste powder was obtained from discarded tiles and sanitary ware collected from construction and demolition sites in Katsina State, Nigeria. The material was crushed and ground using a Los Angeles abrasion machine, and then sieved through a 75 µm mesh. The CWP exhibited pozzolanic characteristics with a specific gravity of 2.62 and high silica and alumina content, meeting the minimum requirements of BS EN 450-1:2012 [21].

2.3 Sugarcane Bagasse Ash (Scba)

Sugarcane bagasse ash was sourced from a local sugar mill where sugarcane residues are burned to generate steam. The ash was calcined at 600°C for 2 hours and sieved through a 75 µm mesh. Its chemical composition confirmed a high amorphous silica content, making it suitable for pozzolanic use. The specific gravity was 2.38.

2.4 Fine and Coarse Aggregates

Natural river sand with a fineness modulus of 2.78 was used as the ne aggregate, conforming to BS EN 12620:2013 [22]—crushed granite with a maximum size of 20 mm served as the coarse aggregate. The aggregates were free from deleterious substances and tested for bulk Density, moisture content, and water absorption.

2.5 Water

Potable tap water, free of organic and inorganic impurities, was used for mixing and curing in accordance with BS EN 1008:2002 [23].

3.0 Mix Proportions

Six concrete mixtures were formulated: one control mixture (M0) comprising 100% Ordinary Portland Cement (OPC), and five modified mixtures adding binary blends of Ceramic Waste Powder

(CWP) and Sugarcane Bagasse Ash (SCBA) at total cement replacement levels of 10%, 20%, and 30% by binder weight. The mix design adhered to the Department of Environment (DOE) approach [24], aiming for a 28-day compressive strength of 25 MPa with a water-cement ratio of 0.45. Table 1 delineates the proportions of the control mix.

Table 1: The mix ratio (by weight) for the control batch

Material	**Quantity (kg/m³)**
Cement (OPC)	400
Fine Aggregate	720
Coarse Aggregate	1100
Water	180
Water/Cement Ratio	0.45

While a 1:1 CWP–SCBA ratio was used in most modified mixes, variations were introduced in M4 (CWP-rich) and M5 (SCBA-rich) to study the effect of dominant pozzolan type on performance. These variations are outlined in Table 2.

Table 2: Replacement level

Mix ID	**% OPC**	**% CWP**	**% SCBA**	**Description**
M0	100	0	0	Control mix (no replacement)
M1	90	5	5	10% total replacement
M2	80	10	10	20% total replacement
M3	70	15	15	30% total replacement
M4	80	15	5	CWP-rich blend (20% total)
M5	80	5	15	SCBA-rich blend (20% total)

4.0. MIXING AND CASTING PROCEDURE

All dry ingredients were combined in a rotary drum mixer, after which water was added incrementally, followed by five minutes of mixing. Fresh concrete underwent slump and density testing prior to being cast into 100 mm cube molds in two layers. Manual tamping was used to ensure proper compaction. Specimens were removed from their molds after 24 hours and immersed in water at 25 ± 2°C until testing.

5.0 TESTING PROCEDURES

5.1. Slump and Density

Workability was assessed using the slump test confirm to (ASTM C143)[25].Fresh Density was determined in accordance with (ASTM C138) [26].

5.2. Compressive Strength

Compressive strength tests were performed on 100 mm cubes at 7, 28, and 90 days using BS EN 12390-3:2019 [27]. Three specimens per mix were tested.

5.3 Sulfate Exposure and Durability Testing

After 28 days of water curing, selected specimens were immersed in 5% sodium sulfate (Na_2SO_4) solution to simulate sulfate attack. Durability performance was assessed in accordance with BS EN 12390-13:2013 [28], focusing on mass change and strength retention at 28, 56, and 90 days.

5.4. Mass Change

Surface-dried specimens were weighed before and after sulfate exposure. Mass change (%) was calculated to assess deterioration due to sulfate-induced expansion and crystallization.

5.5 Water Absorption Test

Water absorption testing was performed using ASTM C642 [29] to evaluate the porosity and permeability properties of the concrete mixtures. This test is essential for assessing the durability performance, particularly for concrete subjected to harsh environments like sulfate-laden soils or groundwater.

6.0 RESULTS AND DISCUSSION

6.1 Slump Test Results

Figure 1 and Table 1 illustrate the slump values of the concrete mixtures (M0–M5), demonstrating the impact of ceramic waste powder (CWP) and sugarcane bagasse ash (SCBA) on the workability of fresh concrete. The control mix (M0), consisting exclusively of Ordinary Portland Cement (OPC), exhibited the maximum slump value (75 mm), signifying enhanced flowability and ideal paste cohesiveness without segregation or bleeding. As the level of cement replacement increased, a gradual decrease in slump was noted. Mix M1 (10% complete replacement) had a slump of 70 mm, but Mix M3 (30% replacement) decreased to 60 mm. This phenomenon is attributed to the increased surface area and angular morphology of pozzolanic materials, such as CWP and SCBA, which increase water consumption and reduce the availability of free water, thereby decreasing the slump.

Interestingly, between the two 20% replacement mixes — M4 (CWP-rich) and M5 (SCBA-rich) — a slightly higher slump was recorded in M5 (62 mm) compared to M4 (65 mm). The result suggests that SCBA's porous, lightweight nature might retain internal moisture, aiding internal lubrication and improving workability during mixing. These findings align with previous research highlighting SCBA's effect on enhancing flow due to the presence of residual organic content and fine particles [5]. Despite the decrease in slump with higher SCM content, all mixes remained within the S2 slump class (50–90 mm), as defined by BS EN 206 [30], making them suitable for typical reinforced concrete applications. Moreover, no signs of bleeding or segregation were noted, confirming that the pozzolanic additions maintained adequate cohesiveness in fresh concrete.

These results confirm that up to 30% replacement of OPC with a combined CWP and SCBA does not impair fresh workability beyond acceptable limits and can therefore be safely adopted in structural concrete applications with standard workability requirements.

Table 1: Slump Values of Fresh Concrete

Mix ID	OPC (%)	CWP (%)	SCBA (%)	Slump (mm)	Workability Class
M0	100	0	0	75	S2 (medium)
M1	90	5	5	72	S2 (medium)
M2	80	10	10	68	S2 (medium)
M3	70	15	15	60	S2 (medium)
M4	80	15	5	65	S2 (medium)
M5	80	5	15	62	S2 (medium)

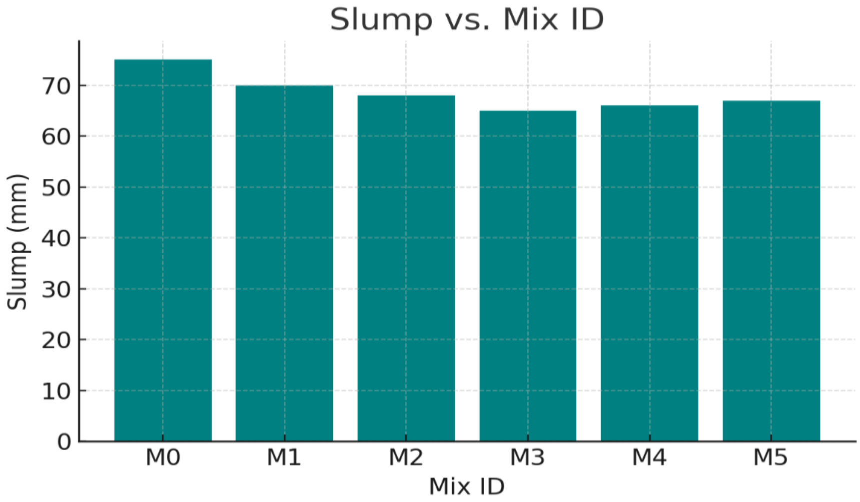

Figure 1: Slump Values of Mixes

6.2 Fresh Density of Concrete

The fresh density values for all concrete mixes (M0–M5) are presented in Table 2 and illustrated in Figure 2. The control mix (M0), made entirely with OPC, recorded the highest Density (2435 kg/m³), consistent with typical normal weight concrete. A consistent reduction in fresh Density was observed across the modified mixes as the replacement level of OPC with ceramic waste powder (CWP) and sugarcane bagasse ash (SCBA) increased. Mix M1 (10% total SCMs) recorded a slight decrease to 2410 kg/m³, while Mix M3 (30% replacement) showed the lowest Density at 2368 kg/m³. This density reduction trend can be directly attributed to the lower specific gravities of the pozzolanic materials used—CWP (2.62) and SCBA (2.38)—compared to OPC (3.14). The inclusion of these lightweight, porous materials results in a decreased bulk mass per unit volume.

The comparison of Mix M4 (CWP-rich, 2382 kg/m³) and Mix M5 (SCBA-rich, 2370 kg/m³) further substantiates this conclusion. The more porous microstructure and reduced intrinsic Density of SCBA resulted in a somewhat lower fresh density in M5, highlighting its effect on decreasing the overall mass of the concrete mix. Notwithstanding these decreases, all mixtures sustained fresh densities exceeding 2300 kg/m³, hence fulfilling the minimum density criterion for normal-weight concrete as stipulated by BS EN 206:2013 [31]. The study confirms that replacing OPC with up to 30% CWP–SCBA does not compromise the structural classification of the concrete. It may offer potential advantages for producing relatively lighter concrete, which can be beneficial in scenarios where a reduction in dead load is desired (e.g., precast components, seismic regions). Thus, the findings validate the suitability of CWP and SCBA as sustainable supplementary cementitious materials (SCMs), contributing to the development of structurally sound, eco-efficient concrete.

Table 2: Fresh Density of Concrete Mixes

Mix ID	OPC (%)	CWP (%)	SCBA (%)	Fresh Density (kg/m³)
M0	100	0	0	2435
M1	90	5	5	2410
M2	80	10	10	2395
M3	70	15	15	2368
M4	80	15	5	2382
M5	80	5	15	2370

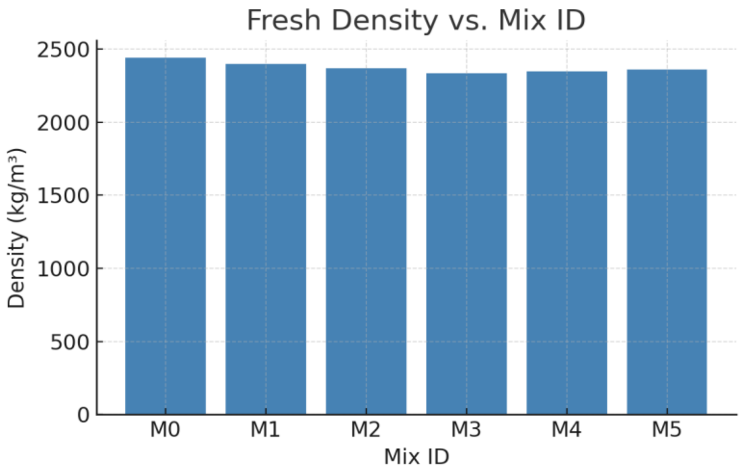

Figure 2: Fresh Concrete Density of Mixes

6.3 Compressive Strength (Water-Cured Specimens)

The compressive strength results of water-cured concrete specimens at 7, 28, 56, and 90 days are presented in Table 3. As expected, the control mix (M0), composed entirely of OPC, consistently delivered the highest strength at all curing ages, reaching 40.5 MPa at 90 days. This benchmark performance underscores the high early and long-term reactivity of pure Portland cement. The blended mixes containing ceramic waste powder (CWP) and sugarcane bagasse ash (SCBA) showed a gradual reduction in strength as the replacement level increased. Mixes M1 and M2, with 10% and 20% total replacement respectively, recorded 28-day strengths of 33.8 MPa and 31.6 MPa — reflecting a modest strength reduction of about 4% to 10% compared to M0. Despite this reduction, these values remain well above the minimum required for structural-grade concrete, indicating that the pozzolanic reactions of CWP and SCBA were sufficient to compensate for the lower clinker content.

All mixes exhibited progressive strength gain over time, highlighting the pozzolanic activity of the SCMs used. The strength development was particularly notable between 28 and 90 days, which aligns with the long-term reactivity of SCBA's amorphous silica and CWP's alumina-silicate phases. This ongoing reaction likely led to the formation of secondary calcium silicate hydrate (C–S–H) gel, enhancing the microstructure and strength at later ages [32]. Mix M3, which contained the highest replacement level (30% total SCMs), recorded the lowest strength values at all ages (e.g., 28.4 MPa at 28 days and 34.8 MPa at 90 days). Nevertheless, this mix still achieved compressive strengths above 30 MPa, demonstrating that even high-volume substitutions with CWP and SCBA can yield structurally viable concrete. This finding supports the sustainability-driven push for high-replacement cementitious systems in green construction.

Moreover, the performance of Mixes M4 and M5 (comprising CWP and SCBA-rich blends, respectively) demonstrated a subtle influence of blend ratios. M4 demonstrated marginally superior strength (30.2 MPa at 28 days) compared to M5 (29.6 MPa), indicating that CWP may be more conducive to early strength development than SCBA. Nevertheless, the disparity diminishes by 90 days, suggesting that SCBA's reduced reactivity converges over time. The findings indicate that CWP and SCBA can successfully substitute OPC by up to 30% without significantly compromising compressive strength. The strength characteristics of the mixtures correspond with established hydration kinetics of pozzolanic materials, hence endorsing their incorporation in resilient, sustainable concrete compositions.

Table 3: Compressive Strength of Water-Cured Concrete (MPa)

Mix ID	7 Days	28 Days	56 Days	90 Days
M0	26.5	35.2	38.6	40.5
M1	25.0	33.8	37.2	39.0
M2	23.2	31.6	35.0	37.4
M3	21.5	28.4	32.5	34.8
M4	22.8	30.2	33.4	35.6
M5	22.2	29.6	33.1	35.0

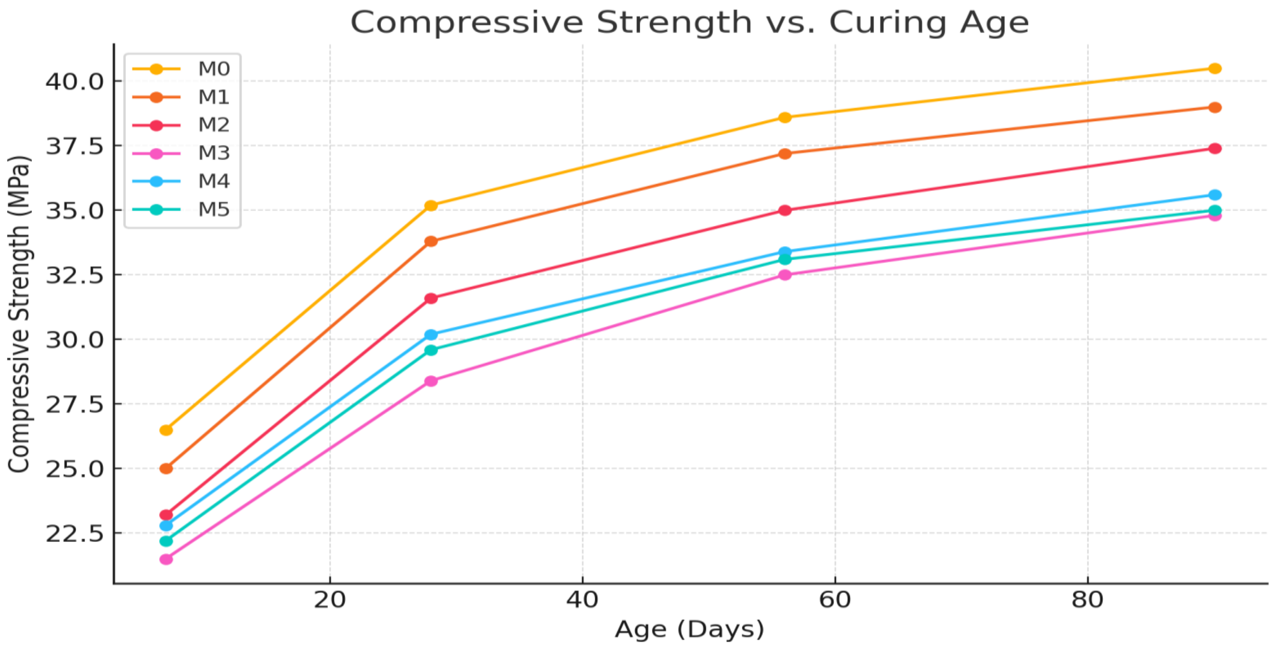

Figure 3: Compressive Strength vs. Age for Water-Cured Specimens

6.4 Compressive Strength After Sulfate Exposure

The compressive strength performance of sulfate-exposed concrete specimens is presented in Table 4 and Figure 4. All mixes exhibited a progressive decline in strength from 28 to 90 days of immersion in 5% sodium sulfate (Na_2SO_4) solution, demonstrating the adverse effect of sulfate attack on the cementitious matrix. This trend aligns with the known mechanism of sulfate-induced expansion and cracking due to the formation of ettringite and gypsum in vulnerable cementitious systems. The control mix (M0), comprising 100% OPC, experienced the most pronounced deterioration, with strength reducing from 30.4 MPa at 28 days to 26.9 MPa at 90 days — a cumulative drop of approximately 11.5%. This behavior is attributed to the higher availability of calcium hydroxide ($Ca(OH)_2$) in OPC, which readily reacts with sulfate ions to form expansive ettringite, leading to internal microcracking and strength loss over time.

Conversely, all pozzolan-modified mixtures (M1–M5) exhibited enhanced resistance to sulfate-induced degradation. Specifically, mixes M1 and M5 demonstrated remarkable endurance, sustaining compressive strengths of 29.0 MPa and 28.1 MPa, respectively, after 90 days of testing. Notably, Mix M5 (containing 5% CWP and 15% SCBA) retained over 93% of its initial strength compared to its value at 28 days. The enhanced resistance is primarily attributed to the elevated amorphous silica content in SCBA, which interacts with calcium hydroxide to form supplementary calcium silicate hydrate (C–S–H), thereby optimizing the pore structure and reducing permeability to external sulfate ions[33]. Even Mix M3, featuring the maximum replacement amount of 30% total SCMs, exceeded the control mix in long-term strength during sulfate exposure, achieving 25.0 MPa at 90 days. Although its absolute strength was inferior to that of other modified mixtures, its enhanced performance compared to M0 underscores the advantages of a diminished OPC content in alleviating harmful chemical reactions.

The results confirm that incorporating CWP and SCBA improves the sulfate resistance of concrete. The reduced calcium hydroxide content, denser microstructure, and ongoing pozzolanic activity contribute to the enhanced durability of these sustainable binders[34]. These findings support the application of agro-industrial and ceramic waste as viable supplementary cementitious materials (SCMs) in aggressive chemical environments.

Table 4: Compressive Strength of Sulfate-Exposed Specimens (MPa)

Mix ID	28 Days	56 Days	90 Days
M0	30.4	28.7	26.9
M1	31.2	30.1	29.0
M2	29.8	28.6	27.3
M3	27.4	26.2	25.0
M4	29.4	28.5	27.8
M5	30.0	28.9	28.1

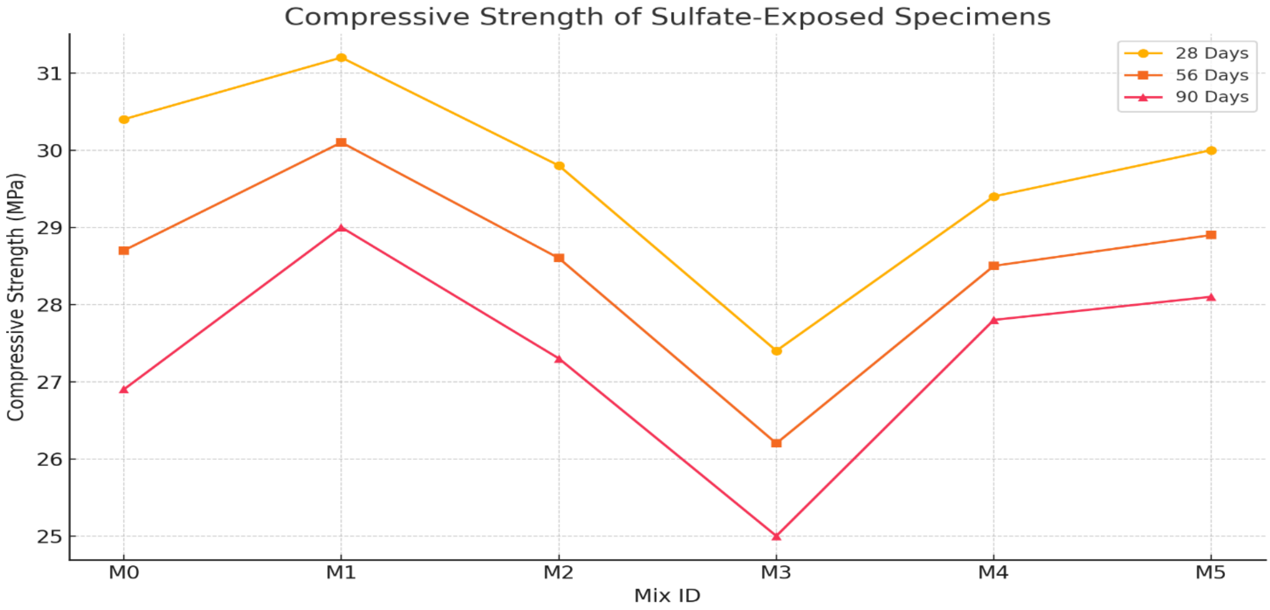

Figure 4: Compressive Strength of Sulfate-Exposed Specimens (MPa)

6.5 Strength Retention after 90 Days Sulfate Exposure

The sulfate resistance of concrete mixes was further evaluated by calculating strength retention percentages, which represent the ratio of compressive strength of sulfate-exposed specimens to their corresponding water-cured counterparts at 90 days. Table 5 and Figure 5 present the results, which reveal significant trends in the durability behavior of both the control and modified mixes. The control mix (M0), composed entirely of OPC, exhibited the lowest strength retention (66.4%), confirming its high susceptibility to chemical deterioration under prolonged sulfate exposure. This significant loss is attributed to the unmodified OPC matrix, which contains abundant calcium hydroxide ($Ca(OH)_2$), readily available for reaction with sulfate ions to form expansive ettringite and gypsum. The resulting internal stresses can lead to microcracking and a loss of mechanical integrity

All pozzolan-incorporated mixtures (M1–M5) exhibited significantly greater strength retention, ranging from 71.8% to 80.3%, indicating their enhanced resistance to sulfate-induced deterioration. This improvement can be attributed mainly to the inclusion of SCBA and CWP, which facilitate supplementary pozzolanic processes that utilize calcium hydroxide and generate more calcium silicate hydrate (C–S–H). The compacted microstructure hinders sulfate ion penetration and inhibits the development of harmful chemicals. Of all the adjusted mixtures, Mix M5 (5% CWP + 15% SCBA) exhibited the greatest strength retention at 80.3%, indicating the beneficial effect of increased SCBA content. The elevated amorphous silica content in SCBA enhances secondary hydration and pore refinement, hence markedly decreasing permeability and susceptibility to chemical assault. Likewise, Mix M4, which contains a higher concentration of CWP, demonstrated commendable longevity, maintaining 78.1% of its initial strength.

Even Mix M3, despite its higher total SCM replacement (30%), outperformed the OPC control mix in sulfate environments, further affirming the long-term durability benefits of incorporating ceramic and agro-waste pozzolans. Overall, these results support the viability of blended binders as sustainable alternatives for use in sulfate-rich environments, such as marine, sewage, or sulfate-bearing soils.

Table 5: Strength Retention after 90 Days Sulfate Exposure

Mix ID	Water-Cured Strength (MPa)	Sulfate-Exposed Strength (MPa)	Strength Retention (%)
M0	40.5	26.9	66.4%
M1	39.0	29.0	74.4%
M2	37.4	27.3	73.0%
M3	34.8	25.0	71.8%
M4	35.6	27.8	78.1%
M5	35.0	28.1	80.3%

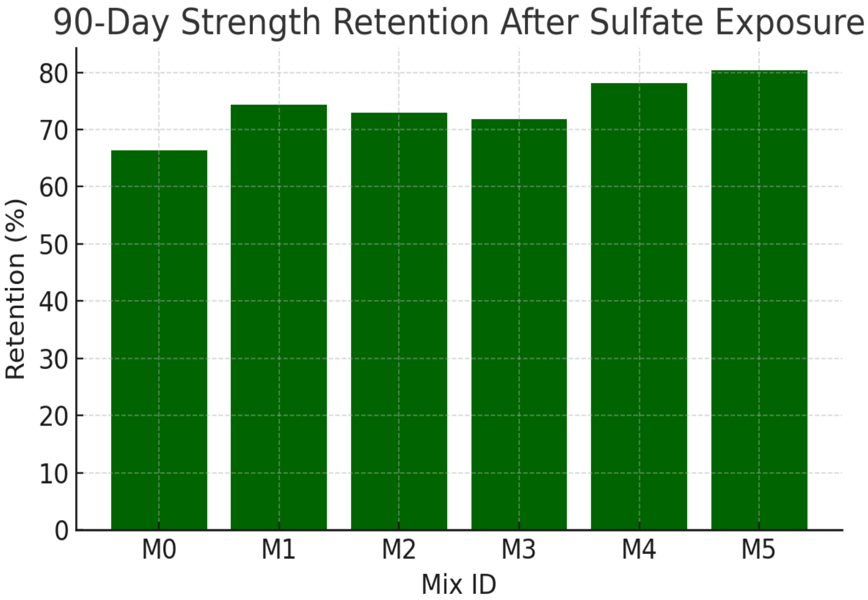

Figure 5: 90-Day Strength and Retention Comparison

6.6 Mass Change After Sulfate Exposure

The mass change behavior of concrete specimens subjected to sulfate exposure is presented in Table 6 and Figure 6. All mixes initially showed a positive mass increase up to 56 days, primarily due to the ingress of sulfate ions and formation of expansive reaction products such as gypsum and ettringite within the pore structure. This early mass increase is consistent with typical sulfate-induced absorption trends in hydrated cement matrices. However, by 90 days, a distinct pattern emerged. The control mix (M0) exhibited a net mass loss of −0.85%, reflecting the onset of material leaching, internal cracking, and surface degradation caused by advanced sulfate attack. This performance underscores the vulnerability of OPC-only systems in aggressive environments.

In contrast, all pozzolan-modified mixes (M1–M5) demonstrated superior resistance to mass loss. The magnitude of change decreased progressively with increasing CWP and SCBA content. Notably, Mix M5—containing 15% SCBA and 5% CWP—recorded a minimal net gain of +0.02% after 90 days, indicating exceptional sulfate durability. This improvement is attributed to the pozzolanic refinement of the pore structure, which reduces permeability and limits the ingress of sulfate ions, thus mitigating the formation and expansion of deleterious products[35].

These findings affirm that incorporating CWP and SCBA contributes to a more stable and durable cementitious matrix, enhancing long-term performance under chemical attack. The trends also validate the synergistic role of SCBA's amorphous silica in densifying the microstructure and minimizing deterioration.

Table 6: Mass Change (%) of Concrete under Sulfate Exposure

Mix ID	28 Days	56 Days	90 Days
M0	+0.50	+0.65	−0.85
M1	+0.42	+0.55	−0.20
M2	+0.40	+0.48	−0.10
M3	+0.38	+0.42	−0.05
M4	+0.41	+0.47	−0.08
M5	+0.39	+0.46	+0.02

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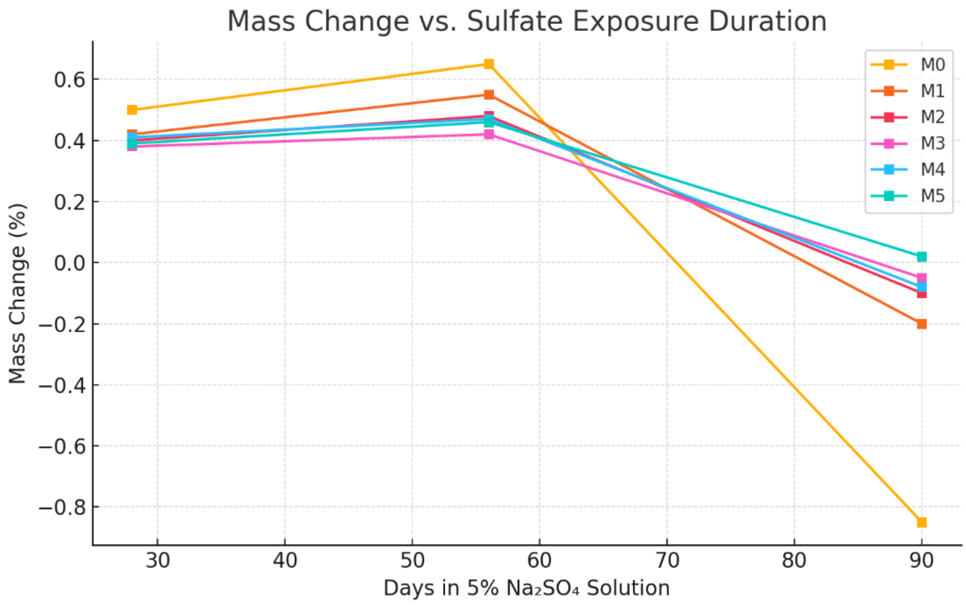

Figure 6: Mass Change vs. Exposure Duration

6.7 Visual Inspection and Surface Integrity

A Visual assessment conducted after 90 days of exposure to 5% Na_2SO_4 solution offered critical qualitative insight into the surface degradation of concrete mixes under sulfate attack. The control mix (M0) exhibited visible spalling, surface erosion, ne cracking, and white crystalline deposits, all of which are indicative of advanced sulfate-induced deterioration. These are characteristic signs of gypsum and ettringite formation, caused by the reaction of sulfate ions with calcium hydroxide in the OPC-rich matrix [36].

All pozzolan-modified mixtures (M1–M5) exhibited significantly enhanced surface durability. No substantial fissures were observed in any of the blended specimens, and the surface textures mainly remained unaltered. Mix M5, being the most excellent SCBA content, exhibited no obvious faults, discoloration, or alterations in texture, thus affirming its exceptional endurance. The M4 and M2 mixes exhibited unblemished surfaces, indicating reduced sulfate penetration and little production of expanding products.

Minor issues were observed in M3 (slight edge wear) and M1 (light surface discoloration), though no structural compromise was evident. These visual trends align with mass change and strength retention data, suggesting that CWP and SCBA synergistically enhance microstructural Density, limit chemical ingress, and suppress sulfate-induced damage mechanisms.

The observations substantiate that replacing OPC with blended supplementary cementitious materials (SCMs), particularly those rich in amorphous silica, provides significant protection against sulfate attack, both in terms of quantitative strength retention and qualitative surface integrity.

Table 7: Visual Degradation Summary at 90 Days

Mix ID	Surface Condition	Crack Formation	Color Change
M0	Spalling, erosion	Yes (fine cracks)	White patches
M1	Slight discoloration	Minor	Light white
M2	Smooth, intact	None	Minimal
M3	Slight edge wear	Very minor	Light grey
M4	Intact, good surface	None	None
M5	Smooth, dense surface	None	None

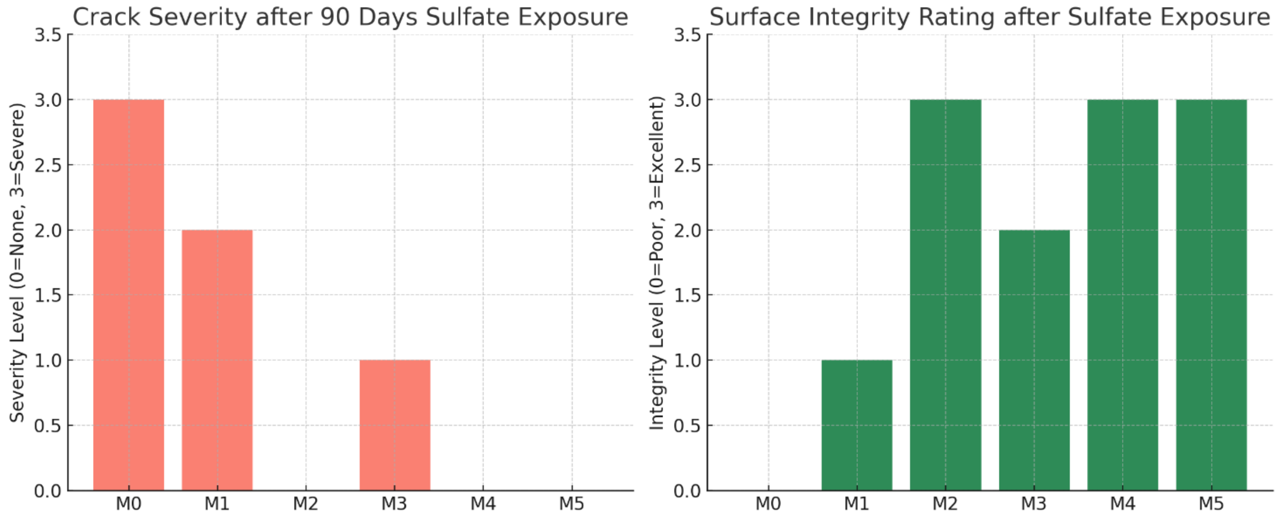

Figure 7: Visual Assessment of Surface Integrity and Crack Severity of Concrete Specimens after 90 Days Sulfate Exposure

6.8 Water Absorption

The water absorption test reflects concrete's permeability and resistance to fluid ingress—an essential factor for durability, particularly in sulfate-rich environments. As shown in Table 8 and Figure 8, all mixes containing ceramic waste powder (CWP) and sugarcane bagasse ash (SCBA) recorded a marked reduction in water absorption compared to the control (M0).

At 28 days, the control mix exhibited the highest absorption (6.10%), indicating a relatively porous matrix. In contrast, ternary blend M3 (15% CWP + 15% SCBA) had the lowest absorption (4.30%), followed closely by M5 (5% CWP + 15% SCBA) at 4.60%. The trend continued at 90 days, where M5 exhibited the most significant improvement with the lowest absorption (4.00%).

These findings validate the densifying impact of pozzolanic interactions between CWP/SCBA and $Ca(OH)_2$, which enhance pore structure and diminish capillary porosity. The improved matrix density corresponds with earlier mentioned trends in strength enhancement and sulfate resistance, especially in M3 and M5.

Table 8. Water Absorption (%) of Concrete Mixes at 28 and 90 Days

Mix ID	**OPC (%)**	**CWP (%)**	**SCBA (%)**	**Absorption @28 Days (%)**	**Absorption @90 Days (%)**
M0	100	0	0	6.10	5.40
M1	90	5	5	5.40	4.90
M2	80	10	10	5.00	4.40
M3	70	15	15	4.30	4.10
M4	80	15	5	4.80	4.30
M5	80	5	15	4.60	4.00

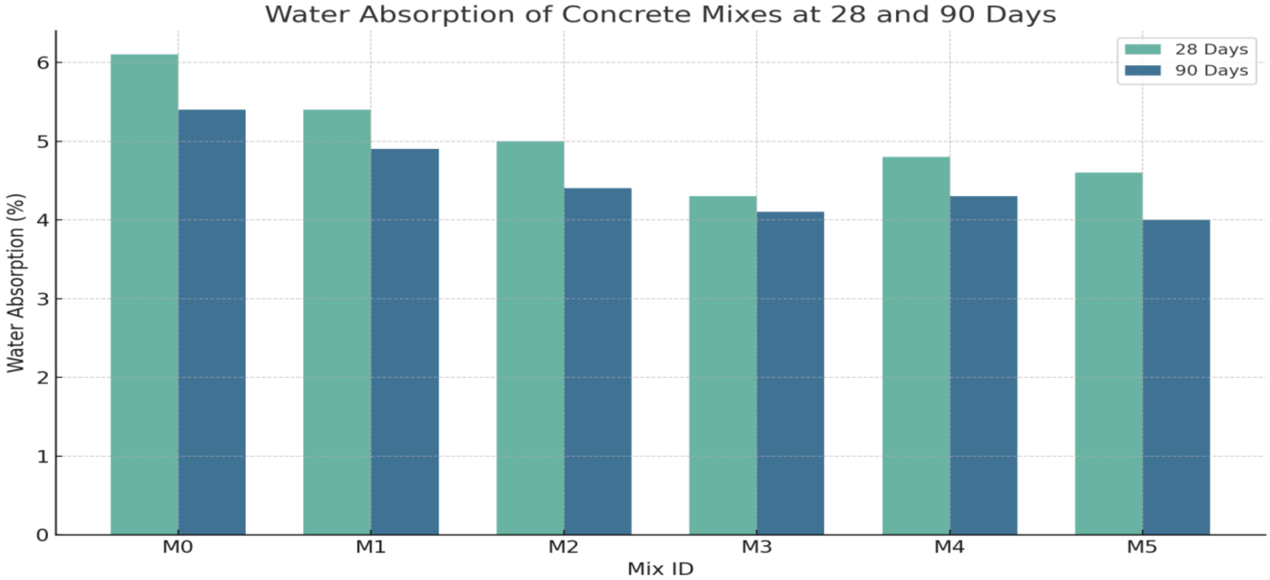

Figure 8: Water Absorption (%) of Concrete Mixes at 28 and 90 Days

7.0 Conclusion

This study evaluated the performance of concrete incorporating ceramic waste powder (CWP) and sugarcane bagasse ash (SCBA) as sustainable supplementary cementitious materials (SCMs) to replace Ordinary Portland Cement (OPC) partially. Six mixes were tested, including a control and five modified mixes with OPC replacement levels ranging from 10% to 30%, using CWP and SCBA in varying proportions. The key conclusions are as follows:

1. All concrete mixes fell within the acceptable S2 slump range. Increasing CWP and SCBA led to moderate reductions in slump and fresh Density due to their high surface area and porous structure. However, workability and cohesion remained satisfactory for structural applications.
2. The SCM-modified mixes exceeded the 28 MPa structural benchmark at 28 days and achieved compressive strengths of 34–39 MPa at 90 days. A mix containing 80% OPC, 5% CWP, and 15% SCBA (i.e., 20% total replacement) emerged as optimal, achieving 35.0 MPa at 90 days

in water curing, and 28.1 MPa after 90 days of sulfate exposure. This demonstrates the effectiveness of this blend in maintaining structural integrity while reducing cement consumption.

3. The 80% OPC + 5% CWP + 15% SCBA mix exhibited the highest sulfate resistance, with strength retention of 80.3% after 90 days in 5% sodium sulfate solution. This performance is attributed to the dense microstructure and reduced calcium hydroxide content resulting from the high amorphous silica content in SCBA, which limits the formation of expansive ettringite and gypsum.
4. Mass change results indicated improved resistance to sulfate-induced deterioration in SCM blends. The optimum mix (80% OPC + 5% CWP + 15% SCBA) retained its mass (+0.02%) and showed no visible cracks or surface degradation after sulfate exposure, outperforming the control, which lost mass (−0.85%) and suffered cracking.
5. The optimum mix also recorded the lowest water absorption (4.00%) at 90 days, confirming its superior impermeability and durability. This reduction in permeability is linked to the enhanced formation of C-S-H gel through pozzolanic reactions, resulting in a refined pore structure and improved microstructural integrity.
6. The blend containing 80% OPC, 5% CWP, and 15% SCBA is the most effective formulation in this study. It optimally balances strength, durability, and sustainability.
7. The environmental and practical significance of using CWP and SCBA lies in their ability to not only improve performance but also support sustainable construction by recycling industrial and agricultural waste, thereby reducing the carbon footprint associated with OPC production.
8. Applicability: These findings recommend the adoption of CWP–SCBA concrete for applications in sulfate-prone environments, such as marine structures, sewage infrastructure, and foundations, particularly where long-term durability is crucial.

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Author Contributions

The author solely conducted all aspects of the research, including conceptualization, methodology, experimental investigation, data analysis, visualization, writing—original draft, and writing—review and editing.

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Data Availability

The data used to support the findings of this study are included within the article.

Conflict Of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

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