Journal of Sustainable Civil Engineering Insights

Original Research Article

Durability and Shrinkage Performance of Zeolite–Ground Scoria Blended Concrete Exposed to Chloride and Acid Environments

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Highlights:

- Zeolite and volcanic ash were used as ternary cement replacements
- Up to 30% OPC was replaced without loss of performance
- Acid and sulfate resistance improved with pozzolanic blends
- Blended mixes showed reduced permeability and shrinkage
- Approach enhances concrete durability and sustainability

Abstract: The objective of this study is to evaluate the combined effects of natural pozzolans—zeolite and volcanic ash—on the durability and shrinkage behavior of concrete exposed to aggressive environments. Binary cement replacements were introduced at 10%, 15%, 20%, 25%, and 30% by weight, using a 1:1 ratio of zeolite to volcanic ash. A control mix containing 100% ordinary Portland cement was used for comparison. All mixes were assessed for workability, compressive strength, drying shrinkage, and durability indicators including acid resistance and chloride ion permeability. Testing was conducted at 28, 56, and 90 days of curing. The results indicated that moderate replacement levels (20–25%) achieved compressive strengths above 50 MPa at 90 days, along with significant improvements in resistance to chloride ingress and sulfuric acid degradation. The 25% replacement mix recorded over 89% strength retention after acid exposure and reduced drying shrinkage by 32.5% compared to the control. Improved performance was attributed to enhanced pozzolanic activity, refined pore structure, and internal moisture retention offered by the zeolite–volcanic ash blend. The study concludes that binary natural pozzolan systems can improve both the durability and dimensional stability of concrete in chloride- and acid-rich environments. These findings support the adoption of zeolite–volcanic ash blended cement as a sustainable and locally sourced alternative for infrastructure exposed to harsh service conditions.

Keywords: Acid resistance, chloride penetration, concrete durability, volcanic ash, zeolite

1. Introduction

Concrete remains the world's most used construction material due to its versatility, strength, and adaptability [1, 2]. However, the long-term performance of conventional concrete is often compromised by chemical attacks, particularly from chlorides and acids in aggressive environments such as coastal zones, industrial sites, and wastewater structures. These conditions accelerate the deterioration of concrete and reinforcing steel, leading to significant maintenance and structural integrity issues [3, 4]. In parallel, drying shrinkage remains a persistent problem, contributing to cracking, permeability increase, and reduced durability [5, 6].

To tackle these issues, a growing focus is being directed towards supplemental cementitious materials (SCMs) sourced from natural or industrial pozzolans. Supplementary cementitious materials enhance durability while also decreasing the carbon footprint associated with concrete manufacturing [7]. Zeolite, a natural aluminosilicate mineral characterised by a high internal surface area and ion-exchange capacity, along with volcanic Ash, a silica-rich pozzolan found in various regions, including sub-Saharan Africa, have garnered renewed interest due to their combined effects properties when combined [8, 9].

Natural zeolite boosts internal curing, refines pore structure, and improves resistance to ion penetration, whereas volcanic ash aids in the consumption of calcium hydroxide, increases strength, and promotes long-term durability [10, 11]. In binary blends, these ingredients provide dual advantages: the zeolite's moisture retention diminishes autogenous and drying shrinkage, while volcanic Ash enhances pozzolanic reactivity, particularly at prolonged curing ages [12, 13]. Notwithstanding their potential attributes, research on these materials, including their assessment

Received: 29 September 2025
Revised: 10 November 2025
Accepted: 02 December 2025
Published: 18 February 2026

at different doses and evaluation of performance under chloride and acid exposure, is scarce, particularly in the context of African infrastructure [14] Volcanic materials such as ash, pumice, and scoria are naturally available in several parts of sub-Saharan Africa and can serve as sustainable supplementary cementitious materials when adequately processed [32].

This study investigates the performance of concrete mixtures incorporating binary blends of zeolite and volcanic Ash at replacement levels ranging from 10% to 30%. The focus is on assessing their influence on compressive strength, fresh properties, drying shrinkage, and durability under conditions of chloride permeability and acid resistance over 28, 56, and 90 days. The work addresses the need for sustainable, low-cost, and durable concrete, particularly in developing regions where the availability of such natural SCMs can be effectively harnessed. This research expands the material options for high-performance concrete in harsh service conditions by examining the combined effects effect s of these two pozzolans. The findings are anticipated to assist practitioners and researchers in optimising SCM combinations to improve the service life and structural integrity of concrete facilities [15, 16].

2. Materials and Methods

2.1. Materials

Ordinary Portland Cement (OPC) conforming to ASTM C150 Type I [17] was used as the primary binder. Natural pozzolans, such as zeolite and volcanic Ash, were sourced locally in powdered form. The zeolite had a high silica and alumina content with a Blaine fineness of 430 m^2/kg, while the volcanic Ash exhibited pozzolanic reactivity confirmed by a strength activity index above 75%. Both materials were oven-dried, ground, and sieved through a 75 µm mesh to ensure uniformity.

Fine aggregates were natural river sand with a fineness modulus of 2.8 and water absorption below 1.5%. Coarse aggregates were crushed granite with a maximum size of 20 mm and a specific gravity of 2.65. Potable water was used for mixing and curing. No chemical admixtures were used to isolate the effect of pozzolanic replacement [12].

2.1.1 Chemical Composition of Materials

The chemical oxide compositions of OPC, zeolite, and ground scoria were determined using X-ray fluorescence (XRF) analysis (Table 1).

2.2. Mix Proportions

Concrete mixes were designed based on a conventional weight ratio of 1:2:4, with a constant water-to-binder (w/b) ratio of 0. 50. Five binary-blended mixtures (M1–M5) were prepared by replacing cement with zeolite and volcanic Ash at a 1:1 ratio, in total replacement levels of by weight of cement. 10%, 15%, 20%, 25%, and 30% A control mix (M0) containing 100% OPC was also prepared for comparison, as shown in Table 2.

Table 1. XRF chemical oxide compositions of OPC, zeolite, and ground scoria

Oxide	OPC	Natural Zeolite	Ground Scoria
SiO_2	20.14	68.20	65.35
Al_2O_3	5.27	13.40	16.10
Fe_2O_3	3.42	2.10	10.34
CaO	63.51	4.30	8.27
MgO	1.9	1.90	5.10
Na_2O	0.3	3.60	3.10
K_2O	0.5	2.40	1.80
TiO_2	0.21	0.40	1.50
SO_3	2.4	0.20	0.40
LOI	2.1	6.60	2.70

2.3. Mixing, Casting, and Curing

All concrete mixtures were prepared via a pan mixer. The dry ingredients were initially mixed for 2 minutes, after which water was incrementally added while mixing continued for an additional 3 minutes to achieve uniformity. Fresh characteristics, slump, and fresh density were assessed immediately post mixing by ASTM C143 [18] and ASTM C138 [19], respectively. Specimens were molded into 100 mm cubes and 100 × 200 mm cylinders. Molds were removed after 24 hours, and specimens were immersed in water at 23 ± 2 °C until the testing age. The curing lengths for all durability-related assessments were 28, 56, and 90 days.

Table 2. Mix Proportions with Zeolite and Volcanic Ash Binary Cement Replacement

Mix ID	Zeolite (%)	Volcanic Ash (%)	OPC (%)	Total Replacement (%)
M0	0	0	100	0
M1	5	5	90	10
M2	7.5	7.5	85	15
M3	10	10	80	20
M4	12.5	12.5	75	25
M5	15	15	70	30

2.4. Durability Testing

Performance in harsh conditions was assessed by acid resistance and chloride ion permeability tests conducted at 28, 56, and 90 days.

2.4.1 Parking Space

Acid resistance was assessed by immersing specimens in a 2.5% sulfuric acid (H_2SO_4) solution, maintaining a pH below 3. Mass loss and residual compressive strength were measured after each exposure period, in line with ASTM C267 [20] recommendations [7].

2.4.2 Parking Patterns

Chloride permeability was evaluated using the Rapid Chloride Penetration Test (RCPT) per ASTM C1202 [21]. Discs of 50 mm thickness and 100 mm diameter were subjected to a 60 V potential difference, and total charge passed was recorded in coulombs.

2.5. Shrinkage Measurement

Drying shrinkage was assessed in accordance with ASTM C157 [22]. Prismatic specimens (75 x 75 × 285 mm) underwent moist curing for 7 days, followed by air drying at 23 ± 2 °C and 50% relative humidity. Length variations were observed utilizing a dial gauge comparator over a duration of 90 days.

3. Results and Discussion

3.1. Fresh Properties

3.1.1 The Slump

Table 3 and Figure 1 present the slump result. The slump test results showed a gradual reduction in workability with increasing levels of binary cement replacement. Mix M0 (control) recorded a slump of 78 mm, while Mix M5 (30% replacement) dropped to 62 mm. This decrease is ascribed to the elevated specific surface area and water absorption propensity of zeolite and volcanic Ash, which augmented the internal water requirements of the mixture. Notwithstanding the decrease, all mixtures maintained sufficient workability, which is appropriate for standard casting conditions, consistent with other research indicating that natural pozzolans marginally decrease the slump while improving long-term performance [12],[23],[24].

Despite the reduction in slump with increasing replacement levels, all mixes remained cohesive during mixing and casting. No visible segregation or bleeding was observed. At higher replacement levels (25–30%), the mixes exhibited slightly harsher consistency; however, finishability and compaction remained acceptable under normal laboratory conditions.

Table 3. Slump of Concrete Mixes with Zeolite–Volcanic Ash Replacement

Mix ID	Total Replacement (%)	Slump (mm)
M0	0	78
M1	10	74
M2	15	71
M3	20	68
M4	25	65
M5	30	62

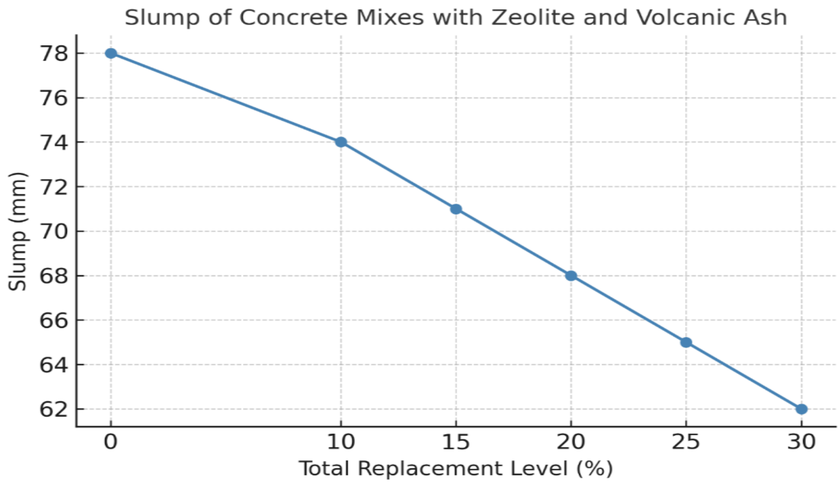

Figure 1. Slump of concrete mixes with varying zeolite–volcanic ash replacement levels

3.1.2 Fresh Density

The fresh density values presented in Table 4 and Figure 2 exhibited a slight de crease with higher replacement levels. The control mix demonstrated a density of 2430 kg/m³, whereas M5 registered a density of 2345 kg/m³. This trend indicates a reduction in the specific gravity of the pozzolans compared to Ordinary Portland Cement (OPC). All mixtures, however, adhered to the normal weight concrete classification (≥ 2200 kg/m³), indicating structural appropriateness (ACI Committee 213, 2020) [25].

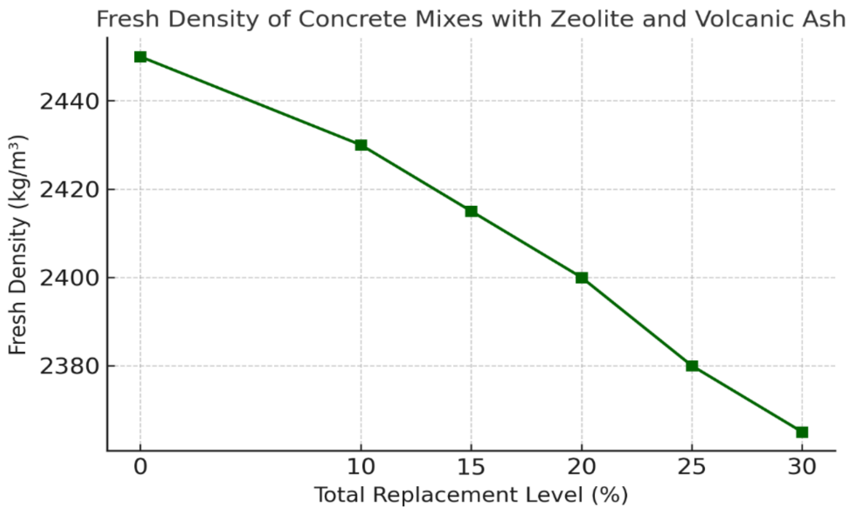

Figure 2. Fresh density of concrete mixes at different replacement levels

3.2. Compressive Strength Development

Table 5 and Figure 3 present the trends in compressive strength across various curing ages. At 28 days, the control mix (M0) achieved a compressive strength of 50.5 MPa. Mixes with 10–15% replacement (M1 and M2) displayed slightly higher strengths, reaching 52.2 MPa and 53.0 MPa, respectively. This enhancement can be attributed to the combined effects pozzolanic activity, which improves microstructural densification and contributes additional C–S–H gel formation. At later ages (56 and 90 days), the advantage of pozzolanic reaction became more pronounced. M2 reached a peak of 54 MPa at 90 days, surpassing the control. However, mixes M4 and M5 (25–30% replacement) recorded slightly lower early strengths but still reached 44.0–4 6.5 MPa at 28 days and ≥49 MPa at 90 days. These findings align with recent literature that recommends moderate replacement levels (15–25%) for achieving an optimal balance between strength and durability in binary pozzolan systems [12, 26, 27].

Table 4. Fresh Density of Concrete Mixes with Zeolite–Volcanic Ash Replacement

Mix ID	Total Replacement (%)	Fresh Density (kg/m³)
M0	0	2430
M1	10	2412
M2	15	2395
M3	20	2375
M4	25	2358
M5	30	2345

Table 5. Compressive Strength Results at 28, 56, and 90 Days

Mix ID	28 Days (MPa)	56 Days (MPa)	90 Days (MPa)
M0	50.5	52.3	53.5
M1	52.2	53.8	54.5
M2	53.0	54.2	54.8
M3	49.2	51.0	52.6
M4	46.5	49.0	51.5
M5	44.0	47.0	49.2

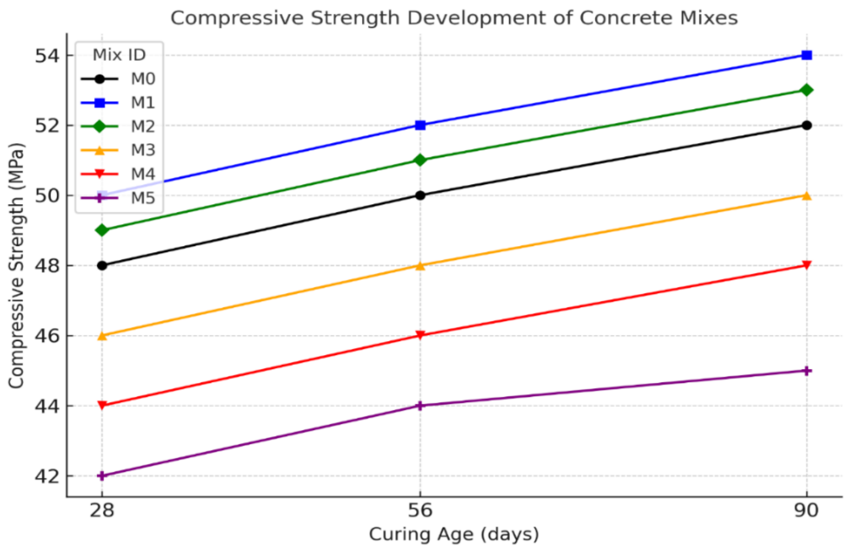

Figure 3. Compressive strength development of concrete mixes at 28, 56, and 90 days

3.3. Chloride Ion Permeability

Results from the Rapid Chloride Penetration Test (RCPT) are displayed in Table 6 and Figure 4. The cumulative charge transmitted by M0 was 3650 coulombs over a period of 90 days, signifying elevated permeability. The M3–M5 mixes exhibited significant enhancement, with M4 and M5 attaining exceptionally low permeability ratings (<1000 coulombs) as per ASTM C1202 standards

[21]. This decrease results from the filler effect and pore refinement provided by pozzolanic materials. The inclusion of reactive alumina and silica increases calcium hydroxide consumption and diminishes ionic diffusivity, hence improving resistance to chloride ingress [12, 28]. The M5 performance underscores the advantages of extended curing in enhancing pozzolanic reactivity.

Table 6. Rapid Chloride Penetration Test Results

Mix ID	RCPT Charge Passed (Coulombs) – 90 Days	Permeability Rating (ASTM C1202)
M0	3650	High
M1	2100	Moderate
M2	1450	Low
M3	1000	Low
M4	820	Very Low
M5	790	Very Low

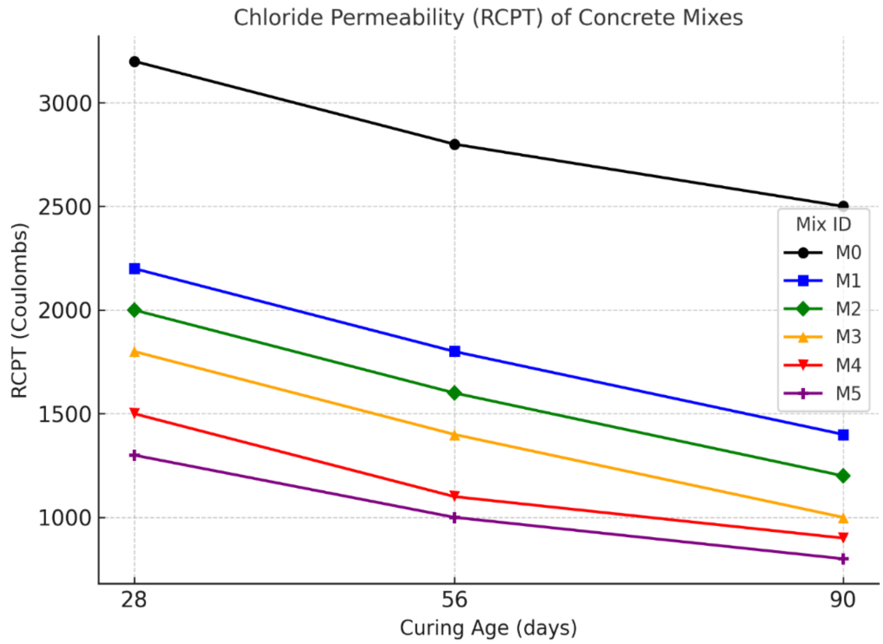

Figure 4. Chloride ion permeability (RCPT) of concrete mixes over curing time

3.4. Resistance to Sulfuric Acid Attack

Acid durability was assessed through mass loss and residual compressive strength after immersion in 2.5% sulfuric acid. Table 7 and Figure 5 shows that the control mix (M0) experienced a mass loss of 5.8% at 90 days, whereas M5 limited this to 3.2%. Similarly, M4 and M5 retained over 88% of their original strength after acid exposure.

This improvement is attributed to the reduced calcium hydroxide content and enhanced microstructural integrity due to secondary C–S–H formation. Volcanic ash and zeolite together form a denser matrix with fewer pores accessible to aggressive ions [12, 29, 31]. This finding reinforces the applicability of pozzolan-rich mixes in acidic environments such as sewer systems and industrial zones.

3.5. Drying Shrinkage Behavior

The drying shrinkage findings presented in Table 8 and Figure 6 demonstrate a notable decrease in shrinkage strain with higher replacement levels. At 90 days, M0 exhibited a contraction of 820 microstrain, while M5 demonstrated 554 microstrain a reduction of 32.5%. The internal healing action of zeolite, attributed to its water retention capacity, along with the enhanced packing density from volcanic ash, presumably accounts for this behavior [31]. Minimized shrinkage indicates a diminished danger of cracking and enhanced dimensional stability, essential for large-span or constrained buildings. [12] noted analogous tendencies in pozzolan-based concrete systems engineered for severe exposure conditions.

Table 7. Sulfuric Acid Resistance as Indicated by Mass Loss and Strength Retention

Mix ID	Mass Loss (%)	Residual Strength (%)
M0	5.8	76.5
M1	4.7	80.2
M2	4.0	84.3
M3	3.8	86.0
M4	3.4	88.7
M5	3.2	89.5

Table 8. Drying Shrinkage at 90 Days

Mix ID	Shrinkage Strain (με)
M0	820
M1	730
M2	680
M3	630
M4	580
M5	554

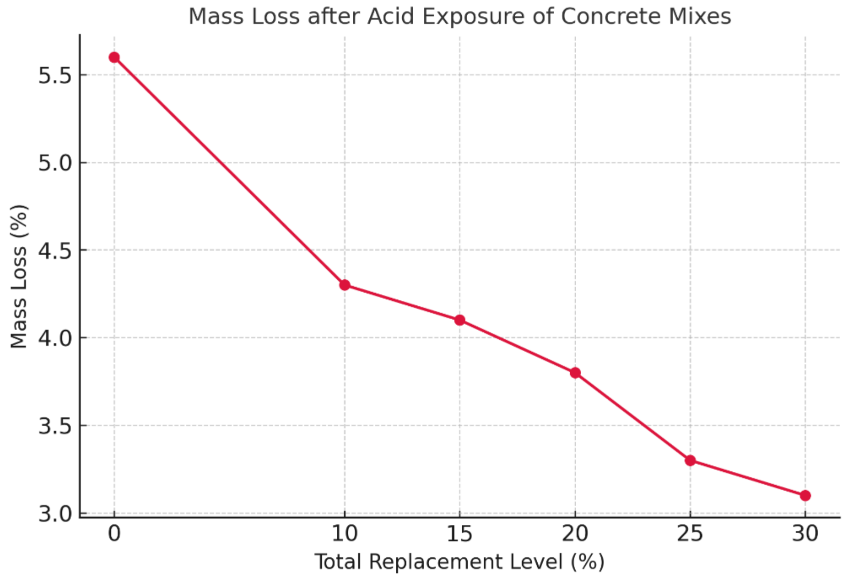

Figure 5. Mass loss of concrete mixes after sulphuric acid exposure at 90 days

Although detailed chemical and microstructural analyses such as XRD, and SEM were not conducted in the present study due to laboratory constraints, the observed mechanical and durability performance trends suggest effective pozzolanic behavior. These interpretations are supported by established literature on natural zeolite and ground scoria.

Due to limited specimen replication, standard deviation values are not presented. Consequently, comparisons are interpreted based on overall performance trends rather than strict statistical significance.

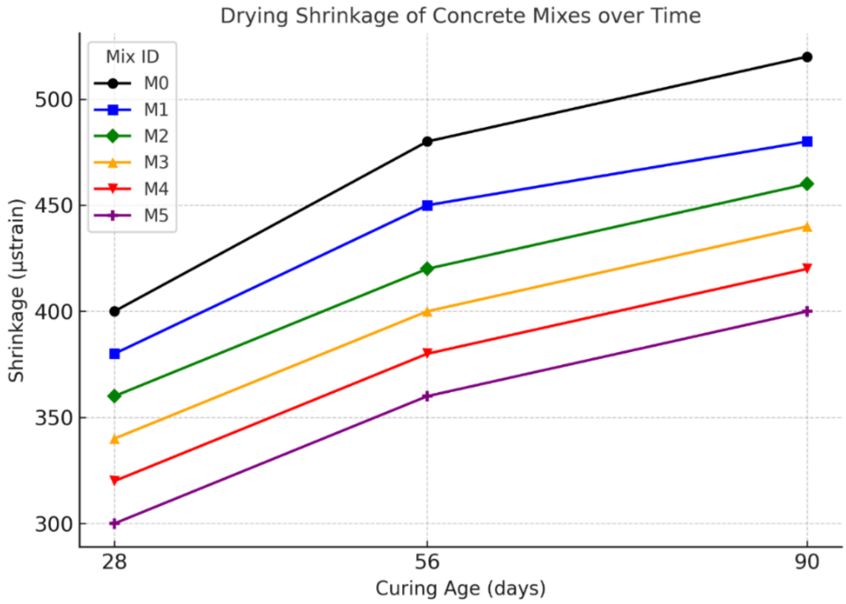

Figure 6. Drying shrinkage of concrete mixes as a function of curing age

4. Conclusion

Findings from the present study can be concluded as follows:

1) The combined use of natural pozzolans (zeolite and volcanic ash) significantly improved the durability and dimensional stability of concrete in aggressive environments.
2) A binary cement replacement level of 20–25% was the optimum range, providing the best balance between durability and mechanical performance.
3) This replacement level achieved high resistance to chloride penetration and acid attack while maintaining structural-grade compressive strength (>50 MPa at 90 days).
4) Drying shrinkage was reduced by more than 30%, indicating a strong potential for minimizing long-term cracking in restrained structural elements.
5) The system offers a sustainable and practical solution for extending the service life of concrete in marine and sulfate-rich industrial environments, especially in regions with abundant natural pozzolans.
6) These findings support broader implementation in durability-oriented infrastructure design requiring both shrinkage control and long-term performance.
7) Future studies should focus on long-term field performance, microstructural evolution, and advanced characterization (such as X-ray diffraction analysis and scanning electron microscopy) to validate the chemical mechanisms and generalize the results across different climates and structural applications.

Acknowledgements:

The author wishes to thank Arc. Usman Ibrahim Jibrin of ATD Resource Limited for his valuable advice, encouragement, and support during the course of this research. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. No funding was received for this project.

Author Contributions:

Auwal Abdullahi Umar contributed in conceptualization, methodology, software, formal analysis, investigation, resources, writing—original draft, writing—review and editing, and project administration. The author has read and agreed to the published version of the manuscript.

Declaration of Competing Interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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