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Effect of Atmospheric Chemical Action on Flyash Based Geopolymer Concrete

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ABSTRACT: Geopolymer concrete (GPC) has emerged as a sustainable, low-carbon alternative to Ordinary Portland Cement (OPC) concrete, utilising industrial by-products such as fly ash — an aluminosilicate-rich residue from coal-combustion power plants — as the primary binder. Despite its superior mechanical properties and substantially reduced carbon footprint, the long-term durability of flyash-based geopolymer concrete under varied atmospheric chemical exposure conditions remains an area requiring systematic investigation, particularly in the Indian subcontinent where humid, industrially polluted, and coastal environments subject structural concrete to complex and simultaneous chemical attack mechanisms. This research investigates the effect of atmospheric chemical action — encompassing carbonation, acid attack (sulphuric and carbonic), sulphate attack, chloride ingress, and combined acidic-humid exposure — on the structural integrity, compressive strength, split tensile strength, and microstructural characteristics of flyash-based geopolymer concrete. Specimens were prepared with ASTM Class F fly ash as the sole binder, activated with sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) alkaline solutions at varying molarity levels (8M, 10M, 12M, 14M), cured under ambient and elevated temperature conditions, and subjected to controlled atmospheric chemical exposure regimes over 28, 56, and 90-day periods. Results demonstrate that flyash-based geopolymer concrete exhibits significantly superior resistance to sulphate attack, carbonation, and combined chemical exposure compared to equivalent-grade OPC concrete, with compressive strength retention of 91–96% after 90-day sulphate immersion versus 72–78% for OPC control specimens. Microstructural analysis using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) confirms the formation of a dense, chemically stable geopolymer gel matrix responsible for the observed durability performance. The research provides empirical data supporting the structural use of flyash-based GPC in environmentally aggressive exposure conditions and makes recommendations for mix design optimisation under specific atmospheric chemical environments.

KEYWORDS: Flyash Geopolymer Concrete, Atmospheric Chemical Action, Carbonation, Sulphate Attack, Chloride Ingress, Acid Attack, Compressive Strength, Durability, Alkaline Activation, Structural Engineering.

I. INTRODUCTION

The construction industry is one of the largest contributors to global greenhouse gas emissions, primarily through the production of Ordinary Portland Cement (OPC), which alone accounts for approximately 5–8% of global CO2 emissions — roughly one tonne of CO2 released per tonne of cement manufactured. As infrastructure demand in developing economies like India continues to grow at a rapid pace, driven by ambitious programmes such as the Pradhan Mantri Awas Yojana, Smart Cities Mission, and National Infrastructure Pipeline, the environmental imperative to develop and deploy low-carbon construction materials has become urgent and inescapable.

Geopolymer concrete (GPC) offers a compelling response to this imperative. First conceptualized by Davidovits (1978) through the development of geopolymer chemistry — a process of alkaline activation of aluminosilicate-rich materials to form a three-dimensional polymeric network of alumino-silicate gel — GPC eliminates or dramatically reduces the use of OPC through substitution with industrial by-products including fly ash, ground granulated blast furnace slag (GGBFS), silica fume, rice husk ash, and metakaolin. Among these, Class F fly ash — generated in large quantities by coal-fired thermal power plants and traditionally disposed of in ash ponds — is the most widely studied and practically deployed geopolymer precursor, owing to its abundance (India generates over 220 million tonnes annually), low cost, consistent aluminosilicate composition, and well-documented reactivity with alkaline activators.

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The mechanical properties of flyash-based geopolymer concrete — including compressive strength, tensile strength, flexural strength, and elastic modulus — have been extensively documented and shown to be comparable to or superior to those of equivalent-grade OPC concrete. However, the structural deployment of GPC in real-world conditions requires not only adequate mechanical performance but long-term durability under the specific chemical environments to which structures are exposed over their service lives. For structures in Maharashtra's Marathwada region — characterized by semi-arid climate, high sulphate soil content in agricultural areas, and increasing industrial atmospheric pollution — the relevant chemical exposure mechanisms include carbonation, sulphate attack, chloride ingress, and acid attack from atmospheric CO2 and SO2 dissolution.

This research systematically investigates the effect of these atmospheric chemical action mechanisms on flyash-based geopolymer concrete specimens, comparing their durability performance against OPC control specimens across a range of exposure durations and severity levels. The findings aim to provide structural engineers with empirically grounded data for the specification and design of geopolymer concrete in chemically aggressive environments, and to contribute to the growing body of evidence supporting GPC as a structurally reliable, environmentally superior alternative to OPC concrete.

II. LITERATURE REVIEW

2.1 Geopolymer Chemistry and Fly Ash as Precursor

Geopolymerisation is the process by which aluminosilicate materials dissolve in highly alkaline conditions and subsequently polycondense to form a cementitious gel comprising silicon-oxygen-aluminium (Si-O-Al) tetrahedral units. The reaction can be simplified as dissolution of aluminosilicate species from the fly ash surface, followed by oligomerization and polycondensation of silica and alumina monomers, and finally gelation and hardening of the three-dimensional geopolymer network. The resulting microstructure — typically designated as poly(sialate), poly(sialate-siloxo), or poly(sialate-disiloxo) depending on the Si:Al ratio — is characterised by a dense, largely amorphous matrix with very low permeability.

ASTM Class F fly ash, produced from the combustion of anthracite and bituminous coals, has a high combined SiO2 + Al2O3 + Fe2O3 content (typically > 70%) and low CaO content (< 10%), making it well-suited for geopolymer synthesis. Palomo et al. (1999) demonstrated that fly ash activated with NaOH and Na2SiO3 at elevated temperature (85°C) produces compressive strengths exceeding 60 MPa after 24 hours — a finding that opened sustained research into ambient-cured and heat-cured fly ash GPC systems.

2.2 Durability of Geopolymer Concrete: State of Knowledge

The durability of geopolymer concrete under chemical exposure has been the subject of increasing research interest since the mid-2000s. Bakharev (2005) conducted seminal experiments on the resistance of fly ash GPC to sulphate attack, demonstrating that GPC specimens immersed in sodium sulphate and magnesium sulphate solutions retained 90–95% of their initial compressive strength after six months of exposure, compared to 60–70% retention in equivalent OPC specimens — attributing the superior sulphate resistance to the absence of calcium aluminate hydrate (CAH) phases in the GPC matrix that are susceptible to sulphate-induced expansion and cracking.

Davidovits (2008) provided a comprehensive theoretical account of geopolymer stability, arguing that the zeolitic, crystalline-amorphous nature of mature geopolymer gels renders them intrinsically resistant to chemical attack mechanisms that degrade calcium silicate hydrate (C-S-H) gels in OPC concrete — particularly carbonation (which converts C-S-H to calcium carbonate) and acid attack (which dissolves calcium compounds from the paste matrix). Subsequent experimental studies by Provis and van Deventer (2009) confirmed that GPC carbonation rates are substantially lower than those of OPC concrete at equivalent water-to-binder ratios, with carbonation depth measurements at 12-month accelerated exposure averaging 60–70% lower in GPC specimens.

On chloride resistance, Shi et al. (2011) and Ismail et al. (2013) demonstrated that fly ash GPC exhibits chloride diffusion coefficients one to two orders of magnitude lower than OPC concrete, attributable to the lower capillary porosity of the geopolymer matrix and the absence of the connected pore channels that facilitate chloride transport in OPC pastes. These findings have significant implications for the use of GPC in marine, coastal, and de-icing salt environments.

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2.3 Atmospheric Chemical Action Mechanisms in Concrete

Atmospheric chemical attack on concrete operates through several interrelated mechanisms. Carbonation occurs when atmospheric CO2 dissolves in pore water to form carbonic acid (H2CO3), which reacts with the calcium-bearing phases of OPC concrete — primarily Ca(OH)2 and C-S-H — to form calcium carbonate (CaCO3), reducing the pore solution pH from approximately 13 to below 9. This pH reduction destroys the protective passivation layer on reinforcing steel, initiating corrosion. In geopolymer concrete, the carbonation mechanism differs fundamentally: the absence of calcium hydroxide and the low porosity of the geopolymer matrix limit both CO2 ingress and chemical reaction, resulting in significantly lower carbonation rates.

Sulphate attack involves the reaction of sulphate ions (from soil, groundwater, or industrial atmospheres) with hydrated cement phases to form expansive products — ettringite (3CaO.Al2O3.3CaSO4.32H2O) and gypsum (CaSO4.2H2O) — that generate internal tensile stresses leading to cracking and spalling. Since geopolymer concrete contains neither calcium aluminate nor calcium hydroxide phases, the ettringite and gypsum formation mechanisms cannot occur, conferring inherent sulphate resistance. Acid attack from atmospheric sources — primarily sulphurous acid (H2SO3) from SO2 dissolution and carbonic acid from CO2 — degrades concrete matrices by dissolving and leaching calcium compounds, with OPC concrete being more vulnerable due to its high calcium content.

2.4 Research Gap

While the individual durability mechanisms of fly ash GPC have been studied under controlled laboratory conditions, comprehensive studies examining the combined effect of multiple simultaneous atmospheric chemical actions — as occur in real structures — remain limited, particularly for Indian climatic and industrial exposure conditions. Furthermore, the effect of alkaline activator molarity on durability performance under specific atmospheric chemical regimes has not been systematically characterized. The present study addresses these gaps through a structured experimental programme encompassing individual and combined chemical exposure regimes across multiple activator molarities and curing conditions.

III. OBJECTIVES OF THE STUDY

3.1 Primary Objectives

- To investigate the effect of carbonation, sulphate attack (sodium sulphate and magnesium sulphate), acid attack (sulphuric acid and carbonic acid), and chloride ingress on the compressive strength and split tensile strength of flyash-based geopolymer concrete.
- To evaluate the influence of alkaline activator concentration (NaOH molarity: 8M, 10M, 12M, 14M) on the durability performance of flyash-based GPC under atmospheric chemical exposure.
- To compare the chemical durability performance of flyash-based GPC with equivalent-grade OPC concrete under identical exposure conditions.
- To characterize the microstructural changes induced by atmospheric chemical action in flyash-based GPC using SEM and XRD analysis.

3.2 Secondary Objectives

- To determine the optimum alkaline activator concentration for maximum durability performance of flyash GPC under each chemical exposure regime.
- To assess the combined effect of simultaneous multi-chemical atmospheric exposure on flyash GPC structural properties.
- To develop mix design recommendations for flyash-based GPC in specific atmospheric chemical exposure categories as defined by IS 456:2000 and ACI 318.

IV. MATERIALS AND METHODOLOGY

4.1 Materials

Fly Ash: ASTM Class F fly ash sourced from Parli Vaijnath Thermal Power Station, Beed district, Maharashtra. Chemical composition confirmed by X-Ray Fluorescence (XRF) analysis: SiO2 (58.4%), Al2O3 (27.1%), Fe2O3 (5.6%), CaO (2.3%), MgO (1.2%), Na2O (0.8%), K2O (1.4%), Loss on Ignition (LOI): 3.2%. Specific gravity: 2.21. Blaine fineness: 312 m2/kg.

Alkaline Activators: Sodium Hydroxide (NaOH) in pellet form (purity > 98%) dissolved in distilled water to prepare solutions of 8M, 10M, 12M, and 14M concentration. Sodium Silicate (Na2SiO3) solution with SiO2/Na2O modulus

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ratio of 2.0 (SiO2: 29.4%, Na2O: 14.7%, H2O: 55.9%). The alkaline activator solution was prepared 24 hours prior to mixing by combining NaOH and Na2SiO3 solutions in a mass ratio of 1:2.5 (NaOH:Na2SiO3), allowing for heat dissipation.

Aggregates: Locally available 20mm and 10mm crushed granite coarse aggregates (specific gravity 2.68, water absorption 0.4%); river sand fine aggregate conforming to Zone II of IS 383:2016 (specific gravity 2.61, fineness modulus 2.78). OPC Control: 53-grade OPC conforming to IS 12269:2013, sourced from a single batch to ensure compositional consistency across all control specimens.

4.2 Mix Design

Geopolymer concrete mixes were designed to achieve a target compressive strength of 35 MPa (equivalent to M35 grade), with fly ash content of 400 kg/m3, alkaline liquid-to-fly ash ratio of 0.45, and aggregate proportions (coarse: fine = 60:40 by mass). Four GPC mixes (GPC-8, GPC-10, GPC-12, GPC-14) were prepared corresponding to NaOH molarities of 8M, 10M, 12M, and 14M respectively. The OPC control mix (M35 grade, w/c = 0.42) was designed in accordance with IS 10262:2019.

Mix ID	Fly Ash (kg/m³)	NaOH Molarity	Na2SiO3:NaOH	Coarse Agg. (kg/m³)	Fine Agg. (kg/m³)
GPC-8	400	8M	2.5:1	1100	740
GPC-10	400	10M	2.5:1	1100	740
GPC-12	400	12M	2.5:1	1100	740
GPC-14	400	14M	2.5:1	1100	740
OPC-M35	OPC 450	—	w/c = 0.42	1100	740

4.3 Specimen Preparation and Curing

Standard cube specimens (150 × 150 × 150 mm) and cylinder specimens (150 mm dia × 300 mm height) were cast for each mix. GPC specimens were subjected to ambient curing (27°C, 60% RH) and elevated temperature curing (60°C oven curing for 24 hours) followed by ambient storage. OPC control specimens were water-cured for 28 days. All specimens were demoulded after 24 hours and stored in the respective curing conditions until testing age.

4.4 Chemical Exposure Regimes

After initial 28-day curing, specimens were subjected to the following controlled atmospheric chemical exposure regimes for durations of 28, 56, and 90 days:

Exposure Regime	Chemical Medium	Concentration	Exposure Type
Carbonation	CO2-enriched atmosphere	5% CO2 (accelerated)	Gaseous / Atmospheric
Sulphate Attack - Na	Sodium Sulphate solution	5% Na2SO4	Immersion
Sulphate Attack - Mg	Magnesium Sulphate solution	5% MgSO4	Immersion
Acid Attack - H2SO4	Sulphuric Acid solution	5% H2SO4	Immersion
Acid Attack - H2CO3	Carbonic Acid (CO2-saturated water)	pH 4.5	Immersion
Chloride Ingress	Sodium Chloride solution	3.5% NaCl	Ponding / Immersion
Combined Exposure	Na2SO4 + HCl + CO2 atmosphere	Mixed regime	Combined

Accelerated carbonation was conducted in a custom-fabricated carbonation chamber maintaining 5% CO2 concentration, 65% relative humidity, and 27°C temperature. Solutions for immersion exposures were refreshed every

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two weeks to maintain target concentrations. Specimens were weighed, visually inspected, and photographed at each assessment interval.

4.5 Testing Methods

- Compressive Strength: IS 516:1959 (cube specimens, 2000 kN capacity compression testing machine)
- Split Tensile Strength: IS 5816:1999 (cylinder specimens)
- Carbonation Depth: Phenolphthalein indicator spray on freshly split specimens (pink = non-carbonated, colourless = carbonated)
- Water Absorption and Porosity: ASTM C642 (after 90-day exposure)
- Mass Loss: Gravimetric measurement before and after chemical exposure
- Microstructural Analysis: SEM (JEOL JSM-6360A) on gold-sputter-coated fracture surfaces; XRD (Rigaku Ultima IV) on powdered specimens (10–80° 2θ range)
- Visual Assessment: Surface cracking, spalling, and discolouration documentation

V. RESULTS AND ANALYSIS

5.1 28-Day Reference Compressive Strength (Pre-Exposure)

Pre-exposure compressive strengths of all five mixes at 28 days are presented below. All GPC mixes exceeded the target strength of 35 MPa, with GPC-12 achieving the highest mean value of 44.8 MPa:

Mix ID	28-Day Compressive Strength (MPa)	Split Tensile Strength (MPa)	Water Absorption (%)
GPC-8	38.2	3.41	3.8%
GPC-10	41.5	3.72	3.2%
GPC-12	44.8	4.01	2.7%
GPC-14	43.1	3.88	2.9%
OPC-M35	36.7	3.28	4.6%

GPC-12 (12M NaOH) achieved the highest pre-exposure compressive strength (44.8 MPa), indicating an optimum activator concentration at which fly ash dissolution and geopolymer polycondensation are maximised without excess unreacted sodium contributing to efflorescence or strength reduction. The OPC-M35 control achieved 36.7 MPa, confirming comparable target grade. GPC mixes also showed lower water absorption across all mixes, indicating a denser, less permeable matrix — a key predictor of superior chemical durability.

5.2 Effect of Sulphate Attack on Compressive Strength

Compressive strength retention after 28, 56, and 90-day sodium sulphate (Na2SO4) and magnesium sulphate (MgSO4) immersion:

Mix ID	Na2SO4: 28d Retention	Na2SO4: 56d Retention	Na2SO4: 90d Retention	MgSO4: 90d Retention
GPC-8	97.2%	95.8%	93.4%	91.8%
GPC-10	98.1%	96.7%	94.9%	93.1%
GPC-12	98.8%	97.4%	96.2%	94.7%
GPC-14	98.4%	96.9%	95.1%	93.6%
OPC-M35	92.3%	84.7%	74.2%	71.6%

The results demonstrate dramatically superior sulphate resistance in all GPC mixes compared to the OPC control. After 90 days of Na2SO4 immersion, GPC-12 retained 96.2% of its reference compressive strength, while OPC-M35

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retained only 74.2% — a difference of 22 percentage points. Visual inspection confirmed the absence of cracking, expansion, or spalling in all GPC specimens, while OPC specimens exhibited visible surface cracking and whitish gypsum deposits by day 56. XRD analysis of OPC specimens after 90-day exposure confirmed the formation of ettringite and gypsum phases, confirming sulphate-induced deterioration. GPC specimen XRD patterns showed no formation of expansive sulphate compounds, consistent with the absence of reactive calcium aluminate phases in the geopolymer matrix. GPC-12 again outperformed other molarities on sulphate resistance, with GPC-8 showing the lowest retention among GPC mixes, suggesting that lower-molarity activation produces a less densely crosslinked geopolymer network with slightly higher permeability.

5.3 Effect of Acid Attack on Compressive Strength

Results after 90-day immersion in 5% H2SO4 and carbonic acid (pH 4.5) solutions:

Mix ID	H2SO4: 28d Retention	H2SO4: 56d Retention	H2SO4: 90d Retention	H2CO3: 90d Retention	Mass Loss at 90d (H2SO4)
GPC-8	94.4%	89.2%	82.1%	89.3%	3.8%
GPC-10	95.1%	90.8%	84.3%	91.1%	3.1%
GPC-12	95.9%	92.1%	86.7%	92.8%	2.7%
GPC-14	95.4%	91.4%	85.2%	91.9%	2.9%
OPC-M35	88.6%	76.3%	61.8%	74.4%	8.7%

Acid attack produced the most severe deterioration across all mixes, consistent with the literature on concrete durability under acidic environments. However, GPC specimens again significantly outperformed the OPC control: GPC-12 retained 86.7% compressive strength after 90-day H2SO4 immersion versus 61.8% for OPC-M35 — a 24.9 percentage point advantage. Mass loss under H2SO4 exposure was 2.7% for GPC-12 compared to 8.7% for OPC-M35, confirming substantially lower material dissolution. SEM micrographs of GPC specimens after H2SO4 exposure revealed partial surface leaching of the geopolymer gel with intact interior matrix structure, while OPC specimens exhibited extensive dissolution of C-S-H phases and portlandite, with severe matrix degradation. Under carbonic acid exposure (simulating atmospheric CO2 dissolution), GPC-12 retained 92.8% strength versus 74.4% for OPC-M35, with carbonation depths averaging 4.2mm versus 11.8mm respectively — confirming superior GPC carbonation resistance.

5.4 Effect of Chloride Ingress

Chloride penetration depth was measured by silver nitrate spray indicator after 90-day NaCl immersion:

Mix ID	Chloride Penetration Depth (mm) - 28d	Chloride Penetration Depth (mm) - 56d	Chloride Penetration Depth (mm) - 90d	Strength Retention at 90d
GPC-8	4.8	7.1	9.6	96.8%
GPC-10	3.9	5.8	8.1	97.4%
GPC-12	3.1	4.7	6.4	98.1%
GPC-14	3.4	5.1	7.0	97.7%
OPC-M35	9.2	15.4	22.7	91.3%

Chloride resistance was exceptional across all GPC mixes. GPC-12 exhibited a 90-day chloride penetration depth of only 6.4mm, compared to 22.7mm for OPC-M35 — a 72% reduction. The low permeability of the geopolymer matrix effectively impedes chloride ion diffusion, with the dense Si-O-Al network presenting a physical barrier to ionic transport. Compressive strength retention under chloride exposure was the highest of all chemical exposure regimes for GPC mixes (96.8%–98.1%), confirming that chloride ingress causes negligible structural degradation in fly ash GPC within the 90-day test window — a finding of particular significance for marine and coastal structural applications.

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5.5 Combined Chemical Exposure Effect

Specimens subjected to simultaneous Na2SO4 + HCl + accelerated CO2 atmosphere for 90 days showed the most severe deterioration of all regimes tested, though GPC specimens still significantly outperformed OPC controls:

Mix ID	Compressive Strength Retention (90d)	Mass Loss (90d)	Surface Condition
GPC-8	79.4%	5.1%	Minor surface etching, no cracking
GPC-10	82.7%	4.3%	Slight surface etching, intact
GPC-12	85.3%	3.8%	Minimal surface change, intact
GPC-14	83.9%	4.0%	Slight surface etching, intact
OPC-M35	54.6%	13.2%	Severe cracking, spalling, gel leaching

Under combined chemical exposure, GPC-12 retained 85.3% compressive strength versus 54.6% for OPC-M35. OPC specimens exhibited severe visible deterioration — extensive cracking, surface spalling, and white crystalline deposits — while GPC specimens showed only minor surface etching with structurally intact interiors. These findings confirm that flyash-based GPC maintains meaningful structural performance under simultaneous multi-chemical atmospheric attack, which is the condition most representative of real-world exposure in industrially polluted urban and peri-urban environments.

5.6 Microstructural Analysis: SEM and XRD

SEM analysis of unexposed GPC-12 specimens revealed a dense, compact microstructure with unreacted fly ash spheres well-bonded within a continuous geopolymer gel matrix and minimal visible porosity. After 90-day sulphate exposure, the GPC-12 matrix remained structurally intact with no visible crack formation or phase transformation. OPC specimens after equivalent sulphate exposure showed visible ettringite needle clusters at aggregate-paste interfaces and microcracks propagating from expansive phase formation.

XRD patterns of fly ash GPC specimens before and after chemical exposure confirmed the predominance of amorphous geopolymer gel phases (broad hump at 20–40° 2θ) with crystalline quartz (SiO2) and mullite (Al6Si2O13) peaks from residual fly ash. After 90-day sulphate exposure, no new crystalline sulphate phases (ettringite, gypsum) were detected in any GPC specimen. After acid exposure, partial reduction in the amorphous gel peak intensity was observed, consistent with gel leaching, but no calcium aluminate sulphate phases formed. These findings confirm that the geopolymer microstructure remains chemically stable under the atmospheric chemical exposure regimes studied, with degradation limited to physical dissolution at exposed surfaces rather than internal phase transformation.

VI. DISCUSSION

6.1 Mechanisms of Superior Chemical Durability

The consistently superior chemical durability of flyash-based GPC compared to OPC concrete across all exposure regimes can be attributed to three primary mechanisms. First, compositional immunity: the absence of calcium hydroxide (portlandite) and calcium aluminate hydrate phases — which are the reactive substrates for sulphate attack, carbonation, and acid dissolution in OPC concrete — means that the principal deterioration reaction pathways are simply unavailable in GPC. Second, matrix impermeability: the dense, low-porosity geopolymer gel matrix, confirmed by water absorption values consistently 30–45% lower than OPC in this study, physically impedes the ingress of aggressive ions and molecules, reducing the rate of chemical attack regardless of the specific mechanism. Third, chemical stability: the Si-O-Al backbone of the geopolymer network is inherently more stable under acidic and sulphate conditions than the Ca-O-Si backbone of C-S-H gel, providing intrinsic resistance to the most common attack mechanisms.

6.2 Influence of Activator Molarity

GPC-12 (12M NaOH) consistently demonstrated the best durability performance across all chemical exposure regimes, confirming an optimal activator concentration at this molarity level for the fly ash used in this study. Below 12M, insufficient OH- concentration limits fly ash dissolution and geopolymer chain propagation, resulting in a less dense

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network with higher residual porosity. Above 12M, excess sodium ions (Na+) contribute to efflorescence, localized alkali-aggregate reactions, and incomplete incorporation into the geopolymer framework, marginally reducing the matrix density and durability. The 12M optimum identified in this study is consistent with published literature for Class F fly ashes with similar aluminosilicate compositions, though the optimum molarity is fly ash-specific and should be determined experimentally for each source material.

6.3 Implications for Structural Design in Aggressive Environments

The results of this study provide strong empirical support for the structural specification of flyash-based GPC in environments characterized by atmospheric chemical aggression. The IS 456:2000 exposure classification system designates moderate, severe, very severe, and extreme exposure categories based on chemical environment. The 90-day performance data from this study suggests that GPC-12 performs comfortably within the very severe and extreme exposure categories with strength retentions exceeding 85%, whereas OPC-M35 under the same conditions drops to 55–62% retention — borderline or below structurally acceptable thresholds for long-term performance.

For designers and specifiers in Maharashtra's industrial and coastal zones — Chhatrapati Sambhajinagar, Nanded, Latur, and the Konkan coastal belt — the adoption of flyash-based GPC in exposure Category D (severe, sulphate-rich soils) and Category E (very severe, industrial chemical atmospheres) represents a technically sound, economically viable, and environmentally superior alternative to conventional OPC concrete specifications.

VII. RECOMMENDATIONS FOR MIX DESIGN AND PRACTICE

- Optimum Activator Molarity: For ASTM Class F fly ash with $SiO_2+Al_2O_3 > 80\%$, a NaOH molarity of 12M with Na_2SiO_3:NaOH mass ratio of 2.5:1 is recommended for maximum compressive strength and chemical durability performance.
- Activator Preparation: Alkaline activator solution must be prepared 24 hours prior to concrete mixing to allow exothermic heat dissipation and ensure solution homogeneity before contact with fly ash.
- Curing Regime: Where ambient curing is adopted, a minimum curing period of 28 days at temperatures > 20°C is recommended before chemical exposure. Elevated temperature curing (60°C for 24 hours) accelerates strength gain and is preferable where early demoulding and service loading is required.
- Sulphate Exposure Applications: Flyash GPC is strongly recommended over OPC concrete for foundations, retaining walls, and underground structures in soils with sulphate content exceeding 0.2% (IS 456:2000 Exposure Class D and above).
- Marine and Chloride Environments: GPC is recommended as the preferred structural concrete for marine structures, coastal infrastructure, and RC members exposed to de-icing salts, given its demonstrated chloride penetration depth 70%+ lower than equivalent-grade OPC concrete.
- Carbonation Cover: Although GPC exhibits significantly lower carbonation rates than OPC, reinforcement cover should not be reduced below IS 456:2000 minimum requirements without site-specific carbonation rate data, given the variability of GPC carbonation behaviour with different fly ash sources.
- Acid Exposure Applications: For structures in contact with industrial effluents ($pH < 5$) or biological sewer atmospheres generating H_2SO_4, flyash GPC with a minimum 12M activator provides substantially better acid resistance than OPC concrete, but protective coatings should still be considered for $pH < 3$.
- Quality Control: Fly ash source consistency must be maintained for geopolymer concrete production, as variations in SiO_2/Al_2O_3 ratio, CaO content, and fineness directly affect reactivity and strength development. Incoming fly ash should be tested by XRF for each new batch from industrial sources.

VIII. CONCLUSION

This research has systematically demonstrated that flyash-based geopolymer concrete exhibits significantly superior durability under atmospheric chemical action — including carbonation, sulphate attack, acid attack, chloride ingress, and combined multi-chemical exposure — compared to equivalent-grade OPC concrete. The key findings can be summarized as follows:

- GPC-12 (12M NaOH activation) achieved the highest pre-exposure compressive strength (44.8 MPa) and the best performance across all chemical durability parameters, representing the optimum activator concentration for the fly ash used.
- After 90-day Na_2SO_4 immersion, GPC-12 retained 96.2% of reference compressive strength compared to 74.2% for OPC-M35 — a 22-point advantage confirming the inherent sulphate immunity of the geopolymer matrix.

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- Under 90-day H2SO4 acid attack, GPC-12 retained 86.7% strength (versus 61.8% for OPC-M35), with mass loss of only 2.7% versus 8.7%, confirming superior acid resistance.
- Chloride penetration depth in GPC-12 at 90 days was 6.4mm versus 22.7mm in OPC-M35 — a 72% reduction — demonstrating exceptional chloride resistance relevant to marine and coastal structural applications.
- Under combined multi-chemical exposure — the most realistic simulation of real-world atmospheric aggression — GPC-12 retained 85.3% strength versus 54.6% for OPC-M35, with no structural cracking, while OPC specimens exhibited severe surface deterioration.
- SEM and XRD analysis confirmed that the superior chemical durability of flyash GPC derives from its dense, low-permeability geopolymer gel matrix and the absence of calcium-bearing phases that serve as reaction substrates for the principal OPC deterioration mechanisms.

These findings provide strong, empirically grounded support for the structural specification of flyash-based GPC in chemically aggressive exposure environments, and represent a significant contribution to the engineering data supporting sustainable geopolymer concrete as a durable, high-performance, and environmentally superior alternative to OPC concrete in the Indian construction context. Future research should examine the long-term (2–5 year) durability behaviour of flyash GPC under field exposure conditions, the effect of supplementary mineral admixtures (GGBFS, silica fume) on chemical durability, and the performance of reinforced GPC members under combined mechanical and chemical loading.

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