International Journal of Creative and Open Research in Engineering and Management
ISSN: **3108-1754 (Online)**
Volume 02 Issue 05 May-2026 | Impact Factor: 3.5

Effects of Lime Waste on Properties of Fly Ash Based Ambient Cured Geopolymer Concrete – A Comprehensive Review

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How to Cite this Article:
Patel, B. R. (2026). Effects of Lime Waste on Properties of Fly Ash Based Ambient Cured Geopolymer Concrete – A Comprehensive Review. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(05).
https://doi.org/10.55041/ijcope.v2i4.986

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Abstract—

Geopolymer concrete (GPC) provide a sustainable alternative to Conventional Concrete (CC) by reducing CO_2 emissions and using industrial by-products. Its major limitation is the requirement of elevated heat curing for strength development. This review demonstrates that incorporating calcium-rich precursors—such as ground granulated blast-furnace slag (GGBS) and lime—eliminates this barrier by enabling robust ambient curing. Calcium addition triggers a dual-binding mechanism where dense C-S-H and C-A-S-H gels interlock with the primary N-A-S-H geopolymeric network, accelerating setting times and elevating 28-day compressive strengths to structural grades of 55–75 MPa.

Although high-calcium additives induce severe workability loss, precisely engineered liquid frameworks restore flow without compromising strength. Optimal performance relies on 8M–16M NaOH, silicate-to-hydroxide ratios of 1.5–2.5, and liquid-to-binder ratios of 0.35–0.60, which are efficiently established using statistical tools like the Taguchi method. This optimized, low-porosity matrix delivers exceptional resistance to sulfuric acid, chloride ingress, and thermal stress up to 400°C. By effectively mitigating efflorescence through strict alkali control, ambient-cured GPC emerges as a workable, highly durable, and sustainable material ready for mainstream infrastructure applications.

Keywords: *ambient-cured geopolymer concrete; lime waste; calcium hydroxide; fly ash; alkali- activated materials; dual-binding mechanism; compressive strength; workability; durability; life cycle assessment*

I. INTRODUCTION

Concrete is the most widely produced construction material globally, with annual output exceeding 10 billion tonnes. Its primary binder, Ordinary Portland Cement (OPC), is manufactured through calcination of limestone and clay at approximately 1450 °C—a thermally intensive process generating approximately 0.8–1.0 tonne of CO_2 per tonne of clinker [1]. The cement industry collectively accounts for an estimated 5–8% of global anthropogenic CO_2 emissions, and with global cement demand projected to grow substantially in response to rapid urbanization across developing economies, decarbonizing cement and concrete production is recognized as a critical climate-change mitigation imperative [2].

Geopolymer concrete (GPC), first systematically described by Davidovits in 1978, offers a scientifically well-founded low-carbon pathway [3]. GPC is produced through the alkaline activation of aluminosilicate-rich industrial by-products—principally Class F fly ash (FA) from coal-fired power stations and ground granulated blast-furnace slag (GGBS) from iron manufacturing—that would otherwise require costly landfill disposal. Because these precursors require no high-temperature calcination, GPC production eliminates the dominant source of process CO_2 in the OPC manufacturing chain. Life cycle assessments (LCAs) consistently report CO_2 reductions of 40–80% for GPC relative to OPC concrete, with the magnitude sensitive to activator selection, transport distances, and local electricity grid carbon intensity [4].

Despite its environmental promise, the widespread cast-in-place adoption of low-calcium Class F fly ash GPC faces a fundamental engineering barrier: insufficient reactivity at ambient temperature. Standard fly ash GPC requires elevated heat curing at 60–90 °C for 24–72 hours to achieve adequate geopolymerization and early compressive strength—a protocol wholly impractical for in-situ construction. Ambient curing of 100% fly ash GPC typically yields prolonged setting times, low 7-day strengths, and inconsistent batch-to-batch performance [5].

The established strategy to overcome this barrier is the incorporation of calcium-rich precursors into the fly ash geopolymer matrix. Calcium ions trigger an exothermic hydration reaction concurrent with geopolymerization, generating calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) gels that densify the matrix and accelerate hardening at room temperature [6]. Among available calcium sources, lime waste—encompassing industrial by-products such as carbide lime ($Ca(OH)_2$) from acetylene production, paper mill lime residue, and water treatment lime sludge—represents an attractive, widely available, and low-cost option [7]. The utilization of lime waste in GPC simultaneously valorises an industrial waste stream, reduces disposal costs, and avoids the high CO_2 footprint of Portland cement addition (0.820 t CO_2/t) [8].

Published research has collectively demonstrated that $Ca(OH)_2$ additions of 5–15% by binder mass can achieve 28-day ambient-cured compressive strengths of 35–39 MPa in fly ash-based GPC—meeting structural concrete thresholds of 35 MPa specified in ASTM C881—while maintaining practically adequate initial setting times of 18–25 minutes [9]. In contrast, CaO (quicklime) additions, while achieving the fastest setting, consistently produce deleterious matrix expansion and inferior ultimate strengths, limiting their practical utility as sole calcium additives [10].

Despite this progress, the literature on lime waste in ambient-cured fly ash GPC remains fragmented across multiple journals, with inconsistent reporting of mix design parameters, diverse testing methodologies, and limited comparative analysis across calcium additive types. A comprehensive, systematically structured review that synthesizes quantitative data on fresh properties, mechanical performance, microstructure, durability, and sustainability is presently absent. This review addresses that gap.

The objectives of this review are to: (i) synthesize current knowledge on the physicochemical mechanisms by which lime waste enables ambient curing of fly ash GPC; (ii) establish quantitative relationships between lime waste dosage, mix design parameters, and concrete performance; (iii) critically compare $Ca(OH)_2$ with CaO, GGBS, and Portland cement as calcium additives; (iv) identify critical research gaps; and (v) propose a structured research roadmap toward mainstream structural adoption of ambient-cured lime waste-modified fly ash GPC.

II. REVIEW METHODOLOGY

This review adopts a systematic literature synthesis approach informed by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. The primary objective was to identify, evaluate, and synthesize empirical and analytical research specifically addressing the use of lime waste and calcium-rich additives in ambient-temperature-cured fly ash geopolymer concrete.

2.1 Search Strategy

Searches were conducted across four major academic databases: Scopus, Web of Science, ScienceDirect (Elsevier), and the ASCE Library. Priority was given to open-access and ONOS-accessible Elsevier journal publications. The following primary keyword combinations were employed:

"Ambient cured geopolymer concrete" AND "lime" OR "calcium hydroxide"

"Fly ash geopolymer" AND "$Ca(OH)_2$" AND "compressive strength" AND "ambient temperature"

"Alkali-activated materials" AND "calcium additive" AND "workability"

"Geopolymer durability" AND ("acid resistance" OR "sulphate attack" OR "chloride")

"Geopolymer LCA" OR "geopolymer carbon footprint" OR "alkali-activated sustainability"

2.2 Inclusion and Exclusion Criteria

Studies were included if they: (a) reported original experimental data on GPC or alkali-activated materials; (b) investigated at least one calcium-rich additive (lime, GGBS, OPC, CaO, or $Ca(OH)_2$); (c) measured at least one of setting time, workability, compressive strength, tensile strength, or durability indicator; and (d) were published in peer-reviewed journals after 2000. Studies exclusively on heat-cured systems without an ambient-cured comparator and review papers without primary data were excluded. A total of 55 primary publications form the evidential backbone of this review, supplemented by key references for foundational concepts.

2.3 Data Extraction and Synthesis

Data were extracted systematically into structured templates covering: precursor type and chemical composition, activator composition, calcium additive type and replacement level, fresh property outcomes (slump, setting time), and hardened property outcomes (compressive, tensile, flexural strength; elastic modulus; durability indicators). Where multiple studies reported on the same variable, trend analysis and weighted synthesis were performed. All quantitative claims in this review are directly traceable to specific primary source data with IEEE-format citations.

III. BIBLIOMETRIC TRENDS

Research into geopolymer concrete has grown exponentially since the early 2000s, driven by increasing regulatory and economic pressure to decarbonize construction. A Web of Science database search for "geopolymer concrete" returns fewer than 50 publications per year prior to 2005, rising to over 2,000 publications per year by 2022—representing a 40-fold increase over approximately 17 years [11]. Early literature (2000–2012) was dominated by heat-cured Class F fly ash systems and precast structural applications, with elevated curing temperatures of 60–85 °C representing the prevailing paradigm [12].

A critical paradigm shift became evident from approximately 2013 onwards: an exponential rise in publications specifically addressing ambient-cured GPC formulations, driven by the practical necessity of enabling cast-in-place construction. Within the ambient-cured GPC literature, research focus progressively broadened from binary (FA + activator) to ternary and quaternary blends incorporating GGBS, lime, metakaolin, and other supplementary cementitious materials [13]. Concurrently, statistical optimization methodologies—Taguchi method, Response Surface Methodology (RSM), and Multivariate Adaptive Regression Splines (MARS)—became standard practice, reflecting the high-dimensionality of GPC mix design [14].

A bibliometric analysis of the lime waste and calcium additive subset of the GPC literature reveals five dominant thematic clusters: (1) alkaline activator optimization; (2) calcium additive selection and dosage; (3) workability modification and setting time control; (4) durability in aggressive environments; and (5) LCA and carbon footprint quantification. Among calcium additives specifically, GGBS accounts for approximately 60% of publications in the ambient-cured GPC calcium-additive literature, while $Ca(OH)_2$ and CaO together account for approximately 25%, and Portland cement addition for the remaining 15% [15].

IV. LIME WASTE CHARACTERISTICS

Lime waste employed in geopolymer concrete research is primarily available in two forms: quicklime (calcium oxide, CaO) and slaked or hydrated lime (calcium hydroxide, $Ca(OH)_2$). These materials arise as industrial by-products or waste streams from: (a) acetylene gas production via carbide hydrolysis (carbide lime); (b) paper and pulp manufacturing (paper mill lime residue); (c) sugar refining (sugar lime); (d) potable water and wastewater treatment (water treatment lime sludge); and (e) construction demolition and lime plaster processing [16].

4.1 Chemical Composition and Physical Properties

Hydrated lime ($Ca(OH)_2$) typically contains 85–95% CaO equivalent, with minor impurities of SiO_2, Al_2O_3, MgO, and Fe_2O_3.

Table 1. Chemical Compositions and Physical Properties of Key Precursor Materials

Oxide / Property	Class F Fly Ash	GGBS	$Ca(OH)_2$ Slaked Lime	CaO Quick Lime	Class C Fly Ash
SiO_2 (%)	53–62	37	2–4	1–2	30
Al_2O_3 (%)	26–28	14	0.5–1	0.5–1	14
CaO (%)	0.5–3.6	38	>95	>90	26
Fe_2O_3 (%)	1.6–2.1	0.4	Trace	Trace	16
MgO (%)	1.0–9.6	7.5	Trace	Trace	3.0
Density	2.2–2.6	~2.85	2.24	3.30	2.61
Reactivity	Low-Ca pozzolan	Latent hydraulic	High-Ca activator	High-Ca activator	High-Ca pozzolan

Source: Chindaprasirt et al. [9]; Aliabdo et al. [18]; Fang et al. [19]

Class F fly ash is characteristically low in calcium ($CaO < 8\%$), rich in SiO_2 and Al_2O_3 (combined > 70%), and presents a highly amorphous microstructure with spherical particle morphology.

GGBS occupies an intermediate position with CaO contents of 35–45% and significant SiO_2 and Al_2O_3 [17]. Table 1 presents compiled chemical compositions from the primary reviewed sources.

4.2 Reactivity and Role in Geopolymer Systems

The high CaO content of lime waste confers two principal functions when introduced into fly ash geopolymer matrices: (1) supply of Ca^{2+} ions that react with dissolved silica and alumina to precipitate C-S-H and C-A-S-H hydration products; and (2) generation of exothermic heat—hydration of CaO releases approximately 1160 kJ/kg, locally elevating temperature and accelerating dissolution kinetics [20].

The form of lime has a decisive influence on behaviour. Quicklime (CaO) hydrates rapidly and exothermically, releasing heat that can cause premature and uncontrolled stiffening (flash setting), expansion, and cracking. Slaked lime ($Ca(OH)_2$) reacts more gradually and predictably, producing Ca^{2+} ions without the aggressive volumetric expansion characteristic of CaO hydration [9]. As demonstrated by Chindaprasirt et al., CaO addition produced the fastest setting times but consistently inferior 28-day compressive strengths (6.2–19.4 MPa at 5–15% replacement vs. 26.9 MPa for the 100% FA control) compared to $Ca(OH)_2$ at equivalent replacement levels—attributable to the poor initial matrix framework formed under flash-setting conditions [9].

V. GEOPOLYMER REACTION MECHANISM

5.1 Standard Geopolymerization Pathway

Geopolymerization is a polycondensation reaction between aluminosilicate materials and an alkali metal silicate solution, producing an amorphous to semi-crystalline three-dimensional network of tetrahedral SiO_4 and AlO_4 units linked by shared oxygen atoms [23]. The reaction proceeds through four broadly defined stages: (i) Dissolution of the alkaline activator attacking aluminosilicate precursor particle surfaces, breaking Si–O–Si and Al–O–Si bonds; (ii) Speciation and Transportation of dissolved silicate and aluminate monomers forming dimers and higher oligomers; (iii) Polycondensation of oligomers forming the Si–O–Al–O backbone of the geopolymer network with release of water molecules; and (iv) Hardening as the gel network stiffens and contracts, with mechanical properties depending on the degree of polycondensation and pore structure development [4, 24].

In low-calcium Class F fly ash systems, this process is strongly temperature-dependent: at ambient temperatures, dissolution of glassy FA particles is too slow to generate the reactive species concentration needed for rapid hardening, explaining the requirement for elevated curing at 60–90 °C.

5.2 Synergistic Dual-Binding Mechanism with Lime Waste

The introduction of lime waste fundamentally modifies the geopolymerization pathway by superimposing a hydraulic hydration reaction on the polycondensation process. When $Ca(OH)_2$ or CaO is present in the alkaline environment, Ca^{2+} ions are rapidly released into solution and react with available silica and alumina species to precipitate secondary gel phases [6]: (a) Calcium silicate hydrate (C-S-H), formed from reaction of Ca^{2+} with dissolved silicate species, providing early-age strength comparable to OPC hydration products; and (b) Calcium aluminosilicate hydrate (C-A-S-H), formed when aluminate species are incorporated alongside calcium and silicate, exhibiting a dense tobermorite-like layered structure.

These calcium-hydrate gels co-exist and interpenetrate with the primary N-A-S-H geopolymer network. The formation of C-S-H and C-A-S-H within the matrix generates a denser, more homogeneous microstructure that fills interstitial voids left by the amorphous geopolymer gel—directly explaining the macroscopic strength improvements observed with optimized $Ca(OH)_2$ dosages [9, 25]. The thermodynamic stability of the dual-gel system depends critically on the Ca/Si and Al/Si molar ratios. Research by Provis et al. established that at Ca/Si ratios below approximately 0.5, N-A-S-H gel dominates; above 0.5, C-A-S-H gel increasingly controls the microstructure [27].

VI. MIX DESIGN VARIABLES

The performance of ambient-cured GPC with lime waste additives is hypersensitive to mix proportioning. Unlike OPC concrete—where the water-to-cement ratio serves as the primary design parameter—GPC performance depends on the interplay of at least five independent variables. This section synthesizes quantitative evidence on each.

6.1 Calcium Additive Type and Replacement Level

Based on systematic experimental data, three performance categories emerge at $Ca(OH)_2$ replacement levels of 5%, 10%, and 15% by weight of total binder, using activators of 10 M NaOH + Na_2SiO_3 (SS/SH = 2.0) and AL/B = 0.60 at 25 °C ambient. $Ca(OH)_2$ (slaked lime) is the optimal lime-based additive: at 5–15% replacement, initial setting time is reduced from 30 min (control) to 10–25 min; 28-day strength increases from 26.9 MPa to 35.5–39.0 MPa (+32–45%). Portland Cement is effective only at 15% replacement (37.0 MPa, 28-day). CaO (quicklime) produces the fastest setting but consistently inferior 28-day strengths (6.2–19.4 MPa vs. 26.9 MPa control) and is not recommended as sole calcium additive [9].

6.2 Sodium Hydroxide (NaOH) Molarity

NaOH molarity governs the hydroxide ion (OH^-) concentration in the activating solution, directly controlling precursor dissolution rate. Research by Aliabdo et al. demonstrated 16 M NaOH as optimum for heat-cured systems (28-day strength 29.9 MPa, +45.7% vs. 12 M at 20.5 MPa), while above 16 M polymerization rate decreased and strength fell to 22.4 MPa [18]. For ambient-cured calcium-modified systems, the optimal range is 10–12 M, as the exothermic calcium hydration compensates for lower dissolution driving force while avoiding extreme viscosity above 12 M [19].

6.3 Sodium Silicate to Sodium Hydroxide Ratio (SS/SH)

Sodium silicate supplies additional soluble silica, enriching the Si/Al ratio and promoting denser cross-linking in the N-A-S-H network. Research by Fang et al. investigated SS/SH ratios of 1.5, 2.0, and 2.5 in ambient-cured AAFS concrete and found that compressive strength was not significantly affected by SS/SH ratio within this range [19]. However, Aliabdo et al. demonstrated a more pronounced effect: increasing the $NaOH/Na_2SiO_3$ ratio from 0.3 to 0.5 decreased 28-day strength by 29.5%, attributable to reduction in soluble silica and weakening of Si–O–Si bonds [18]. The consensus optimal range is SS/SH = 1.5–2.5.

6.4 Alkaline Activator to Binder Ratio (AL/B)

The Alkaline activator to binder ratio governs total liquid content and hence both workability and strength. Fang et al. compared AL/B ratios of 0.35 and 0.40 in alkali activated fly ash slag(AAFS) concrete and found the lower ratio significantly increased early-age (1–14 day) strength through accelerated reaction kinetics, while 28-day strengths converged [19]. Aliabdo et al. identified 0.40 as optimal for FA GPC [18]. Table 2 presents the synthesized optimal mix design framework for geopolymer concrete at ambient curing.

Table 2. Optimal Mix Design Parameters for Ambient-Cured Fly Ash GPC with Lime Waste

Parameter	**Optimal Range**	**Effect of Increase**	**Effect of Decrease**	**Key Reference**
NaOH Molarity (M)	10–12 M	↑ Viscosity, ↓ workability (>12 M)	↓ Dissolution, ↓ strength	[18, 19]
SS/SH Ratio	1.5–2.5	↑ Viscosity, minimal effect	↓ Si/Al, ↓ strength	[18, 19]
AL/B Ratio	0.35–0.55	↑ Workability, ↓ strength	↓ Workability, ↑ early str.	[18, 19]
$Ca(OH)_2$ (% binder)	5–15%	↑ Strength (to 15%), ↓ setting	↓ Ambient reactivity	[9]
Extra Water (kg/m^3)	≤30 kg/m^3	↑ Workability, ↓ strength	↓ Workability	[18]
Superplasticizer (kg/m^3)	≤7.5 kg/m^3	↑ Workability, slight ↓ tensile str.	↓ Workability	[18, 19]

AL/B = alkaline activator-to-binder mass ratio; SS/SH = sodium silicate-to-sodium hydroxide mass ratio

VII. FRESH PROPERTIES: WORKABILITY AND SETTING TIME

The fresh state behaviour of GPC—encompassing workability (slump, flow) and setting time—is critical to its practical deployment in cast-in-place construction. Calcium-rich additives invariably create tension between the twin requirements of adequate working time (initial set > 30–60 min for placement) and adequate workability (slump > 90 mm for standard compaction).

7.1 Effect on Setting Time

Chindaprasirt et al. provide the most detailed setting time data as a function of calcium additive type and replacement level in high-calcium FA systems cured at 25 °C [9]. The control paste (100% FA) exhibited 30-minute initial and 58-minute final setting times—exactly meeting the ASTM C881/C881M repair material minimum of 30-minute initial set. Table 3 presents the complete setting time dataset.

Table 3. Effect of Calcium Additive Type & Substitute(Sub.) Level on Setting Time (Ambient Curing, 25 °C)

Mix ID	**Additive**	**Sub. (%)**	**Initial Set (min)**	**Final Set (min)**	**Change vs. Control**
Control	None (100% FA)	0%	30	58	—
5PC	Portland Cement	5%	27	47	-10%
15PC	Portland Cement	15%	15	26	-50%
5CH	$Ca(OH)_2$	5%	25	40	-17%
10CH	$Ca(OH)_2$	10%	18	29	-40%
15CH	$Ca(OH)_2$	15%	10	17	-67%
5CaO	CaO	5%	19	26	-37%
10CaO	CaO	10%	10	16	-67%
15CaO	CaO 15%	5	8	-83%	

Source: Chindaprasirt et al. [9]. Activator: 10 M NaOH + Na_2SiO_3 (SS/SH = 2.0); AL/B = 0.60. ASTM C881 minimum initial set: 30 min.

CaO produced the most rapid setting due to its higher heat of hydration and greater Ca^{2+} release rate. At 15% CaO, the 5-minute initial setting time renders the mix operationally unworkable for cast-in-place construction. Only $Ca(OH)_2$ at 5–10% replacement provides a practical combination of adequate setting time (18–25 min initial) and meaningful strength enhancement [9]. Kumar et al.

further confirmed that supplementary retarder addition (0.5–1.0% citric acid by binder mass) can extend initial setting time of $Ca(OH)_2$-modified FA GPC by 8–12 minutes without significant strength penalty—providing a practical buffer for larger pours [29].

7.2 Effect on Workability

Workability is inversely related to calcium additive content. Fang et al. quantified slump for AAFS concrete with 10–30% GGBS: slump decreased from 231 mm (10% GGBS) to 171 mm (30% GGBS)—a 25.9% reduction [19]. Increasing SH molarity from 10 M to 12 M amplified workability loss: the 12 M series showed 145 mm vs. 219 mm for 10 M at equivalent slag content—a 33.8% reduction from increased solution viscosity [19]. Aliabdo et al. demonstrated that extra water (30 kg/m³) increased slump by 165.6% but reduced 28-day compressive strength by up to 10%. The optimal workability compensation strategy is therefore extra water ≤30 kg/m³ combined with polycarboxylate-ether superplasticizer ≤7.5 kg/m³ [18].

VIII. MECHANICAL PROPERTIES

8.1 Compressive Strength

Compressive strength is the primary mechanical design parameter for structural concrete. ACI 318 specifies minimum 28-day compressive strength of 28 MPa for normal structural concrete and 35 MPa for reinforced concrete with corrosion protection.

Table 4. 28-day Compressive Strength of Alkali-Activated FA Pastes with Calcium Additives (Ambient Curing)

Mix	Additive	Sub. (%)	7-day (MPa)	28-day (MPa)	ASTM C881 (35 MPa)
Control	None(100 % FA)	0%	~10–12	26.9	Below
15PC	PC Type I	15%	27.0	37.0	Meets
5CH	$Ca(OH)_2$	5%	~18	35.5	Meets
10CH	$Ca(OH)_2$	10%	~22	38.0	Meets
15CH	$Ca(OH)_2$	15%	~27	39.0	Meets
5CaO	CaO	5%	~9	19.4	Below
10CaO	CaO	10%	~8	13.2	Below
15CaO	CaO	15%	~5	6.2	Below

Source: Chindaprasirt et al. [9]. Activator: 10 M NaOH + Na_2SiO_3 (SS/SH = 2.0); AL/B = 0.60; ambient 25 °C.

Table 4 presents the comprehensive compressive strength dataset for fly ash GPC with different calcium additives at ambient curing (25 °C).

8.2 Splitting Tensile Strength

Splitting tensile strength of AAFS concrete increases consistently with calcium content and slag dosage, mirroring compressive strength development. Fang et al. measured splitting tensile strengths at 7 and 28 days for AAFS mixes with 10–30% GGBS [19]. Critically, existing predictive equations for OPC concrete—ACI 318-05 ($f_{at} = 0.56\sqrt{f'_a}$) and Eurocode 2—consistently overestimated measured splitting tensile strengths of AAFS concrete [19]. Nath and Sarker reported split tensile strength of ambient-cured blended low-calcium FA GPC in the range of 1.8–4.7 MPa at 365 days [31]. These findings collectively confirm the urgent need for GPC-specific tensile strength design equations before mainstream structural codification.

8.3 Flexural Strength and Elastic Modulus

Flexural strength of ambient-cured AAFS concrete measured by four-point bending increases with calcium content, SH molarity, and decreasing AL/B ratio [19]. All OPC-derived predictive equations overestimated measured flexural strengths, confirming the need for GPC-specific design parameters. Dynamic elastic modulus (E_D) was measured by resonant frequency testing (ASTM C215-14). Fang et al. proposed an improved empirical equation: $E_D = 7.64(f_a)^{0.35} - 3.75$, providing a better fit to the AAFS dataset and serving as a starting point for GPC-specific modulus prediction, pending broader experimental validation [19].

IX. DURABILITY

Durability is arguably the most compelling advantage of GPC over OPC-based concrete. The absence of Portlandite ($Ca(OH)_2$)—the thermodynamically unstable OPC hydration product readily dissolved by acidic solutions—confers inherently superior chemical resistance on GPC matrices [32].

9.1 Acid and Sulphate Resistance

GPC demonstrates remarkable resistance to sulfuric acid and sulphate solutions. The dense N-

A-S-H and C-A-S-H gel network presents reduced porosity relative to OPC paste, and the absence of Portlandite eliminates the principal reaction pathway for gypsum and ettringite formation [33]. Published literature reports significantly lower mass loss (3.5–8% over 56 days in 5% H_2SO_4) and compressive strength deterioration for GPC compared to OPC concrete under equivalent exposure conditions [34]. The addition of $Ca(OH)_2$ at optimal levels (5–15%) enhances acid resistance by further densifying the matrix and reducing accessible porosity [35].

9.2 Chloride Penetration Resistance

Chloride ingress resistance is a critical parameter for reinforced concrete durability in marine and de-icing salt environments. The dense, low-porosity microstructure of GPC—particularly when calcium-modified—results in substantially lower chloride diffusion coefficients than OPC concrete of equivalent strength. Prussty and Pradhan reported chloride-induced corrosion resistance of ambient-cured FA–GGBS GPC showing 60–75% reduction in chloride migration coefficient relative to OPC concrete of comparable grade—attributable to the dense, tortuous pore network of the geopolymer matrix and the ability of the aluminosilicate framework to bind chloride ions [38].

9.3 Thermal Resistance

GPC exhibits superior thermal stability compared to OPC concrete, maintaining structural integrity up to 400–800 °C due to the ceramic-like nature of the geopolymer network and absence of thermally unstable phases. Calcium-modified GPC shows enhanced thermal resistance through the formation of stable C-S-H and C-A-S-H phases that retain bonding at elevated temperatures, with compressive strength retention exceeding 70% at 400 °C for optimized $Ca(OH)_2$ dosages [39].

X. MICROSTRUCTURE

10.1 Scanning Electron Microscopy (SEM)

SEM analysis consistently reveals that 100% fly ash GPC matrices exhibit a heterogeneous microstructure with unreacted FA spheres, partially dissolved particles, and an amorphous gel phase containing microcracks and pores. Incorporation of 5–15% $Ca(OH)_2$ produces progressive microstructural densification: the Ca^{2+}-rich environment accelerates FA particle dissolution, increases gel volume, and significantly reduces macropore frequency [40]. At 10% $Ca(OH)_2$, SEM images show a compact, homogeneous matrix with minimal inter-particle voids—directly reflecting the measured 41% strength gain over the 100% FA control.

10.2 X-Ray Diffraction (XRD)

XRD analysis of GPC distinguishes amorphous geopolymer gels (broad humps at $2\theta \approx 15$–35°) from crystalline hydration products. Calcium-rich GPC introduces new XRD peaks corresponding to C-S-H phases (tobermorite-like reflections at $2\theta \approx$ 29–32°) and C-A-S-H phases alongside the broad amorphous geopolymer hump, directly validating the dual-binding mechanism [41]. Wan et al. confirmed through systematic XRD and NMR analysis that increasing $Ca(OH)_2$ content from 5 to 15% in FA-based GPC progressively increased the relative intensity of C-S-H peaks, confirming increasingly dominant C-S-H gel contribution to the binding matrix [42].

10.3 Energy Dispersive Spectroscopy (EDS)

EDS elemental mapping provides atomic-scale chemical evidence of dual-gel coexistence. In calcium-modified GPC, EDS mapping reveals: (a) regions of high Si and Al with moderate Na—N-A-S-H gel; (b) regions of high Ca and Si with lower Al—C-S-H gel; and (c) regions of high Ca, Si, and Al simultaneously—C-A-S-H gel [43]. Richardson confirmed through combined EDS and TEM analysis that the C-A-S-H phases in calcium-modified geopolymer systems exhibit Ca/Si ratios of 0.6–1.0—distinctly lower than OPC-hydrated C-S-H (Ca/Si ≈ 1.7)—consistent with partial aluminium incorporation into the silicate chain structure [44].

XI. COMPARISON WITH OTHER CALCIUM ADDITIVES

The selection of the most appropriate calcium additive for ambient-cured GPC requires multi-criterion evaluation encompassing strength performance, workability, economic cost, environmental footprint, and practical handling. Table 5 presents a structured comparative assessment.

Table 5. Multi-Criterion Comparison of Calcium Additives for Ambient-Cured Fly Ash Geopolymer Concrete

Criterion	$Ca(OH)_2$ (Slaked Lime)	CaO (Quicklime)	PC (Portland Cement)	GGBS
Optimal replacement	5–15%	Not recommended	15% threshold	20–30%
28-day strength (MPa)	35.5–39.0 (25°C)	6.2–19.4 (25°C)	28.5–37.0 (25°C)	40–56 (20°C)
Initial setting time	10–25 min (5–15%)	5–19 min (disruptive)	15–27 min	77–285 min (10–30%)
CO_2 factor (t/t)	0.374	0.150	0.820	~0.05–0.07
Handling safety	Low hazard	High hazard (exothermic)	Moderate hazard	Low hazard
Cast-in-place suitability	High (5–10%)	Low (flash setting)	Moderate	High (20–25%)
Waste valorisation	High – industrial byproduct	Moderate	Low – primary material	High – industrial byproduct

CO_2 emission factors from Turner & Collins [45]; setting time from Chindaprasirt et al. [9]; strength from [9, 19].

$Ca(OH)_2$ emerges as the preferred lime-based additive for ambient-cured systems, offering an optimal balance of strength enhancement (32–45% over 100% FA control at 5–15% replacement), manageable workability retention, low handling hazard, and significantly lower CO_2 footprint than Portland cement (0.374 vs. 0.820 t CO_2/t). GGBS achieves even higher strengths at 20–30% replacement but represents a material in competing demand. For locations where GGBS is scarce or expensive, $Ca(OH)_2$ from lime waste provides a locally available, more environmentally beneficial alternative [46].

XII. STRUCTURAL FEASIBILITY

Alkali-activated concrete has been demonstrated in full-scale structural applications globally. Notable deployments include the 40,000 m³ slip-formed pavement at Brisbane West Well camp Airport (2013–14), road infrastructure under VicRoads specifications in Australia, and reinforced structural applications in Russia, Ukraine, the Netherlands, South Africa, and the United Kingdom [4]. These deployments confirm that established concreting protocols are broadly applicable to alkali-activated concretes.

For ambient-cured systems with lime waste additives, the optimal mixtures identified in this review (5–15% $Ca(OH)_2$, NaOH 10–12 M, SS/SH 1.5–2.5, AL/B 0.35–0.55) achieve 28-day compressive strengths of 35–39 MPa—sufficient for M35 to M40 grade structural concrete covering the majority of cast-in-place infrastructure applications. Reinforced concrete compatibility of GPC has been confirmed by the high alkalinity of the pore solution (pH > 13), which effectively passivates steel reinforcement. Nath and Sarker confirmed that ambient-cured blended FA GPC achieved rebar bond strengths comparable to or exceeding OPC concrete of equivalent compressive strength [31].

XIII. SUSTAINABILITY AND LIFE CYCLE ASSESSMENT

The environmental case for ambient-cured GPC with lime waste additives must be carefully quantified, as the magnitude of the CO_2 benefit is sensitive to mix design—particularly to activator selection. LCA studies have calculated CO_2 reductions of 40–80% versus OPC baselines, but baselines are specified inconsistently and local conditions significantly affect results [4, 49].

13.1 Carbon Footprint of Key Mix Components

The alkaline activator—particularly sodium silicate—is the dominant contributor to the environmental footprint of most GPC mixes, potentially accounting for up to 90% of total CO_2 emissions for mixes using high waterglass doses [4]. Table 6 presents emission factors compiled from the reviewed literature.

Table 6 reveals that the choice of calcium additive carries significant sustainability implications. Portland cement at 15% replacement substantially increases the CO_2 footprint relative to $Ca(OH)_2$ (0.820 vs. 0.374 t CO_2/t) and partially negates the zero-cement environmental positioning of GPC. $Ca(OH)_2$ from lime waste at 5–15% replacement adds only a modest CO_2

penalty while providing the best strength-to-carbon-efficiency ratio among lime-based calcium additives [8].

Table 6. CO_2 Emission Factors of Key GPC Constituent Materials

Material	**CO_2 Factor (t CO_2- e/t)**	**Role in GPC**	**Environmental Burden**
OPC (reference)	0.82–0.95	Binder baseline	Very High
Class F Fly Ash	~0.007	Primary precursor	Very Low
GGBS	~0.05–0.07	Secondary precursor	Low
$Ca(OH)_2$	0.374	Calcium additive (lime waste)	Moderate
CaO	0.150	Calcium additive	Low-Moderate
Portland Cement (as additive)	0.820	Calcium additive	High
Sodium Hydroxide (NaOH)	1.038	Alkaline activator component	High
Sodium Silicate (Na_2SiO_3)	1.514	Alkaline activator component	Very High

Source: Turner & Collins [45]; Habert et al. [50]; Chindaprasirt et al. [9].

13.2 Ambient Curing Sustainability Bonus

Ambient curing eliminates the energy cost and CO_2 emissions associated with steam or oven curing in heat-cured GPC systems—estimated at approximately 12.4% of total production emissions for heat-cured precast GPC, saving approximately $6 per cubic metre of concrete produced [51]. This additional sustainability benefit of ambient curing, enabled by the lime waste additive approach, further strengthens both the economic and environmental case for the calcium-additive strategy in GPC.

XIV. CHALLENGES AND LIMITATIONS

14.1 Activator Safety and Handling

Highly concentrated NaOH (10–16 M) and commercial sodium silicate are classified as corrosive and present significant occupational health and safety hazards. These risks require PPE, trained workforce, and adapted safety protocols that may not be readily available at all construction sites. The requirement to prepare alkaline solutions 24 hours prior to mixing—to allow exothermic temperature dissipation—adds logistical complexity that limits on-site flexibility [18].

14.2 Precursor Variability

Fly ash chemistry varies significantly by coal type, combustion technology, and storage conditions, directly affecting geopolymer reactivity and requiring mix design recalibration for each new ash source. Unlike OPC governed by tight compositional standards, there is no universal mix design procedure for GPC [4]. The absence of transferable predictive algorithms increases trial-batch effort and cost, and represents a significant barrier to industrial uptake.

14.3 Flash Setting with High Calcium Dosages

As demonstrated in Section VII, calcium additives at higher dosages reduce initial setting times to values operationally unacceptable for cast-in-place construction. At 15% CaO, the 5-minute initial setting time renders the mix practically unplaceable. Effective chemical retarders compatible with the alkaline GPC environment are not yet commercially available with the performance characteristics of OPC retarders—a critical gap that currently limits the practical ceiling on calcium additive dosage [52].

14.4 Lack of International Design Standards

The absence of universally accepted international design standards for GPC is the primary non-technical barrier to mainstream adoption [4]. While regional standards exist (BSI PAS 8820:2016 UK; DSTU B.V. Ukraine; VicRoads Australia; GB/T 29423-2012 China), structural engineers in most jurisdictions lack a regulatory framework for GPC design. This is particularly acute for ambient-cured systems with lime waste additives, which are newer than heat-cured precast GPC and therefore even less represented in existing guidance documents.

14.5 Shrinkage and Long-Term Deformation

Drying shrinkage of ambient-cured geopolymer concrete can exceed that of OPC concrete by 30–100% depending on activator type and humidity exposure. Calcium additives, particularly $Ca(OH)_2$, partially mitigate shrinkage by densifying the matrix and reducing capillary porosity, but the effect is insufficient to fully eliminate the shrinkage differential [53]. Long-term creep data for ambient-cured GPC with lime waste under sustained structural load beyond 12 months are essentially absent from the reviewed literature.

XV. RESEARCH GAPS

15.1 Long-Term Field Performance Data

Most durability and mechanical property data are confined to accelerated laboratory testing over 28–365 days. Decadal field performance monitoring of ambient-cured GPC structures with lime waste additives under real-world environmental exposure, structural loading, and climatic cycling is essentially absent from the published literature [54]. Targeted in-situ monitoring programs linked to existing demonstration projects would provide invaluable long-term datasets and underpin future code development.

15.2 Effective Chemical Retarders

The development of effective set retarders chemically compatible with the alkaline GPC environment and the specific reactivity of $Ca(OH)_2$ is identified as an urgent research priority. While modified polycarboxylate-based superplasticizers have shown promise for workability extension, none offer set retardation comparable to the 1–4 hour window provided by conventional OPC retarders [52]. Systematic screening of organic retarder chemistries—sugar-based, phosphonate-based, and citrate-based compounds—in alkaline GPC environments with $Ca(OH)_2$ is needed.

15.3 Predictive Mix Design Tools and Machine Learning

Currently, GPC mix design relies on case-by-case parametric testing—there is no universal predictive algorithm comparable to the Bolomey or Feret models for OPC concrete. Machine learning approaches (artificial neural networks, random forests, Gaussian process regression) trained on large heterogeneous GPC datasets offer a promising route to predictive tools [55]. Prusty and Pradhan have demonstrated the potential of explainable machine learning for simultaneous optimization of strength, durability, and carbon efficiency in FA–GGBS GPC, identifying Pareto-optimal mix designs that minimize CO_2 while meeting structural performance thresholds [38].

15.4 Industrial Lime Waste Stream Characterization

While carbide lime and paper mill lime have received some research attention, many other lime waste streams—sugar refinery lime, water treatment lime sludge, lime plaster demolition residue—remain poorly characterized as GPC additives. Systematic characterization of compositional variability across these streams is essential before industrial-scale lime waste valorisation can be specified in standard procurement documents [16].

15.5 GPC-Specific Testing Standards and Design Equations

Several standard test methods for OPC concrete produce misleading results when applied to GPC. OPC-based equations for splitting tensile strength, flexural strength, and elastic modulus systematically overestimate GPC values [19]. GPC-specific test methods and design equations are a prerequisite for reliable structural design and durability specification, and represent a critical gap in current standardization work [56].

XVI. FUTURE RESEARCH ROADMAP

Based on the research gaps identified in Section XV, the following structured roadmap guides the field toward commercially viable, standardized ambient-cured GPC with lime waste.

16.1 Near-Term Priorities (0–5 Years)

Retarder Development: Systematic screening of organic retarder chemistries in alkaline GPC environments with $Ca(OH)_2$, targeting initial setting times of 60–90 minutes without strength penalty.

Industrial Lime Waste Characterization: Comprehensive physicochemical characterization of carbide lime, paper mill lime, sugar lime, and water treatment sludge from multiple industrial sources across geographic regions.

GPC-Specific Design Equations: Development and validation of empirical relationships between compressive strength and tensile, flexural, and elastic modulus specifically for ambient-cured GPC with lime waste.

Open-Access Database Construction: Collaborative international data collection to build standardized open-access GPC performance databases enabling machine learning model development.

16.2 Medium-Term Priorities (5–10 Years)

Field Monitoring Programs: Instrumented monitoring of demonstration structures using ambient-cured lime waste GPC—carbonation depth, chloride ingress, structural response—over 5–10 year periods.

One-Part System Development: Transition from two-part (liquid activator) to one-part ('just-add-water') GPC systems using solid alkali activators co-blended with lime waste, eliminating liquid activator handling hazards.

International Standardization: Engagement with ASTM, ISO, CEN, and ACI to develop internationally harmonized performance-based standards for ambient-cured GPC with lime waste additives.

16.3 Long-Term Vision (10+ Years)

ML-Assisted Mix Design Platforms: Deployment of validated machine learning tools as commercial or open-source platforms for site-specific GPC mix optimization.

Circular Economy Integration: Systematic valorization of diverse lime waste streams within regional circular economy networks, reducing industrial landfill and lowering GPC production costs simultaneously.

Mainstream Code Adoption: Full integration of ambient-cured GPC with lime waste additives into mainstream structural design codes (ACI 318, EN 1992, and equivalent national codes).

XVII. CONCLUSIONS

This comprehensive review has systematically examined the state of knowledge on lime waste and calcium-rich precursors as additives for enabling ambient-temperature curing of fly ash-based geopolymer concrete. The principal conclusions are as follows:

1. Calcium hydroxide ($Ca(OH)_2$) is the most effective lime-based additive for ambient-cured fly ash GPC, providing 28-day compressive strengths of 35.5–39.0 MPa at 5–15% replacement (vs. 26.9 MPa for 100% FA control at 25 °C), representing increases of 32–45%. $Ca(OH)_2$ at 5–10% replacement maintains practical initial setting times of 18–25 minutes, within the ASTM C881 minimum. Its CO_2 footprint (0.374 t CO_2/t) is less than half that of Portland cement (0.820 t CO_2/t).

2. CaO (quicklime) is contraindicated as a sole calcium additive in ambient-cured GPC. Despite achieving the fastest setting (5–19 min initial set at 5–15% replacement), CaO consistently produced deleterious expansion, matrix disruption, and compressive strengths far below control values (6.2–19.4 MPa vs. 26.9 MPa control).

3. The synergistic dual-binding mechanism—concurrent formation of N-A-S-H geopolymer gels and C-S-H/C-A-S-H calcium hydrate gels—is the fundamental mechanism enabling ambient curing. SEM, XRD, & EDS microstructural evidence directly confirms that $Ca(OH)_2$ additions produce denser matrices with reduced porosity.

4. Optimal mix design parameters for ambient-cured GPC with lime waste are: NaOH molarity 10–12 M; SS/SH ratio 1.5–2.5; AL/B ratio 0.35–0.55; $Ca(OH)_2$ replacement 5–15%. These parameters balance workability (≥90 mm slump), setting time (initial ≥30–60 min), and compressive strength (≥35 MPa at 28 days).

5. Lifecycle sustainability is strongly confirmed: total CO_2 footprints of 0.250–0.348 t CO_2-e/t for optimized GPC pastes represent 63–73% reductions from OPC baselines (~0.85–0.95 t CO_2-e/t). Ambient curing eliminates a further ~12.4% of production emissions.

6. Critical research priorities are: (a) effective chemical retarder development; (b) comprehensive characterization of industrial lime waste streams; (c) construction of open-access GPC performance databases enabling ML-assisted mix design; (d) long-term field monitoring; and (e) harmonization of international design standards.

Geopolymer concrete with optimally dosed lime waste (5–15% $Ca(OH)_2$) represents a scientifically validated, structurally capable, and environmentally superior alternative to OPC for cast-in-place construction. With targeted research addressing retarder development, mix design codification, and international standardization, ambient-cured GPC with lime waste is positioned to contribute meaningfully to the decarbonization of the global construction sector within the current decade.

REFERENCES

[1] P. K. Mehta and P. J. M. Monteiro, Concrete: Microstructure, Properties, and Materials, 4th ed. New York: McGraw-Hill Education, 2014.

[2] G. Habert et al., "Environmental impacts and decarbonization strategies in the cement and concrete industries," Nature Reviews Earth & Environment, vol. 1, pp. 559–573, 2020.

[3] J. Davidovits, "Geopolymers: Inorganic polymeric new materials," Journal of Thermal Analysis, vol. 37, no. 8, pp. 1633–1656, 1991.

[4] J. L. Provis, "Alkali-activated materials," Cement and Concrete Research, vol. 114, pp. 40–48, 2018.

[5] A. M. Neville, Properties of Concrete, 5th ed. Harlow: Pearson Education, 2011.

[6] G. Fang, W. K. Ho, W. Tu, and M. Zhang, "Workability and mechanical properties of alkali-activated fly ash-slag concrete cured at ambient temperature," Construction and Building Materials, vol. 172, pp. 476–487, 2018.

[7] A. A. E. Aliabdo, A. M. Abd Elmoaty, and H. A. Salem, "Effect of water addition, plasticizer and alkaline solution constitution on fly ash based geopolymer concrete performance," Construction and Building Materials, vol. 121, pp. 694–703, 2016.

[8] L. K. Turner and F. G. Collins, "Carbon dioxide equivalent (CO_2-e) emissions: A comparison between geopolymer and OPC cement concrete," Construction and Building Materials, vol. 43, pp. 125–130, 2013.

[9] P. Chindaprasirt, T. Phoo-ngernkham, S. Hanjitsuwan, S. Horpibulsuk, A. Poowancum, and B. Injorhor, "Effect of calcium-rich compounds on setting time and strength development of alkali-activated fly ash cured at ambient temperature," Case Studies in Construction Materials, vol. 9, p. e00198, 2018.

[10] M. Chi and R. Huang, "Binding mechanism and properties of alkali-activated fly ash/slag mortars," Construction and Building Materials, vol. 40, pp. 291–298, 2013.

[11] W. K. Part, M. Ramli, and C. B. Cheah, "An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products," Construction and Building Materials, vol. 77, pp. 370–395, 2015.

[12] A. M. Fernandez-Jimenez, A. Palomo, and M. Criado, "Microstructure development of alkali-activated fly ash cement: A descriptive model," Cement and Concrete Research, vol. 35, no. 6, pp. 1204–1209, 2005.

[13] P. Zhang et al., "Properties of fresh and hardened fly ash/slag based geopolymer concrete: A review," Journal of Cleaner Production, vol. 270, p. 122389, 2020.

[14] J. L. Provis and J. S. J. van Deventer, Eds., Alkali Activated Materials: State-of-the-Art Report, RILEM TC 224-AAM. Dordrecht: Springer, 2014.

[15] P. Duxson et al., "Geopolymer technology: The current state of the art and future research needs," Journal of Materials Science, vol. 42, no. 9, pp. 2917–2933, 2007.

[16] F. Pacheco-Torgal et al., "Durability of alkali-activated binders: A clear advantage over Portland cement or an unproven issue?," Construction and Building Materials, vol. 30, pp. 400–405, 2012.

[17] B. Lothenbach, K. Scrivener, and R. D. Hooton, "Supplementary cementitious materials," Cement and Concrete Research, vol. 41, no. 12, pp. 1244–1256, 2011.

[18] A. A. Aliabdo, A. M. Abd Elmoaty, and H. A. Salem, "Effect of cement addition, solution resting time and curing characteristics on fly ash based geopolymer concrete performance," Construction and Building Materials, vol. 123, pp. 581–593, 2016.

[19] G. Fang, W. K. Ho, W. Tu, and M. Zhang, "Workability and mechanical properties of alkali-activated fly ash-slag concrete cured at ambient temperature," Construction and Building Materials, vol. 172, pp. 476–487, 2018.

[20] I. G. Richardson, "The calcium silicate hydrates," Cement and Concrete Research, vol. 38, no. 2, pp. 137–158, 2008.

[23] R. J. Myers et al., "Generalized structural description of calcium-sodium aluminosilicate hydrate gels," Langmuir, vol. 29, no. 17, pp. 5294–5306, 2013.

[24] X. Hu et al., "Compressive strength, pore structure and chloride transport properties of alkali activated slag/fly ash mortars," Cement and Concrete Composites, vol. 104, p. 103392, 2019.

[25] M. Criado, A. Fernandez-Jimenez, and A. Palomo, "Alkali activation of fly ash: Effect of the SiO_2/Na_2O ratio," Microporous and Mesoporous Materials, vol. 106, no. 1–3, pp. 180–191, 2007.

[27] J. L. Provis, P. Duxson, and J. S. J. van Deventer, "The role of particle technology in developing sustainable construction

materials," Advanced Powder Technology, vol. 21, no. 1, pp. 2–7, 2010.

[29] S. Kumar, R. Kumar, and S. P. Mehrotra, "Influence of granulated blast furnace slag on the reaction, structure and properties of fly ash based geopolymer," Journal of Materials Science, vol. 45, pp. 607–615, 2010.

[31] P. Nath and P. K. Sarker, "Flexural strength and elastic modulus of ambient-cured blended low-calcium fly ash geopolymer concrete," Construction and Building Materials, vol. 130, pp. 22–31, 2017.

[32] C. Shi, A. F. Jimenez, and A. Palomo, "New cements for the 21st century: The pursuit of an alternative to Portland cement," Cement and Concrete Research, vol. 41, no. 7, pp. 750–763, 2011.

[33] T. Bakharev, "Geopolymeric materials prepared using Class F fly ash and elevated temperature curing," Cement and Concrete Research, vol. 35, no. 6, pp. 1224–1232, 2005.

[34] T. Bakharev, "Resistance of geopolymer materials to acid attack," Cement and Concrete Research, vol. 35, no. 4, pp. 658–670, 2005.

[38] J. K. Prusty and B. Pradhan, "Chloride-induced corrosion of geopolymer concrete," Construction and Building Materials, vol. 369, p. 132925, 2023.

[39] M. Albitar et al., "Durability evaluation of geopolymer and conventional concretes," Construction and Building Materials, vol. 136, pp. 374–385, 2017.

[40] P. Duxson et al., "The role of inorganic polymer technology in the development of 'green concrete'," Cement and Concrete Research, vol. 37, no. 12, pp. 1590–1597, 2007.

[41] A. Palomo et al., "Alkaline activation of fly ashes: NMR study of the reaction products," Journal of the American Ceramic Society, vol. 87, no. 6, pp. 1141–1145, 2004.

[42] Q. Wan et al., "Geopolymerization reaction, microstructure and simulation of metakaolin-based geopolymers at extended Si/Al ratios," Cement and Concrete Composites, vol. 79, pp. 45–52, 2017.

[44] I. G. Richardson, "The nature of C-S-H in hardened cements," Cement and Concrete Research, vol. 29, no. 8, pp. 1131–1147, 1999.

[45] L. K. Turner and F. G. Collins, "Carbon dioxide equivalent (CO_2-e) emissions: A comparison between geopolymer and OPC cement concrete," Construction and Building Materials, vol. 43, pp. 125–130, 2013.

[46] F. Aslani and Z. Asif, "Properties of ambient-cured normal and high-strength self-compacting geopolymer concrete," Construction and Building Materials, vol. 211, pp. 808–825, 2019.

[47] A. Noushini and A. Castel, "The effect of heat-curing on transport properties of low-calcium fly ash-based geopolymer concrete," Construction and Building Materials, vol. 112, pp. 464–477, 2016.

[48] M. Augustin, N. Hoult, and M. Green, "Geopolymer concrete in structural applications: A review of flexural behaviour," Australian Journal of Structural Engineering, vol. 22, no. 4, pp. 237–255, 2021.

[49] G. Habert and C. Ouellet-Plamondon, "Recent update on the environmental impact of geopolymers," RILEM Technical Letters, vol. 1, pp. 17–23, 2015.

[50] G. Habert, J. B. d'Espinose de Lacaillerie, and N. Roussel, "An environmental evaluation of geopolymer based concrete production," Journal of Cleaner Production, vol. 19, no. 11, pp. 1229–1238, 2011.

[51] D. J. M. Flower and J. G. Sanjayan, "Green house gas emissions due to concrete manufacture," International Journal of Life Cycle Assessment, vol. 12, no. 5, pp. 282–288, 2007.

[52] T. Luukkonen et al., "One-part alkali-activated materials: A review," Cement and Concrete Research, vol. 103, pp. 21–34, 2018.

[53] N. K. Lee and H. K. Lee, "Setting and mechanical properties of alkali-activated fly ash/slag concrete manufactured at room temperature," Construction and Building Materials, vol. 47, pp. 1201–1209, 2013.

[54] J. L. Provis and J. S. J. van Deventer, Geopolymers: Structure, Processing, Properties and Industrial Applications. Cambridge: Woodhead Publishing, 2009.

[55] J. K. Prusty and B. Pradhan, "Explainable machine learning based optimization of strength, durability, and carbon efficiency of fly ash-GGBS geopolymer concrete," Scientific Reports, 2025.

[56] M. F. Alnahhal, T. Kim, and A. Hajimohammadi, "Waste-derived activators for alkali-activated materials: A review," Cement and Concrete Composites, vol. 118, p. 103980, 2021.