Comparative Evaluation of Durability Parameters in GGBFS-Based Geopolymer Concrete Under Cyclic Chloride and Sulfuric Acid Exposure

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Abstract—Ordinary Portland Cement (OPC) production accounts for roughly 7–8% of global anthropogenic CO_2 emissions, motivating the adoption of alkali-activated binders. While low-calcium fly ash geopolymers typically require elevated-temperature curing, Ground Granulated Blast Furnace Slag (GGBFS) enables calcium-rich aluminosilicate polymerization under ambient conditions. This paper presents an experimental evaluation of 108 GGBFS-based geopolymer concrete (GPC) cubes (150 × 150 × 150 mm) activated with sodium hydroxide (NaOH) at 2 M, 4 M, and 8 M concentrations and a constant Na_2SiO_3/NaOH ratio of 1.5 (alkaline-to-binder ratio 0.55). Specimens were cured under ambient conditions or in an oven at 50°C for 24 hours, then subjected to cyclic wetting and drying in 3.5% NaCl and 5% H_2SO_4 solutions for 28 and 56 days. Results demonstrate a sharp non-linear strength jump at 8 M NaOH, reaching 56.86 MPa (28 days) and 63.44 MPa (56 days) under oven curing, and 52.47 MPa and 58.44 MPa under ambient curing. Under cyclic 3.5% NaCl exposure, all mixes exhibited compressive strength gains of +2.43% to +17.54% relative to unexposed controls due to continued moisture-assisted slag hydration. Conversely, 5% H_2SO_4 induced 19.97%–43.56% strength loss via calcium leaching and gypsum formation, with 8 M oven-cured specimens retaining the highest residual strength (49.73 MPa at 56 days). A critical methodological audit highlights key experimental boundaries and future microstructural requirements.

Main Keywords—Geopolymer concrete, GGBFS, NaOH molarity, ambient curing, oven curing, sulfuric acid resistance, sodium chloride ponding, cyclic wetting and drying.

I. INTRODUCTION

Conventional Portland Cement Concrete (PCC) remains the backbone of global civil infrastructure, yet clinker calcination and fossil-fuel kiln combustion generate approximately 7–8% of global anthropogenic carbon dioxide emissions while consuming substantial limestone and energy reserves. Consequently, replacing OPC clinker with industrial aluminosilicate by-products—particularly Ground Granulated Blast Furnace Slag (GGBFS) and fly ash—has become a central priority in sustainable structural engineering.

Introduced by Davidovits in 1978 [1], geopolymer binders form through the alkali activation of reactive silica and alumina into a three-dimensional polymeric Si–O–Al network. Unlike low-calcium Class F fly ash geopolymers, which typically require prolonged thermal curing (60–80°C) to achieve practical early-age strength and are thus constrained in cast-in-situ construction, GGBFS contains substantial calcium oxide (CaO ≈ 31.2%). This calcium-rich chemistry promotes the co-formation of calcium-aluminosilicate-hydrate (C-A-S-H) and sodium-aluminosilicate-hydrate (N-A-S-H) gels, enabling rapid strength development even under ambient field temperatures [2], [3].

Despite promising mechanical performance, infrastructure exposed to marine splash zones, de-icing salts, industrial effluents, or sewer environments experiences cyclic wetting and drying rather than static immersion. Cyclic exposure accelerates capillary suction, salt crystallization, and acid-induced decalcification. The present study systematically evaluates the combined influence of NaOH molarity (2 M, 4 M, 8 M), curing regime (ambient vs. 50°C oven), and exposure age (28 and 56 days) on the compressive strength and chemical durability of GGBFS-based geopolymer concrete under cyclic 3.5% NaCl and 5% H_2SO_4 ponding.

II. LITERATURE SURVEY

Prior research establishes that activator concentration, source-material CaO/SiO_2 ratio, and curing temperature govern both the pore structure and chemical resistance of alkali-activated concrete. Murthy and Rai [2] reported that GGBFS-based geopolymer concrete achieved 13.82% higher compressive strength, 18.23% higher split tensile strength, and 30.19% higher flexural strength than conventional OPC concrete. Pithadiya and Nakum [3] demonstrated that increasing GGBFS replacement in fly ash geopolymers (0%–100%) substantially improved ambient-cured early strength, reducing reliance on thermal chambers.

Under aggressive chemical exposure, however, binder chemistry creates distinct trade-offs. Lavanya and Jegan [4] observed that 12 M high-calcium fly ash GPC suffered up to 20% strength loss after 45 days in 2% H_2SO_4 compared with 28% loss in OPC. Pruthviraj and Anadinni [5] tested 50:50

GGBFS–fly ash GPC (8 M NaOH) in 5% H_2SO_4 for 28 days, recording 12.92% strength loss in M40 grade versus 31.81% in M20 grade, confirming that matrix density strongly governs acid resistance. Similarly, Nagajothi et al. [6] and Ojha and Aggarwal [7] reported lower water absorption and sorptivity in slag-blended GPC compared to OPC, while Okoye et al. [8] and Paruthi et al. [9] showed that 10% silica fume densifies the gel matrix against 2% H_2SO_4 and 5%–6% NaCl attack.

More recently, Prusty and Pradhan [10] and Maradani and Pradhan [11] emphasized that alternate wetting–drying cycles alter ionic strength and leaching kinetics differently from continuous immersion. Table I synthesizes these prior investigations alongside the present experimental matrix, highlighting the specific gap addressed by testing pure GGBFS across three NaOH molarities under cyclic ponding.

TABLE I

Comparison of Existing Geopolymer Durability Studies and Present Work

Study	Binder / Mix	Exposure	Key Finding
Pithadiya & Nakum [3]	Fly Ash + GGBFS (0–100%)	Ambient vs. 70°C oven	GGBFS enables ambient strength gain
Lavanya & Jegan [4]	High-Ca Fly Ash (12 M)	2% H_2SO_4, 5% $MgSO_4$ (45d)	20% acid loss vs. 28% in OPC
Pruthviraj & Anadinni [5]	50:50 GGBFS–FA (8 M)	5% H_2SO_4, chloride (28d)	M40 lost 12.92% vs. 31.81% (M20)
Paruthi et al. [9]	GGBFS + Silica Fume	2% H_2SO_4, 6% NaCl (62d)	10% SF peak strength (48.35 MPa)
Maradani & Pradhan [11]	FA & FA–GGBFS	Cyclic NaCl + sulfate	Wetting–drying alters ion leaching
Present Study	100% GGBFS (2M, 4M, 8M)	Cyclic 3.5% NaCl, 5% H_2SO_4	8M Oven: 63.44 MPa; NaCl gain, acid loss

III. EXPERIMENTAL PROGRAM AND METHODOLOGY

A. Materials and Chemical Characterization

Commercial GGBFS procured from COUNTO Microfine Products Pvt. Ltd. (Goa, India) served as the sole aluminosilicate precursor. As detailed in Table II, the slag contains 35.2% SiO_2 and 21.4% Al_2O_3—providing abundant reactive silicate and aluminate monomers—alongside 31.2% CaO, roughly half the calcium content of conventional Portland cement (62%).

TABLE II

Chemical Composition Comparison: GGBFS vs. Portland Cement

Oxide Constituent	GGBFS (%)	Portland Cement (%)
Silicon Dioxide (SiO_2)	35.2	25.0
Aluminum Oxide (Al_2O_3)	21.4	7.0
Ferric Oxide (Fe_2O_3)	3.0	0.5
Calcium Oxide (CaO)	31.2	62.0
Magnesium Oxide (MgO)	8.4	3.5
Sulfur Trioxide (SO_3)	0.8	2.5

The alkaline activator combined sodium hydroxide (NaOH) flakes (98% purity) and semi-solid sodium silicate (Na_2SiO_3, specific gravity 1.66 g/cc). NaOH solutions of 2 M (80 g/L), 4 M (160 g/L), and 8 M (320 g/L) were prepared 24 hours prior to casting to allow exothermic dissolution heat to dissipate. Single-source coarse aggregates (20 mm and 10 mm fractions) and fine river sand (passing 2.36 mm sieve) were used in saturated-surface-dry condition per IS 383:1970 [12].

B. Mix Proportions and Specimen Matrix

Because no standardized Indian codal mix-design procedure exists for geopolymer concrete, proportions were fixed from preliminary trials: GGBFS at 425 kg/m³, fine aggregate at 505 kg/m³, 20 mm coarse aggregate at 663 kg/m³, and 10 mm coarse aggregate at 442 kg/m³. The alkaline liquid-to-binder ratio was held constant at 0.55, with a Na_2SiO_3-to-NaOH mass ratio of 1.5 across all mixes.

A total of 108 standard cubes (150 × 150 × 150 mm) were cast across 36 experimental combinations (3 NaOH molarities × 2 curing regimes × 3 exposure conditions × 2 testing ages, with 3 replicate cubes per cell). Of these, 36 cubes served as unexposed controls, 36 were assigned to salt ponding, and 36 to acid ponding.

C. Casting, Curing, and Cyclic Ponding Protocols

Dry aggregates and GGBFS were blended for 5 minutes in a 3/4-bag rotating drum mixer, followed by 5 minutes of wet mixing after adding the freshly combined Na_2SiO_3 + NaOH activator. Cubes were cast in three layers (25 tamping strokes each) and compacted on a vibrating table. After 24 hours of laboratory rest, demolded specimens were split equally between ambient curing (direct sunlight at room temperature) and oven curing (50°C for 24 hours, followed by ambient storage).

Following 28 days of initial curing, durability specimens underwent cyclic wetting and drying in 3.5% NaCl or 5% H_2SO_4 solutions for 28 and 56 days. Cubes were removed each morning for daytime air-drying and re-immersed each evening, with solutions renewed every two weeks to maintain concentration. Compression tests were executed on a 2000 kN Compression Testing Machine (CTM) at a loading rate of 140 kg/cm²/min in accordance with IS 516:1959.

IV. GOVERNING REACTIONS AND ANALYTICAL METRICS

Alkaline activation proceeds via exothermic dissolution of NaOH and subsequent silicate speciation:

$$NaOH(s) + H_2O(l) \rightarrow NaOH(aq) + \Delta H$$

$$Na_2SiO_3(l) + 2NaOH(aq) \rightarrow Na_4SiO_4(aq) + H_2O(l)$$

The high-pH medium attacks glassy slag phases, releasing $Si(OH)_4$ and $Al(OH)_4^-$ monomers that polycondense with Ca^{2+} and Na^+ into a cross-linked C-A-S-H / N-A-S-H binding matrix. Compressive strength (f_c, MPa) for each 150 mm cube under peak load P (kN) is:

$$f_c = (P \times 1000) / (150 \times 150) = P / 22.5 \quad [MPa]$$

To evaluate chemical durability objectively across replicate scatter, relative strength change (Δf_c) and coefficient of variation (CV) across n = 3 replicates are computed as:

$$\Delta f_c\ (\%) = [(f_c,exp - f_c,norm) / f_c,norm] \times 100$$

V. EXPERIMENTAL RESULTS AND CRITICAL DISCUSSION

A. Unexposed Compressive Strength Development

Table III and Fig. 1 summarize the compressive strength of unexposed GGBFS-GPC cubes at 28 and 56 days. Raising NaOH molarity from 2 M to 4 M produced only marginal gains (+2.1% at 28d ambient; +5.3% at 28d oven). By contrast, increasing molarity to 8 M triggered a pronounced non-linear jump: 28-day strength rose by 28.3% (ambient, 52.47 MPa) and 30.7% (oven, 56.86 MPa) over 2 M controls, reaching 58.44 MPa and 63.44 MPa at 56 days. Higher OH^- concentration accelerates vitreous slag dissolution, liberating sufficient silicate and aluminate species to form a denser gel network.

TABLE III

Unexposed Control Compressive Strength (Mean ± SD, n = 3)

Mix	Curing	28d Mean±SD (MPa)	28d CV%	56d Mean±SD (MPa)	56d CV%
2 M	Ambient	40.90 ± 2.48	6.1%	42.42 ± 1.34	3.2%
2 M	Oven 50°C	43.52 ± 2.09	4.8%	44.02 ± 1.51	3.4%
4 M	Ambient	41.75 ± 2.26	5.4%	42.67 ± 0.83	1.9%
4 M	Oven 50°C	45.83 ± 0.70	1.5%	46.99 ± 1.31	2.8%
8 M	Ambient	52.47 ± 1.37	2.6%	58.44 ± 3.07	5.3%
8 M	Oven 50°C	56.86 ± 0.77	1.4%	63.44 ± 4.71	7.4%

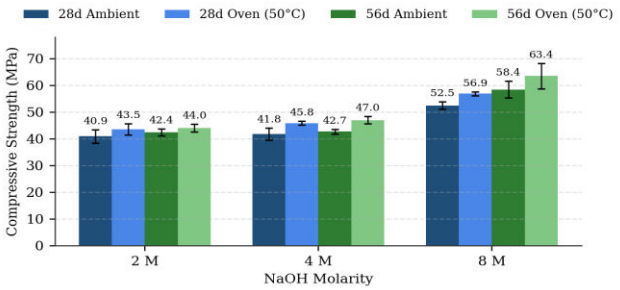


Fig. 1. Compressive strength of unexposed GGBFS-GPC at 28 and 56 days (error bars indicate ±1 SD across n = 3 cubes).

Across all molarities, 50°C oven curing outperformed ambient curing by 6.4%–9.8% at 28 days and 3.8%–10.1% at 56 days. Crucially, however, 8 M ambient-cured concrete still achieved 52.47 MPa at 28 days—exceeding typical M40/M50 structural requirements without thermal energy input.

B. Resistance to Cyclic 3.5% NaCl Exposure

As shown in Table IV and Fig. 2, every mix exposed to cyclic 3.5% NaCl wetting and drying exhibited higher compressive strength (+2.43% to +17.54%) than its unexposed counterpart at both 28 and 56 days. Peak performance occurred at 8 M oven curing (59.98 MPa at 28 days; 65.24 MPa at 56 days). This strength gain reflects continued moisture availability during daily immersion cycles, which promotes secondary hydration of unreacted GGBFS cores, alongside pore-filling by chloride-binding reaction products (such as Friedel's salt).

Nevertheless, replicate variability reveals an important vulnerability at low activator concentration: 2 M NaCl-exposed cubes displayed high scatter (CV = 12.4%–18.2%), whereas 8 M cubes stabilized at CV = 2.1%–2.6% by 56 days. Note also that while compressive strength remains resilient under short-term NaCl ponding, steel reinforcement corrosion risk requires separate electrochemical (RCPT) verification.

TABLE IV

Durability Performance Under Cyclic 3.5% NaCl and 5% H_2SO_4 Exposure

Mix	28d NaCl MPa (Δ%)	56d NaCl MPa (Δ%)	28d H_2SO_4 MPa (Δ%)	56d H_2SO_4 MPa (Δ%)
2M Amb	41.90 (+2.4%)	46.04 (+8.5%)	25.88 (-36.7%)	28.39 (-33.1%)
2M Oven	50.76 (+16.7%)	48.91 (+11.1%)	24.56 (-43.6%)	26.83 (-39.1%)
4M Amb	44.23 (+5.9%)	50.16 (+17.5%)	29.22 (-30.0%)	34.15 (-20.0%)
4M Oven	51.86 (+13.2%)	55.01 (+17.1%)	26.43 (-42.3%)	36.48 (-22.4%)
8M Amb	54.84 (+4.5%)	62.05 (+6.2%)	40.84 (-22.2%)	41.98 (-28.2%)
8M Oven	59.98 (+5.5%)	65.24 (+2.8%)	39.12 (-31.2%)	49.73 (-21.6%)

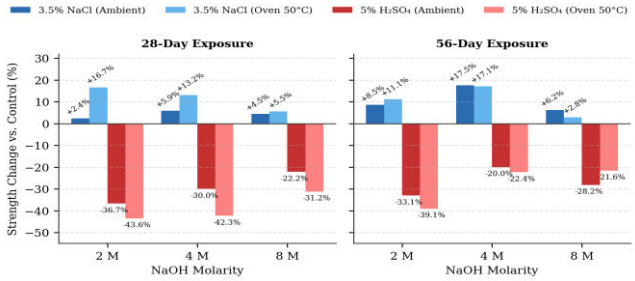


Fig. 2. Percentage change in compressive strength relative to unexposed control cubes after 28 and 56 days of cyclic exposure.

C. Deterioration Under Cyclic 5% H_2SO_4 Exposure

Cyclic immersion in 5% H_2SO_4 caused substantial strength degradation across all mixes (-19.97% to -43.56%), driven by H^+ ions leaching Ca^{2+} from the C-A-S-H gel and reacting with SO_4^{2-} to precipitate expansive gypsum ($CaSO_4 \cdot 2H_2O$), inducing surface spalling and micro-cracking. A notable curing-regime inversion emerged at 28 days: oven-cured specimens suffered greater relative strength loss (-31.20% to -43.56%) than ambient-cured specimens (-22.16% to -36.74%), suggesting that rapid 50°C thermal drying introduces micro-shrinkage channels that facilitate early acid ingress.

By 56 days, continued matrix polymerization in higher-molarity mixes mitigated this effect, with 8 M oven-cured concrete retaining the highest residual strength (49.73 MPa, -21.61% loss) compared to 2 M mixes (26.83–28.39 MPa, up to -39.06% loss, CV up to 26.4%). Compared against published benchmarks, the 21.61%–28.18% acid loss at 8 M aligns with Lavanya and Jegan's [4] 20% loss for 12 M fly ash GPC and remains superior to their 28% loss in OPC, though higher than the 12.92% loss reported by Pruthviraj and Anadinni [5] for 50:50 GGBFS–fly ash M40 concrete (where lower CaO content reduced gypsum susceptibility).

D. Methodological Critique and Scope Boundaries

A rigorous audit of the underlying experimental program identifies three scope boundaries: (1) although parallel OPC and 60°C fly ash GPC control batches were outlined in the initial test matrix, verified mechanical data were recorded exclusively for the 108 GGBFS-GPC specimens, necessitating literature-based cross-binder benchmarking herein; (2) specimen mass-loss logs and microstructural characterization (SEM/XRD) were not instrumented, preventing direct quantification of gypsum depth and gel Ca/Si ratios; and (3) NaCl ponding evaluates matrix strength rather than embedded rebar corrosion.

VI. CONCLUSION AND FUTURE WORK

This investigation evaluated 108 GGBFS-based geopolymer concrete cubes across 2 M, 4 M, and 8 M NaOH concentrations, ambient versus 50°C oven curing, and cyclic 3.5% NaCl and 5% H_2SO_4 exposure:

1) Activator Molarity Threshold: Increasing NaOH from 2 M to 4 M yields modest gains (< 6%), whereas 8 M NaOH drives a 28.3%–30.7% strength surge, achieving 58.44 MPa (ambient) and 63.44 MPa (oven) at 56 days.

2) Viability of Ambient Curing: While 50°C oven curing raises unexposed strength by 3.8%–10.1%, 8 M ambient-cured GGBFS-GPC exceeds 52 MPa at 28 days and exhibits lower initial acid-loss percentages than oven-cured cubes, confirming its practicality for cast-in-situ construction.

3) Aggressive Environment Performance: Cyclic 3.5% NaCl exposure increased compressive strength across all mixes (+2.43% to +17.54%), whereas 5% H_2SO_4 caused 19.97%–43.56% degradation; 8 M NaOH provided the highest acid-resilient residual strength (49.73 MPa at 56 days).

Future work should incorporate parallel OPC and fly ash–GGBFS blended controls under identical cyclic regimes, quantify mass loss and sorptivity, perform Rapid Chloride Penetration Tests (RCPT) and half-cell potential monitoring, and apply SEM/XRD analysis to characterize C-A-S-H/N-A-S-H phase evolution.

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